

# Traffic Assignment and Feedback Research to Support Improved Travel Forecasting



**Prepared for:**  
Federal Transit Administration  
Office of Planning and Environment  
Under Contract No. DTFT60-11-D-00009

**Prepared by:**  
Caliper Corporation

**Cover photos:**

"Link and I-5 southbound from S 144th Street" by SounderBruce / CC BY 2.0

"Dallas\_Exterior\_2086" by Kinkisharyo / CC BY 2.0

"Future City" by Neil Kremer / CC BY 2.0

"Seattle Trolley Bus" by Oran Viriyinci / CC BY 2.0

"Phoenix Traffic Assignment" and "Intersection Simulation" courtesy of Caliper Corporation

# ***Traffic Assignment and Feedback Research to Support Improved Travel Forecasting***

## ***FINAL REPORT***

*Prepared for:*

Federal Transit Administration  
Office of Planning and Environment  
Under Contract No. DTFT60-11-D-00009

### **Prepared by**

Caliper Corporation  
1172 Beacon St  
Newton, MA 02461  
[www.caliper.com](http://www.caliper.com)

July 31, 2015

**DISCLAIMER NOTICE** This document is disseminated under the sponsorship of the United States Department of Transportation (USDOT) in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. The United States Government does not endorse products of manufacturers. Trademarks or manufacturers' names appear in the document only because they are essential to the objective of this report. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the USDOT or of the Metropolitan Planning Organizations that participated in the research.



# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 31-07-2015		<b>2. REPORT TYPE</b> Final Report		<b>3. DATES COVERED (From - To)</b> 23-09-2011 to 31-07-2015	
<b>4. TITLE AND SUBTITLE</b>  Traffic Assignment and Feedback Research to Support Improved Travel Forecasting				<b>5a. CONTRACT NUMBER</b> DTFT60-11-D-00009	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b>  Howard Slavin, Jim Lam, and Kanchana Nanduri				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Caliper Corporation 1172 Beacon St., Suite 300 Newton, MA 02461				<b>8. PERFORMING ORGANIZATION REPORT</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Federal Transit Administration Office of Planning & Environment Analysis Division, TPE-22 1200 New Jersey Avenue, SE Washington, D.C. 20590				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b>					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>  This research investigated whether or not current traffic assignment and model feedback practices are sufficiently accurate for calculating congested highway travel times and for quantifying the highway benefits of major transit projects. Examination of U.S. MPO modeling practices indicated widespread deficiencies in implementation. Empirical investigation of assignment and feedback convergence errors present in some of the better MPO models indicated that with available methodological improvements and more extensive computation, existing methods could produce plausible estimates of highway and transit project impacts. Comparisons between modeled and measured congested travel times from commercial sources indicated that models tended to underestimate travel speeds, and that use of speed data would be beneficial in model calibration and validation.					
<b>15. SUBJECT TERMS</b> Traffic assignment, user equilibrium, travel time measurement, demand model calibration and validation, speed feedback, model convergence					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>  314	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (include area code)</b>

Standard Form 298 (Rev. 8-98)



# Table of Contents

<b>Chapter 1 Introduction and Executive Summary .....</b>	<b>1-1</b>
Study Approach .....	1-2
Inventory of MPO Modeling Practices .....	1-3
MPO traffic assignment practices .....	1-3
MPO feedback practices .....	1-3
Detailed Examination of Selected MPO models .....	1-4
An Overview of the 5 MPO Models .....	1-4
Network geography and attributes .....	1-5
Volume-delay functions .....	1-5
Assignment methods and convergence .....	1-5
Traffic Assignment Investigations and Findings .....	1-5
Validation of models with traffic counts .....	1-6
Feedback Research and Findings .....	1-7
Project Impact Analysis .....	1-7
Congested Travel Times from MPO Models .....	1-8
Summary Conclusions and Recommendations .....	1-9
Recommendations for FTA guidance .....	1-10
Research recommendations .....	1-11
Concluding remarks .....	1-11
<b>Chapter 2: Inventory of MPO Traffic Assignment Modeling Practices .....</b>	<b>2-1</b>
Introduction .....	2-1
Background on Equilibrium Traffic Assignment Models and Convergence .....	2-2
Current MPO Traffic Assignment Procedures .....	2-13
Concluding Remarks .....	2-15
<b>Chapter 3 Current Practices in Computing Model Feedback .....</b>	<b>3-1</b>
Background on Feedback Convergence .....	3-1
Feedback Methods in Use .....	3-5
Concluding Remarks .....	3-7
<b>Chapter 4: Overview of the ARC, MAG, NCTCOG, PSRC, and SANDAG Models .....</b>	<b>4-1</b>
Model Information Summary Tables .....	4-2
MPO Model Formulations .....	4-8
Trip purposes .....	4-8
Travel modes .....	4-9
Traffic Assignment Problem Characteristics .....	4-9
Network size & software .....	4-9
Geographic network representation .....	4-10
Turn prohibitions and penalties .....	4-10
Centroid connectors .....	4-12
Area types .....	4-16

AM trip characteristics .....	4-20
Capacities .....	4-25
PCEs for vehicle classes .....	4-26
Transit preloads .....	4-26
Assignment generalized cost impedance functions .....	4-26
Values of time .....	4-26
Volume-delay functions .....	4-27
MPO Base Model Traffic Assignments .....	4-34
Trip speeds .....	4-35
Concluding Remarks .....	4-39
<b>Chapter 5 Traffic Assignment Models and Tests .....</b>	<b>5-1</b>
Traffic Assignment Runs .....	5-2
Volume-to-capacity ratios .....	5-4
Zero flow link analysis .....	5-7
Convergence Error Analysis .....	5-9
Comparison of Assignment Volumes and Traffic Counts .....	5-14
ARC flows and counts .....	5-15
MAG flows and counts .....	5-17
NCTCOG flow versus count comparison .....	5-20
PSRC flow versus count comparison .....	5-23
SANDAG flow versus count comparisons .....	5-24
Validation of multi-class assignments .....	5-32
Other Traffic Assignment Investigations .....	5-33
Analysis of operating costs in traffic assignment impedance .....	5-33
PSRC trip rounding analysis .....	5-38
Conclusions .....	5-41
<b>Chapter 6 Feedback Methods and Convergence Tests .....</b>	<b>6-1</b>
Overview of the 5 MPO Model Feedback Approaches .....	6-1
Closure metrics and tolerances .....	6-3
Initial speeds .....	6-3
Bus speeds .....	6-3
Appropriateness of feedback closure metrics .....	6-4
Feedback Runs .....	6-5
Feedback runs with the MAG model .....	6-6
NCTCOG model feedback runs .....	6-12
Feedback in the PSRC model .....	6-20
Feedback runs with SANDAG activity-based model .....	6-20
Conclusions .....	6-26
<b>Chapter 7 Project Impact Analysis .....</b>	<b>7-1</b>
Impact of a Roadway Project in Atlanta .....	7-2
Impact of a Roadway Project in Phoenix .....	7-7
MAG mode choice and assignment with highway project added .....	7-11
MAG single loop run with highway project added .....	7-13
MAG full model run with highway project added .....	7-16
Impact of a Transit Improvement Project in Phoenix .....	7-19

MAG mode choice and assignment with transit project added.....	7-20
Transit project impacts assessed with a MAG full model run .....	7-25
Impact of a Roadway Project in Dallas-Ft. Worth.....	7-31
NCTCOG AM highway assignment-only results with highway project added .....	7-32
Added lanes assessed with the NCTCOG mode choice and assignment models .....	7-34
Lane expansion evaluated with a full NCTCOG model run .....	7-37
Impact of a Light Rail Extension in Dallas-Ft. Worth .....	7-41
Light rail extension impact with the NCTCOG mode choice and assignment models.....	7-43
Light rail extension impact assessed with an NCTCOG full model run .....	7-47
Impact of a Roadway Project in the Puget Sound region .....	7-54
Impact of a widened arterial in the PSRC region.....	7-54
PSRC full model run with highway project added.....	7-60
Impact of a Roadway Project in San Diego .....	7-63
Assignment-only analysis .....	7-64
Impacts assessed with a single model loop.....	7-68
SANDAG full model run with highway project added .....	7-70
Impact of a Transit Project in San Diego .....	7-74
Transit project impacts with a SANDAG single loop model run.....	7-75
Transit project impacts from a full SANDAG model run.....	7-79
Conclusions .....	7-85

**Chapter 8 Congested Travel Time Analysis .....8-1**

ARC Model Speed Analysis .....	8-3
MAG Model Speed Analysis.....	8-9
Comparison of MAG Planning Model Travel Times with INRIX and Microsimulation-based DTA Travel Times.....	8-16
NCTCOG Model Speed Analysis .....	8-21
PSRC Model Speed Analysis .....	8-28
SANDAG Model Speed Analysis.....	8-35
MPO Model VHT Summary Comparison.....	8-42
Comparison of Modeled Travel Times with Google Travel Times.....	8-43
Concluding Remarks .....	8-55

**Chapter 9 Concluding Discussion of Study Findings and  
    Recommendations .....9-1**

Perspectives on the Study Findings .....	9-1
User equilibrium traffic assignment models and their convergence .....	9-2
Feedback procedures and guidance .....	9-3
Congested travel times produced by travel models.....	9-3
Validation of traffic assignment models .....	9-4
Project evaluation and benefits estimation .....	9-5
The Value of in-depth empirical review of models.....	9-5
Computational burden .....	9-5
Validation of travel models .....	9-5
Options for National Implementation .....	9-6
Research Suggestions .....	9-8



# List of Figures

- Figure 2-1 Comparisons of the Relative Gap and VHT GAP .....2-4
- Figure 2-2 DC Regional Network PM Frank-Wolfe Assignment.....2-5
- Figure 2-3 Road Traffic Changes Due to Blue Line Service Improvement:  
Relative Gap = 0.01 .....2-6
- Figure 2-4 Road Traffic Changes Due to Blue Line Service Improvement:  
Relative Gap = 0.000001 .....2-7
- Figure 2-5 DC Regional PM Multi-Class Bi-Conjugate FW Assignments.....2-8
- Figure 2-6 DC Regional PM Multi-Class Assignment Runs with Different UE Algorithms.....2-9
- Figure 2-7 Average & Maximum Link Flow Convergence Errors .....2-11
- Figure 2-8 Flow Differences from User Equilibrium at Varying Convergence Levels .....2-12
- Figure 4-1 HERE Turn Prohibitions in the ARC Region .....4-11
- Figure 4-2 Centroid Connectors per Zone for Each MPO .....4-12
- Figure 4-3 Distribution of Centroid Connector Lengths .....4-14
- Figure 4-4 Area Type Maps.....4-17
- Figure 4-5 ARC Freeway Volume-Delay Function .....4-27
- Figure 4-6 ARC Arterial Volume-Delay Function .....4-28
- Figure 4-7 ARC Collector Volume-Delay Function .....4-28
- Figure 4-8 MAG Rural Freeway Volume-Delay Function .....4-29
- Figure 4-9 MAG Outlying CBD Arterial Volume-Delay Function .....4-29
- Figure 4-10 MAG CBD Collector Volume-Delay Function .....4-30
- Figure 4-11 NCTCOG Freeway Volume-Delay Function .....4-30
- Figure 4-12 NCTCOG Arterial Volume-Delay Function .....4-31
- Figure 4-13 NCTCOG Collector Volume-Delay Function .....4-31
- Figure 4-14 PSRC Freeway Volume-Delay Function .....4-32
- Figure 4-15 PSRC Arterial Volume-Delay Function .....4-32
- Figure 4-16 SANDAG Freeway Volume-Delay Function .....4-33
- Figure 4-17 SANDAG Arterial Volume-Delay Function .....4-33
- Figure 4-18 SANDAG Collector Volume-Delay Function .....4-34
- Figure 4-19 MPO Model Speed Histograms.....4-36
- Figure 5-1 V/C Ratios for the ARC Assignment by Functional Class .....5-4
- Figure 5-2 V/C Ratios for the MAG Assignment by Functional Class .....5-5
- Figure 5-3 V/C Ratios for the NCTCOG Assignment by Functional Class .....5-5
- Figure 5-4 V/C Ratios for the PSRC Assignment by Functional Class.....5-6
- Figure 5-5 V/C Ratios for the SANDAG ABM Assignment by Functional Class.....5-6
- Figure 5-6 V/C Ratios for the SANDAG Trip-based Model Assignment by Functional  
Class.....5-7
- Figure 5-7 Flow Convergence Errors in the ARC AM Model.....5-10
- Figure 5-8 Flow Convergence Errors in the MAG AM Model .....5-10
- Figure 5-9 Flow Convergence Errors in the NCTCOG AM Model.....5-10
- Figure 5-10 Flow Convergence Errors in the PSRC AM Model .....5-11
- Figure 5-11 Flow Convergence Errors in the SANDAG AM ABM Model .....5-11
- Figure 5-12 Flow Convergence Errors in the SANDAG AM trip-based model .....5-11
- Figure 5-13 ARC %RMSE Convergence Error.....5-12

Figure 5-14 MAG %RMSE Convergence Error .....	5-12
Figure 5-15 NCTCOG %RMSE Convergence Error.....	5-13
Figure 5-16 PSRC %RMSE Convergence Error .....	5-13
Figure 5-17 SANDAG Trip-based Model %RMSE Convergence Error .....	5-13
Figure 5-18 SANDAG ABM %RMSE Convergence Error .....	5-14
Figure 5-19 System-wide difference between traffic flows and counts for ARC.....	5-15
Figure 5-20 System-wide difference between traffic flows and MPO-provided counts for MAG .....	5-17
Figure 5-21 MAG System-wide Difference between Traffic Flows and Counts (Compiled by Caliper) .....	5-19
Figure 5-22 System-wide difference between traffic flows and counts for NCTCOG .....	5-21
Figure 5-23 System-wide Difference between AM Traffic Flows and Counts for PSRC .....	5-23
Figure 5-24 SANDAG System-wide Difference between the ABM Traffic Flows and MPO-provided Counts .....	5-25
Figure 5-25 System-wide Difference between Traffic Flows and PeMS counts (extracted by Caliper) for SANDAG ABM .....	5-27
Figure 5-26 System-wide Difference between Traffic Flows and MPO-provided Counts for SANDAG Trip-based Model .....	5-29
Figure 5-27 System-wide Difference between Traffic Flows and Counts (extracted by Caliper) for SANDAG Trip-based Model.....	5-31
Figure 5-28 Percentage of Link Impedance from the Distance-based Component in the MAG Model VDF.....	5-35
Figure 5-29 Comparison of MAG Link Flows With and Without a Distance-based Impedance Component .....	5-36
Figure 5-30 Comparison of NCTCOG Link Flows With and Without Operating Costs .....	5-37
Figure 5-31 Comparison of SANDAG Link Flows With and Without Operating Costs .....	5-38
Figure 5-32 Comparison of Rounded and Unrounded PSRC Trip Assignments.....	5-40
Figure 6-1 %RMSE between MAG PM Travel Time Skims from Successive Feedback Loops.....	6-6
Figure 6-2 %RMSE between MAG PM Trips from Successive Feedback Loops.....	6-7
Figure 6-3 %RMSE between MAG PM Link Flows from Successive Loops .....	6-7
Figure 6-4 % Change in MAG PM Skims from Successive Loops .....	6-8
Figure 6-5 % Change in MAG PM Trips from Successive Feedback Loops .....	6-8
Figure 6-6 % Change in MAG PM Link Flows from Successive Feedback Loops .....	6-9
Figure 6-7 Flow Differences with an Additional 20 loops of the MAG Model with MSA Link Flow Averaging .....	6-10
Figure 6-8 Comparison of Flows from MSA and ½ Flow Averaging with the MAG Model .....	6-12
Figure 6-9 %RMSE in NCTCOG AM Skims from Successive Loops .....	6-13
Figure 6-10 %RMSE in NCTCOG AM Trip Tables from Successive Loops.....	6-13
Figure 6-11 %RMSE in NCTCOG AM Link Flows from Successive Loops.....	6-14
Figure 6-12 % Change in NCTCOG AM Skims from Successive Loops.....	6-15
Figure 6-13 NCTCOG percentage changes in trip tables.....	6-15
Figure 6-14 NCTCOG percentage changes in link flows.....	6-16
Figure 6-15 Link flow Differences between the 5th and 10th Feedback Loops for NCTCOG Model with the Weighted Skim Averaging Method.....	6-17
Figure 6-16 Link Flow Differences between the 5th and 10th Feedback Foops for NCTCOG with the MSA on Flows Method.....	6-18
Figure 6-17 %RMSE in PSRC Link Flows from Successive Loops.....	6-20

Figure 6-18 %RMSE between SANDAG AM Travel Time Skims from Successive Loops.....6-21

Figure 6-19 %RMSE between SANDAG AM Trip Tables from Successive Loops .....6-22

Figure 6-20 %RMSE between SANDAG AM Link Flows from Successive Loops .....6-22

Figure 6-21 % Differences between SANDAG AM Travel Time Skims from Successive Loops .....6-23

Figure 6-22 % Change between SANDAG AM Trip Tables from Successive Loops .....6-23

Figure 6-23 % Change between SANDAG AM Link Flows from Successive Loops .....6-24

Figure 7-1 Roadway Project on SR20 Connecting SR108 and I-575 in the ARC Region .....7-2

Figure 7-2 Roadway Project Location and Extent in the ARC Network.....7-3

Figure 7-3 Flow Differences in the ARC Network at 1.E-4 Convergence .....7-4

Figure 7-4 Flow Differences in the ARC Network at 1.E-5 Convergence .....7-5

Figure 7-5 Flow Differences in the ARC Network at 1.E-6 Convergence .....7-6

Figure 7-6 Roadway Project Scope in MAG Network.....7-7

Figure 7-7 Highway Flow Differences in the MAG Network at 1.E-4 Convergence .....7-8

Figure 7-8 Highway Flow Differences in the MAG Network at 1.E-5 Convergence .....7-9

Figure 7-9 Highway Flow Differences in the MAG Network at 1.E-6 Convergence .....7-10

Figure 7-10 MAG Highway Network Flow Differences at 1.E-4 Convergence .....7-11

Figure 7-11 Highway Flow Differences in the MAG Network at 1.E-6 Convergence.....7-12

Figure 7-12 Highway Flow Differences in the MAG Network at 1.E-4 Convergence with Free-Flow Times.....7-14

Figure 7-13 Highway Flow Differences in the MAG Network at 1.E-4 Convergence when Initialized with Congested Times .....7-15

Figure 7-14 Highway Flow Differences in the MAG Network at 1.E-4 Convergence and 4 Feedback Loops .....7-16

Figure 7-15 Highway Flow Differences in the MAG Network at 1.E-5 Convergence and 4 Feedback Loops .....7-17

Figure 7-16 Highway Flow Differences in the MAG Network at 1.E-6 Convergence and 4 Feedback Loops .....7-18

Figure 7-17 Transit Improvements in Phoenix.....7-20

Figure 7-18 Transit Flow Differences in the MAG Network at 1.E-4 RG Convergence .....7-21

Figure 7-19 MAG Highway Flow Differences Due to the Transit Improvements at 1.E-4 Convergence .....7-22

Figure 7-20 Transit Flow Differences in the MAG Network at 1.E-6 RG Convergence .....7-23

Figure 7-21 Highway Flow Differences in the MAG Network at 1.E-6 RG Convergence .....7-24

Figure 7-22 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-4 Convergence.....7-25

Figure 7-23 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-5 Convergence.....7-26

Figure 7-24 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-6 RG.....7-27

Figure 7-25 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-4 RG.....7-28

Figure7-26 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-5 RG.....7-29

Figure 7-27 Roadway Project Scope in NCTCOG Network .....7-31

Figure 7-28 Flow Differences in the NTCOG Network at 1.E-4 Highway Convergence.....7-32

Figure 7-29 Flow Differences in the NCTCOG Network at 1.E-5 Relative Gap .....7-33

Figure 7-30 Flow Differences in the NCTCOG Network at 1.E-6 Relative Gap .....7-34

Figure 7-31 Flow Differences in the NCTCOG Network Evaluated with Mode Choice and at 1.E-4 Assignment Convergence .....7-35

Figure 7-32 Flow Differences in the NCTCOG Network Evaluated with Mode Choice at 1.E-6 Assignment Convergence .....7-36

Figure 7-33 Flow Differences from Lane Expansion in the NCTCOG Network at 1.E-4 Assignment Convergence .....7-37

Figure 7-34 Flow Differences in the Network Evaluated with a Full Model Run at 1.E-5 Assignment Convergence .....7-38

Figure 7-35 Flow Differences in the NCTCOG Network Evaluated with a Full Model Run at 1.E-6 Assignment Convergence .....7-39

Figure 7-36 Light-Rail Extension in the NCTCOG Region .....7-41

Figure 7-37 Zoomed-In View of NCTCOG Transit Line Extension Project.....7-42

Figure 7-38 Light Rail Transit Flow Differences in the NCTCOG Network at 1.E-4 RG Convergence .....7-43

Figure 7-39 Highway Flow Differences at 1.E-4 Convergence as a Result of the Light Rail Extension.....7-44

Figure 7-40 Transit Flow Differences in the Network at 1.E-6 Convergence .....7-45

Figure 7-41 Highway Flow Differences at 1.E-6 Convergence as a Result of the NCTCOG Region Transit Project.....7-46

Figure 7-42 Transit Flow Differences with a Full NCTCOG Model Run at 1.E-4 Convergence.....7-47

Figure 7-43 Transit Flow Differences with a Full NCTCOG Model Run at 1.E-5 Assignment Convergence .....7-48

Figure 7-44 Transit Flow Differences in the NCTCOG Network at 1.E-6 Convergence .....7-49

Figure 7-45 NCTCOG highway Flow Differences at 1.E-4 Convergence as a Result of the Transit Project.....7-50

Figure 7-46 Highway Flow Differences Assessed with a Full Model Run at 1.E-5 Convergence as a Result of the NCTCOG Transit Project .....7-51

Figure 7-47 Highway Flow Differences at 1.E-6 Convergence as a Result of the NCTCOG Transit Project.....7-52

Figure 7-48 Roadway Project on 176 St Connecting SR161 and SR7 .....7-54

Figure 7-49 Roadway Project Location and Limits in PSRC Network .....7-55

Figure 7-50 Flow Differences in the PSRC Network at 1.E-4 Convergence .....7-56

Figure 7-51 Flow Differences in the PSRC Network at 1.E-5 Convergence .....7-57

Figure 7-52 Flow Differences in the Network at 1.E-6 Convergence .....7-58

Figure 7-53 Flow Differences in the PSRC Network with a Full Model Run at 1.E-4 Convergence .....7-60

Figure 7-54 Flow Differences in the PSRC Network at 1.E-5 Convergence .....7-61

Figure 7-55 Flow Differences in the PSRC Network at 1.E-6 Convergence .....7-62

Figure 7-56 Roadway Project Introducing a New Section of Highway on SR-52 in the SANDAG Region .....7-63

Figure 7-57 Roadway Project Location in the SANDAG Regional Network .....7-64

Figure 7-58 Flow Differences in the SANDAG Network at 5.E-4 RG with Assignment-Only Analysis .....7-65

Figure 7-59 Flow Differences in the SANDAG Network at 1.E-5 RG with Assignment-Only Analysis .....7-66

Figure 7-60 Flow Differences in the SANDAG Network at 1.E-6 RG with Traffic Assignment-Only Analysis .....7-67

Figure 7-61 Flow Differences in the SANDAG Network at 5.E-4 RG with a One Loop Model Run .....	7-68
Figure 7-62 Flow Differences in the SANDAG Network at 1.E-6 RG with One Model Loop ..	7-69
Figure 7-63 Flow Differences in the SANDAG Network at 5.E-4 Convergence .....	7-70
Figure 7-64 Flow Differences in the SANDAG Network at 1.E-5 RG .....	7-71
Figure 7-65 Flow Differences in the SANDAG Network at 1.E-6 Convergence .....	7-72
Figure 7-66 Transit Project in the SANDAG Network.....	7-74
Figure 7-67 Transit Flow Differences in the Network at 5.E-4 RG .....	7-75
Figure 7-68 Highway Flow Differences in the Network at 5.E-4 Convergence.....	7-76
Figure 7-69 Transit Flow Differences in the SANDAG Network at 1.E-6 Convergence .....	7-77
Figure 7-70 Highway Flow Differences in the SANDAG Network at 1.E-6 Convergence .....	7-78
Figure 7-71 Transit Flow Differences in the Network at 5.E-4 Convergence .....	7-79
Figure 7-72 SANDAG Highway Flow Differences at 5.E-4 Convergence as a Result of the Transit Project.....	7-80
Figure 7-73 Transit Flow Differences in the Network at 1.E-5 RG .....	7-81
Figure 7-74 Highway Flow Differences at 1.E-5 RG as a Result of the Transit Project.....	7-82
Figure 7-75 Transit Flow Differences in the Network at 1.E-6 Convergence .....	7-83
Figure 7-76 SANDAG Network Highway Flow Differences at 1.E-6 RG as a Result of the Transit Project.....	7-84
Figure 8-1 Comparison of ARC and HERE Speeds for Highways .....	8-3
Figure 8-2 Comparison of ARC and HERE Speeds for Arterials.....	8-4
Figure 8-3 Comparison of ARC and HERE Speeds for Lower Functional Classes.....	8-4
Figure 8-4 Comparison of AM ARC and HERE Speeds for Freeways .....	8-5
Figure 8-5 Comparison of AM ARC and HERE Speeds for Expressways .....	8-6
Figure 8-6 Comparison of ARC and HERE Speeds for Collectors with 34MPH Free Flow Speeds .....	8-7
Figure 8-7 Comparison of ARC and HERE Speeds for Collectors with 25MPH Free Flow Speeds .....	8-7
Figure 8-8 Comparison of MAG and HERE Speeds for Urban Highways .....	8-9
Figure 8-9 Comparison of MAG and HERE Speeds for Suburban Highways .....	8-9
Figure 8-10 Comparison of MAG and HERE Speeds for Urban Arterials/Collectors .....	8-10
Figure 8-11 Comparison of MAG and HERE Speeds for Suburban Arterials/Collectors.....	8-10
Figure 8-12 Comparison of MAG and HERE Speeds for Freeways with 72MPH Free Flow Speeds.....	8-11
Figure 8-13 Comparison of MAG and HERE Speeds for Rural Freeways .....	8-12
Figure 8-14 Comparison of MAG and HERE Speeds for Urban Freeways.....	8-13
Figure 8-15 Comparison of MAG and HERE Speeds for Arterials and Collectors with 41MPH Free Flow Speeds.....	8-14
Figure 8-16 Comparison of MAG and HERE Speeds for Urban Arterials and Collectors.....	8-14
Figure 8-17 Comparison of MAG and HERE Speeds for Suburban Arterials and Collectors.....	8-15
Figure 8-18 Comparison of INRIX and MAG Planning Model Travel Times for Central Phoenix .....	8-17
Figure 8-19 Comparison of Micro-Simulated DTA and Planning Model Travel Times for Central Phoenix for Multi-trip OD Pairs .....	8-18
Figure 8-20 Comparison of Micro-Simulated DTA and Planning Model Travel Times for Central Phoenix for Single-trip OD Pairs.....	8-18

Figure 8-21 Comparison of Micro-Simulated DTA and INRIX Travel Times for Multi-trip OD Pairs for Central Phoenix.....8-19

Figure 8-22 Scatterplot of Micro-Simulated DTA and INRIX Travel Times for ALL OD Pairs in Central Phoenix .....8-20

Figure 8-23 Comparison of NCTCOG and HERE Speeds for Highways .....8-21

Figure 8-24 Comparison of NCTCOG and HERE Speeds for Arterials.....8-21

Figure 8-25 Comparison of NCTCOG and HERE Speeds for Lower Link Classes.....8-22

Figure 8-26 Comparison of NCTCOG and HERE Speeds for Freeways with 65MPH Free Flow Speeds.....8-23

Figure 8-27 Comparison of NCTCOG and HERE Speeds for Freeways with 60 MPH Free Flow Speeds.....8-24

Figure 8-28 Comparison of NCTCOG and HERE Speeds for Arterials with 40MPH Free Flows Speeds and No Modeled Intersection Delay.....8-25

Figure 8-29 Comparison of NCTCOG and HERE Speeds for Arterials with 40MPH Free Flows Speeds and Modeled Intersection Delay .....8-26

Figure 8-30 Comparison of PSRC and HERE Speeds for Highways .....8-28

Figure 8-31 Comparison of PSRC and HERE Speeds for Urban Arterials.....8-28

Figure 8-32 Comparison of PSRC and HERE Speeds for Rural Arterials.....8-29

Figure 8-33 Comparison of PSRC and HERE Speeds for Freeways with 60 MPH Free Flow Speeds.....8-30

Figure 8-34 Comparison of PSRC and HERE Speeds for Expressways with 40 MPH Free Flow Speeds.....8-31

Figure 8-35 Comparison of PSRC and HERE Speeds for Arterials with 35 MPH Free Flow Speeds and No Modeled Intersection Delay .....8-32

Figure 8-36 Comparison of PSRC and HERE Speeds for Arterials with 35 MPH Free Flow Speeds and Modeled Intersection Delay .....8-33

Figure 8-37 Comparison of PSRC and HERE Speeds for Arterials with 25 MPH Free Flow Speeds.....8-34

Figure 8-38 Comparison of SANDAG and HERE Speeds for Highways.....8-35

Figure 8-39 Comparison of SANDAG and HERE Speeds for Arterials .....8-36

Figure 8-40 Comparison of SANDAG and HERE Speeds for Lower Link Classes .....8-36

Figure 8-41 Comparison of SANDAG and HERE Speeds for Freeways with 65 MPH Free Flow Speeds.....8-37

Figure 8-42 Comparison of SANDAG and HERE Speeds for Ramps with 50 MPH Free Flow Speeds.....8-38

Figure 8-43 Comparison of SANDAG and HERE Speeds for Arterials with 35 MPH Free Flow Speeds Modeled without Intersection Delay.....8-39

Figure 8-44 Comparison of SANDAG and HERE Speeds for Arterials with 35 MPH Free Flow Speeds Modeled with Intersection Delay.....8-40

Figure 8-45 Comparison of SANDAG and HERE Speeds for Local Streets with 25 MPH Free Flow Speeds.....8-41

Figure 8-46 Contour Map Comparing ARC AM Model and Google Travel Times to Downtown from all TAZs.....8-44

Figure 8-47 Contour Map Comparing Google AM Travel Times to Downtown for Different Weekdays .....8-45

Figure 8-48 MCD-to-MCD AM Travel Time Comparison for the ARC Region.....8-46

Figure 8-49 Contour Map Comparing MAG AM Model and Google Travel Times to Downtown from all TAZs.....8-47

Figure 8-50 District-to-District Travel Time Comparison for the MAG Region.....8-48

Figure 8-51 Contour Map Comparing NCTCOG AM Model and Google Travel Times to  
Downtown from all TAZs.....8-49

Figure 8-52 District-to-District Travel Time Comparison for the NCTCOG Region .....8-50

Figure 8-53 Contour Map Comparing PSRC AM Model and Google Travel Times to  
Downtown from all TAZs.....8-51

Figure 8-54 MCD-to-MCD Travel Time Comparison for the PSRC Region.....8-52

Figure 8-55 Contour Map Comparing SANDAG AM Model and Google Travel Times to  
Downtown from all TAZs.....8-53

Figure 8-56 District-to-District Travel Time Comparison for the SANDAG ABM Model.....8-54



# List of Tables

- Table 4-1 ARC ABM Model Information Summary .....4-2
- Table 4-2 MAG Model Information Summary .....4-3
- Table 4-3 NCTCOG Model Information Summary.....4-4
- Table 4-4 PSRC Trip-based Model Information Summary .....4-5
- Table 4-5 SANDAG Trip-based Model Information Summary .....4-6
- Table 4-6 SANDAG ABM Model Information Summary .....4-7
- Table 4-7 Model Trip Purposes .....4-8
- Table 4-8 Non-Auto Travel Modes .....4-9
- Table 4-9 Model Network Size and Software .....4-10
- Table 4-10 Use of Turn Prohibitions and Turn Penalties.....4-11
- Table 4-11 ARC AM Trip Characteristics .....4-20
- Table 4-12 ARC Combined Trip Matrix Statistics .....4-20
- Table 4-13 MAG PM Trip Statistics .....4-21
- Table 4-14 MAG Combined PM Trip Matrix Statistics .....4-21
- Table 4-15 NCTCOG AM Trip Statistics .....4-21
- Table 4-16 NCTCOG Combined AM Trip Matrix Statistics.....4-22
- Table 4-17 PSRC AM Trip Statistics .....4-22
- Table 4-18 PSRC Combined AM Trip Matrix Statistics .....4-23
- Table 4-19 SANDAG AM Trip Statistics .....4-23
- Table 4-20 SANDAG Trip-based Combined AM Trip Matrix Statistics .....4-24
- Table 4-21 SANDAG ABM AM Trip Statistics .....4-24
- Table 4-22 SANDAG ABM Combined Trip Matrix Statistics.....4-25
- Table 4-23 MPO Model Link Capacities .....4-25
- Table 4-24 MPO Model Values of Time .....4-26
- Table 4-25 MPO Base Period Traffic Assignments .....4-35
- Table 4-26 Average Travel Speeds .....4-35
- Table 5-1 MPO Assignments to 1.E-4 Relative Gap with Bi-conjugate FW Algorithm on a 6 Core Computer .....5-2
- Table 5-2 Assignments to 1.E-4 Relative Gap with Bi-conjugate FW Algorithm on a 12 Core Computer .....5-3
- Table 5-3 Assignments to 1.E-6 Relative Gap with a Path-based User Equilibrium (PUE) Algorithm on a 6 Core Computer (Cold start) .....5-3
- Table 5-4 Links with Zero Assigned Flows in the ARC Base AM assignment.....5-7
- Table 5-5 Links with Zero Assigned Flows in the MAG Base PM assignment .....5-8
- Table 5-6 Links with Zero Assigned Flows in the NCTCOG Base AM assignment.....5-8
- Table 5-7 Links with zero assigned flows in the PSRC Base AM assignment .....5-8
- Table 5-8 Links with Zero Assigned Flows in the SANDAG ABM Base AM assignment .....5-9
- Table 5-9 Links with Zero Assigned Flows in the SANDAG Trip-based AM Base Assignment.....5-9
- Table 5-10 ARC Flows vs Counts by Functional Class .....5-16
- Table 5-11 ARC Flows vs Counts by Volume Group .....5-16
- Table 5-12 ARC VMT Flows vs Counts by Functional Class .....5-16
- Table 5-13 MAG Flows vs MPO-provided Counts by Functional Class .....5-17
- Table 5-14 MAG Flows vs MPO-provided Counts by Volume Group.....5-18

Table 5-15 MAG VMT Flows vs MPO-provided Counts by Functional Class.....	5-18
Table 5-16 MAG Flows vs Counts (assembled by Caliper) by Functional Class.....	5-19
Table 5-17 MAG Flows vs Counts (assembled by Caliper) by Volume Group.....	5-20
Table 5-18 MAG VMT Flows vs Counts (assembled by Caliper) by Functional Class.....	5-20
Table 5-19 NCTCOG Flows vs Counts by Functional Class.....	5-22
Table 5-20 NCTCOG Flows vs Counts by Volume Group.....	5-22
Table 5-21 NCTCOG VMT Flows vs Counts by Functional Class.....	5-22
Table 5-22 PSRC Flows vs Counts by Functional Class.....	5-24
Table 5-23 PSRC Flows vs Counts by Volume Group.....	5-24
Table 5-24 PSRC VMT Flows vs Counts by Functional Class.....	5-24
Table 5-25 SANDAG ABM Flows vs MPO-provided Counts by Functional Class.....	5-25
Table 5-26 SANDAG ABM Flows vs MPO-provided Counts by Volume Group.....	5-26
Table 5-27 SANDAG ABM VMT Flows vs MPO-provided Counts by Functional Class.....	5-26
Table 5-28 SANDAG ABM Flows vs Counts (extracted by Caliper from PEMS) by Functional Class.....	5-27
Table 5-29 SANDAG ABM Flows vs Counts (extracted by Caliper) by Volume Group.....	5-28
Table 5-30 SANDAG ABM VMT Flows vs Counts (extracted by Caliper) by Functional Class.....	5-28
Table 5-31 SANDAG Trip-based Model Flows vs MPO-provided Counts by Functional Class.....	5-30
Table 5-32 SANDAG Trip-based Model Flows vs MPO-provided Counts by Volume Group.....	5-30
Table 5-33 SANDAG Trip-based Model VMT Flows vs MPO-provided Counts by Functional Class.....	5-30
Table 5-34 SANDAG Trip-based Model Flows vs Counts (extracted by Caliper) by Functional Class.....	5-31
Table 5-35 SANDAG Trip-based Model Flows vs Counts (extracted by Caliper) by Volume Group.....	5-32
Table 5-36 SANDAG Trip-based Model VMT Flows vs Counts (extracted by Caliper) by Functional Class.....	5-32
Table 5-37 Traffic Assignments with Different Operating Costs for NCTCOG.....	5-33
Table 5-38 Traffic Assignments with Different Operating Costs for SANDAG Trip-Based Model.....	5-34
Table 5-39 Traffic Assignments with Different Distance-based Impedances for MAG.....	5-34
Table 5-40 Comparison of Rounded and Unrounded PSRC Trip Assignments.....	5-39
Table 6-1 MPO Model Feedback Methodology.....	6-2
Table 6-2 MAG Model Estimated VMT and VHT Using MSA on PM Link Flows.....	6-9
Table 6-3 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics for the MAG Model.....	6-11
Table 6-4 VMT and VHT Changes by Loop for the NCTCOG Weighted Skim Averaging Method.....	6-19
Table 6-5 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics from the Weighted Skim Averaging Feedback Method for the NCTCOG Model.....	6-19
Table 6-6 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics for the SANDAG Model.....	6-25
Table 6-7 SANDAG ABM VMT and VHT Differences by Feedback Loop (with MSA on flows).....	6-25
Table 7-1 ARC Network Highway Project Impact Summary.....	7-7

Table 7-2 MAG Highway Project Impact Summary .....	7-19
Table 7-3 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-6 RG.....	7-30
Table 7-4 MAG Transit Project Impact Run Summary .....	7-30
Table 7-5 Summary of Model Runs Evaluating Changes Due to Added Lanes in the NCTCOG Network.....	7-40
Table 7-6 NCTCOG Transit Line Extension Model Run Summary .....	7-53
Table 7-7 PSRC Network Highway Project Impact Summary .....	7-59
Table 7-8 Summary of PSRC Full Model Runs for a Highway Project.....	7-62
Table 7-9 SANDAG Highway Project Impact Summary .....	7-73
Table 7-10 SANDAG Transit Project Impact Model Run Summary .....	7-85
Table 8-1 Comparison of ARC AM Modeled and HERE TMC VHT and Speeds .....	8-8
Table 8-2 Comparison of MAG AM Modeled and HERE TMC VHT and Speeds .....	8-15
Table 8-3 Comparison of INRIX (I) and MAG Planning Model Travel Times (T) for Central Phoenix.....	8-17
Table 8-4 Comparison of NCTCOG AM Modeled and HERE TMC VHT and Speeds .....	8-27
Table 8-5 Comparison of PSRC AM Modeled and HERE TMC VHT and Speeds.....	8-34
Table 8-6 Comparison of SANDAG AM Modeled and HERE TMC VHT and Speeds.....	8-42
Table 8-7 Summary Comparisons of HERE Measured and MPO Modeled AM TMC VHT....	8-42



# ***Acknowledgments***

We are especially thankful for the encouragement and technical involvement of Ken Cervenka who served as the FTA technical manager for most of this research. We are also grateful for the support, assistance, and inputs provided by FTA staff including Nazrul Islam, Dwayne Weeks, and Jim Ryan and the contributions of FHWA staff of Brian Gardner, Jeremy Raw, Eric Pihl, Sarah Sun, and Doug Laird who reviewed aspects of our work and gave us many useful comments.

We are particularly appreciative of the effort of the 5 MPOs who willingly submitted to our requests for their models, data, and model runs and patiently answered our questions about their modeling practices. Specifically, we thank Guy Rousseau, Steve Lewandowski, and Kyeil Kim of ARC; Vladimir Livshits and Arup Dutta of MAG; Arash Mirzaei and Behruz Paschai of NCTCOG; Wu Sun, Rick Curry, Tom King, Ziyang Ouyang, and Clint Daniels of SANDAG; and Stefan Coe, Chris Johnson, Suzanne Childress, and Billy Charlton of PSRC.



# Abstract

This research investigated whether or not current traffic assignment and model feedback practices are sufficiently accurate for calculating congested highway travel times and for quantifying the highway benefits of major transit projects. Examination of U.S. MPO modeling practices indicated widespread deficiencies in implementation. Empirical investigation of assignment and feedback convergence errors present in some of the better MPO models indicated that with available methodological improvements and more extensive computation, existing methods could produce plausible estimates of highway and transit project impacts. Comparisons between modeled and measured congested travel times from commercial sources indicated that models tended to underestimate travel speeds, and that use of speed data would be beneficial in model calibration and validation.



# Chapter 1

## Introduction and Executive Summary

This report documents the findings of a research study funded by the Federal Transit Administration (FTA) and the Office of the Secretary (OST) of the U.S. Department of Transportation that had the objective of assessing whether or not current travel demand modeling practices were sufficient for calculating congested highway travel times and for identifying the highway benefits of major transit projects. This objective is closely associated with the effectiveness of the highway traffic assignment and model feedback methodology employed in regional travel demand models. In prior work sponsored by FTA and others, insufficient convergence of traffic assignment models was shown to produce unreliable estimates of network traffic in response to improvement projects of various types. In contrast, setting higher convergence criteria appeared to ameliorate the spurious impacts observed at lower levels of convergence. This insight raised questions about how much convergence is enough, whether traffic assignment convergence is enough, and whether other considerations such as the correctness of congested travel times and the use of model feedback were modeling issues of consequence. These questions led to a DOT-sponsored effort to assess the state of the practice, investigate good practice models, identify needed improvements in modeling methodology, and make recommendations for model-based project benefits estimation.

FTA has grappled with the use of regional travel demand models for predicting patronage for New Starts and the widespread situation in which the forecasts that are presented to FTA typically overstate the realized patronage. In that context and at the core of this research are the questions of whether or not currently deployed and apparently well-constructed regional travel demand models produce plausible forecasts of project impacts and the extent to which variations in traffic assignment methods and feedback practices affect those forecasts. An important but secondary question is whether or not the regional models produce reasonable measures of origin-to-destination congested travel times since congested travel times are central to all model components and transportation analysis in general as well as project benefit-cost analyses. The study is intended to investigate modeling practices particularly with respect to traffic assignment models and feedback methodology and to make recommendations for improvement if warranted and supported by the research.

There has been a presumption that travel demand models can straightforwardly predict the consequences of changes to the highway system as these have impacts that are less complex than those of major transit projects. Not only is there a lack of evidence for this, but deployed traffic assignment models typically yield link level forecasts that can be difficult or embarrassing to explain. Some of these problems have been attributed to insufficient model convergence, particularly of the traffic assignment.

Practitioners who develop and apply travel demand models typically take the position that the models are good enough for planning and indicative of the nature of impacts that would come to pass in the future given the model assumptions. Models are typically run on a base case and on alternative future long-term scenarios. The models are seldom used to produce forecasts for specific projects and are even more infrequently if ever validated against real world impacts leaving open questions of validity, reliability, and accuracy. In this research, we attempt to examine these questions through a detailed examination of regional models and the project impacts they suggest. A strength of this study is that it does not rely on a single Metropolitan Planning Organization (MPO) model or on a single methodological approach. While MPO models can be quite different from one another, comparisons of practices and their consequences can reveal systematic suggestions for modeling improvements.

## Study Approach

---

The study was performed in two primary phases. In the first phase, we conducted an inventory of the modeling practices employed at the 30 largest MPOs in the U.S. The inventory collected basic information about traffic assignment methods, convergence criteria, and feedback practices that are utilized. Based upon the review, FTA selected 5 MPO models for in-depth examination and secured the agreement of those MPOs to participate in the project.

The approach for the second phase of the project was to study the behavior of the selected MPO models to assess their ability to identify the road traffic impacts of highway and transit improvement projects. If it was determined that the models could not do this acceptably in their current form, experimentation with improved methods was to be performed. Based upon prior research, it was expected that additional traffic assignment convergence would be explored and that the effects of additional and more stringent feedback computations would also be assessed.

Extensive experiments were conducted with the 5 MPO models. These included tests of convergence and varied assignment algorithms and feedback computations. At least one highway project and one transit project from each region was evaluated using methods similar to those in the regional models and with various improvements in computational approach.

While it was not part of the original study design, we were also able to accommodate FTA's interest in comparing model-based estimates of congested travel speeds with measurements of travel speeds from commercial sources. Data from HERE, INRIX, and Google were utilized for that purpose.

This was intended to be a largely empirical study with an emphasis on understanding how certain modeling choices might affect the answers obtained to the types of questions typically posed to models. We did not perform research on advanced practices or new methods. This was not because we don't believe in them, but simply because they were off topic for this project.

## **Inventory of MPO Modeling Practices**

---

The project commenced with a review and inventory of the network modeling and feedback practices in use by the 30 largest MPOs. This review, which is summarized in Chapters 2 and 3, was intended to assess current practices and to identify a small number of MPOs with whom the research on best-practice methods and potential improvements would be conducted. Of course, numerous other problems with travel demand models, such as inaccuracies in trip tables, could make benefits estimation problematic. However, our focus in this project has been primarily on traffic assignment and feedback convergence, both of which determine the congested travel times that are key determinants of the spatial pattern of trips and mode choice. If the congested travel times cannot be reliably computed, then the other model components will be error-prone as well.

### ***MPO traffic assignment practices***

Against the backdrop of the movement to introduce advanced activity models and dynamic traffic assignment models, we found that in late 2011 all of the MPOs used static assignment models. While it was expected that multiple time periods would be used, there were still a few large MPOs that did 24-hour assignments, which is not a good practice. Even the MPOs who had activity-based models that predicted trips by half hour interval aggregated trips prior to performing multi-hour AM, PM and other period static traffic assignments.

Our review indicated that deficient methods were in widespread use. We found that many MPO modelers and their models rely on ad hoc procedures historically practiced or simply choose some set of options in their planning software without regard to the potential consequences. Many MPOs used inappropriate assignment algorithms and/or incorrect closure metrics that are now understood to be deficient. Only a few MPOs used efficient algorithms and computed traffic assignments that were converged to tolerances that are thought to be effective in reducing spurious effects.

Research has provided a much deeper understanding of the mathematics of the traffic assignment problem and many of its variants than was previously available, and there are new findings about the convergence of different solution algorithms and the practical consequences of improved convergence. Improved algorithms have been available for some time in various software packages, but have not yet been widely put to use. Advances in computer hardware also have revolutionized the amount of computing that can be accomplished within acceptable running times. As a result, there are straightforward ways to improve modeling practices without incurring additional costs or computing time.

### ***MPO feedback practices***

Based upon the inventory of large MPO models, we could not find a single MPO that performed feedback for each and every time period and also used tight closure criteria for model feedback. A wide array of feedback mechanisms are in use by large MPOs with many relying on stopping feedback when link flows are changing less than some percentage. This practice is deceptive as continued change in the same direction would eventually lead to quite different results. Some MPOs used the naïve method of directly feeding back speeds from the assignment to trip distribution, a practice that is known to be problematic. Some used a small, fixed number of model loops. Others had no criteria whatsoever for feedback closure.

## **Detailed Examination of Selected MPO models**

---

Some MPOs clearly had better modeling practices than others and these were candidates for further research. Based upon the inventory and other factors such as diversity in geography and in the planning software used, FTA selected the Atlanta Regional Commission (ARC), the North Central Texas Council of Governments (NCTCOG), the Maricopa Association of Governments (MAG), the San Diego Association of Governments (SANDAG), and the Puget Sound Regional Council (PSRC) MPOs for the more in-depth research. These MPOs all agreed to participate in the project and to provide their models for more detailed, empirical investigation.

While these MPO staffs were quite cooperative with the research team, virtually all of the models were in flux during our project. This made it challenging to perform the analysis, and there were frequent delays in obtaining the updated models. Moreover, 4 of the 5 MPOs were transitioning to activity-based models that had not yet been deployed and were in varying states of calibration and validation. Because of the limited time for the project, we worked with some of the older deployed models and some of the newer versions before they were fully finalized. As a result, it is likely that many of our results are no longer pertinent with respect to the most recent version of each model. Nevertheless, we feel that our findings will still be of considerable interest to both the participating MPOs and to modelers elsewhere.

We worked with each MPO to document details of their modeling procedures both to provide context for our analysis and to ensure that we were able to replicate their modeling practices closely. For each MPO model, we obtained model scripts and data, inputs and outputs of various model stages, and their available traffic counts.

The models were scrutinized from a conceptual and also an empirical point of view. All of the traffic assignment formulations were re-run in TransCAD to verify that we had successfully understood the models and were able to closely replicate their outputs. We then selectively modified certain aspects of the traffic assignments in order to understand how much difference these modifications would yield in terms of the answers provided to project evaluation. The scrutiny that was applied to each model illustrates that in-depth review of traffic assignment procedures can yield positive benefits. In the next section of this summary, we present some general findings with respect to major aspects of the traffic assignment modeling procedures that the 5 MPOs used.

## **An Overview of the 5 MPO Models**

---

The 5 MPO models were a mix of advanced four-step models and activity models. All but one of the MPOs were in the process of developing an activity-based model, but only one MPO, ARC, had deployed an ABM for planning purposes by the conclusion of our study. We were unable to perform extensive tests with the ARC model because it was not finished early enough for our research. We also worked with the SANDAG ABM that was under development but was not deployed. All of the models used static user equilibrium traffic assignments and ran at least 3 feedback loops. In this section, we provide further background information on the models.

## ***Network geography and attributes***

In this day of mature GIS systems, we were a bit surprised that several of the MPOs were either in the process of moving to more geographically accurate networks or had only recently done so. We reviewed the networks in detail, comparing them with commercially available data utilized for navigation. By the middle of this study, the MPO models that we worked with all had relatively accurate road networks.

We did however find that coverage of turn prohibitions ranged from completely missing to fairly complete and could certainly be improved for many of the models. The representation of turn prohibitions in a network model is important because it directly affects the paths that are found and utilized in the traffic assignment process.

We also found that centroid connector practices were quite variable and could often be improved upon either by increasing the number of connectors and/or by changing the connection points to lower functional class links in the networks.

## ***Volume-delay functions***

In a planning model, the volume-delay function (VDF) relates the travel speed on a link to the volume of traffic that is assigned to that link. Each MPO had a somewhat different selection of the VDF employed and several customized the functions to include signal delay in some fashion.

Often only one free flow speed was used for each functional class by area type when in reality there are significant differences in both speed limits and measured free flow speeds that could have been captured with more detailed network coding.

VDF functions must be strictly increasing such that delay increases with increasing flow. All of the MPO model VDFs were strictly increasing, but some of them were not smoothly increasing, which can result in poor or slow assignment model convergence.

## ***Assignment methods and convergence***

When we began the study, two MPOs used the Frank-Wolfe (FW) assignment algorithm, and two used the bi-conjugate FW method (BFW). One used a path-based assignment. The convergence levels specified were fairly tight with relative gaps ranging from .001 to .0001. As a precursor to the more detailed investigations, we established that we could run all of the MPO traffic assignments and achieve a reasonably close match with their model runs.

## **Traffic Assignment Investigations and Findings**

---

The user equilibrium paradigm is a simple model that allocates traffic from origins to destinations based upon the principal that each trip is assigned to its lowest cost route in terms of travel time and any associated tolls. All of the 5 MPO models performed a user equilibrium traffic assignment with multiple user classes. Each model respected user class restrictions such as those for HOV lane use.

Three of the 5 models used higher passenger car equivalents for large trucks while the other two did not. Only two of the models preloaded buses on the road network.

We established that we could run each MPO traffic assignment to high levels of convergence although this required some minor modifications to the volume-delay functions in some cases. For modest levels of convergence with relative gaps of .0001, we used the bi-conjugate FW (BFW) algorithm, which we found to be always much faster in computing time to reach that gap than the classic FW method. The BFW method is available in all major planning software packages, so there is no impediment to its widespread use.

We also ran all of the traffic assignment models to several orders of magnitude tighter convergence using a path-based algorithm. This enabled us to quantify the convergence error present in each base year model at lesser levels of convergence.

Generally we found that the maximum link convergence error was around 1000 vehicles for an AM peak period at a relative gap of .0001. At the .01 (1%) relative gap that was traditional historically and is still used in some MPO models, the maximum link flow error for the AM peak period was between 5,000 and 10,000 vehicles for each of the models that we examined.

Model-based estimates of vehicle hours of travel (VHT) and vehicle miles of travel (VMT) will vary with the convergence level of the traffic assignment and certainly with the choice of volume-delay functions. They are also impacted by inclusion of distance-based vehicle operating costs in the total link impedance, a practice for which we find no good justification. Chapter 5 presents a full discussion of the above issues and contains more detailed findings.

It is important to recognize that, by itself, tight convergence is not enough to result in a good traffic assignment model. With appropriate algorithms and volume-delay functions, tight convergence will always be achieved. What is important is that the assignment converges to a solution that is in accord with observed traffic flows so as to provide a basis for forecasting traffic when demand and/or supply change in the future.

### ***Validation of models with traffic counts***

One important component of this research was to compare traffic assignment outputs with traffic counts and travel times that were independently measured. This required link counts by direction (i.e., each side of the road) and time period to be meaningful. We asked each MPO to provide us with this information. In general, all of the MPOs had access to a large number of traffic counts but these were often aggregated for a whole day or for both directions on a link. We were surprised to discover that the MPOs had rather little data in the form of directional traffic counts by time period to use in model validation.

ARC had only 130 directional counts for the AM peak period, a number that is insufficient for statistical reliability for even one functional class, let alone the entire system. Of these counts, 71 were on freeways and 44 on arterials.

MAG has made a particular effort to use count and speed data in model development and evaluation. Initially, MAG provided us with roughly 1,600 traffic counts, of which only 56 were directional freeway counts by time period and 218 were daily two-way freeway counts, although they now have many more freeway counts. Also, for MAG, Caliper had previously compiled very detailed traffic count information for an area of over 500 square miles of Central Phoenix as part of building a large traffic microsimulation model. These included 253 highway counts.

NCTCOG had not previously used directional counts by time period to validate their model, but provided us with more than 5,000 counts. Unfortunately, only 119 were on major highways.

PSRC provided us with counts for 284 locations on freeways and expressways.

SANDAG provided roughly 400 counts, but only 30 for arterials. Additional highway counts were obtained from the Californian PeMs system, which provides counts on the freeway system. We collected and processed these counts for the SANDAG region.

We used the available data to compare the assigned traffic flows with the counts, and we mapped the comparisons on each model network. Most of the models did a reasonable job of matching freeway counts with %Root Mean Square Errors (RMSEs) in the range of 20 to 25%. There was less success in matching arterial counts with all of the models. Additionally, difference plots revealed some geographic bias in some of the assignment model results.

Our overall conclusion was that none of the MPOs, with the exception of MAG, had sufficient count data by time of day and direction for validating their models. In our opinion, obtaining fuller count data and using it to evaluate traffic assignment models should be a priority in the future for all MPO models.

## **Feedback Research and Findings**

---

Models are typically run in loops, so that model forecasts are consistent in the sense that the travel times used to forecast trip distribution and mode choice are consistent with those produced by the traffic assignment model. The logic for seeking travel time consistency applies in a straightforward fashion to each time period in the model, so that the forecasts by time period are consistent with the congested travel times input and output from the final loop of the model.

We experimented with 3 of the 5 MPO models by running numerous feedback loops using alternative methods of updating the travel times at each loop. We asked the other two MPOs to perform some full model runs for us, but they did not have the time to do so.

Different averaging strategies are the common and appropriate means of attempting to converge upon a consistent solution to a multi-stage model. We did not identify a single best dominant averaging approach, but several methods seemed fairly effective.

The empirical work established that a closer tolerance between input and output travel times can be computed than is currently being sought. It also established that the final answers in terms of link flows will be different with different stopping tolerances and that feedback methods can give the illusion of convergence when small changes in the same direction for each loop ultimately add up to larger differences in traffic flows after many loops. The analysis suggests that specific and tight feedback closure criteria should be specified for regional models, and tests should be performed to ascertain their sufficiency.

## **Project Impact Analysis**

---

A major element of this research was to assess the ability of regional models and specifically their traffic assignment methods to estimate the impacts of highway and transit improvement projects. Using each MPO model and/or its traffic assignment procedure, we evaluated some proposed future projects that were identified in a future 2025 or 2030 plan. We did at least one road project and one transit project for each MPO.

The analysis protocol was to consider impact assessment using traffic assignment only, mode choice and traffic assignment, a single model loop consisting of trip distribution and mode choice, and multiple loops with model feedback. This was done for several levels of traffic assignment convergence and relied on the MPO base year models as the no-build reference for comparison.

The most surprising and interesting finding was that very tight assignment model convergence was needed to resolve project impacts. The suggestion from prior research that traffic assignment convergence to a .0001 (1.E-4) relative gap was sufficient was repudiated by our empirical experiments. Indeed, we found that for some projects convergence to .000001 (1.E-6) relative gap was necessary to get a plausible estimate of project impacts that appeared free from spurious artifacts.

Importantly, using tightly converged assignment models, we found that it is possible to estimate the road congestion relief benefits of transit improvement projects as well as to estimate the travel time benefits of highway projects. These tests, however, were purely methodological in nature and were not validated against external data. Further confirmation of the validity of the results would require before-and-after studies of actual projects and comparison of impacts with model predictions.

## **Congested Travel Times from MPO Models**

---

Throughout the study, FTA expressed deep interest in the accuracy of the zone-to-zone auto travel times produced by models due to their centrality in modeling and analysis as key model inputs and as the main determinant of competition for transit service. New sources of travel time data make analysis of congested travel times feasible in ways that have never been accessible to modelers and decision makers before.

Using HERE (formerly known as NAVTEQ) data licensed to Caliper and harvested from real-time measurements, we compared modeled versus measured travel speeds at the Traffic Message Channel (TMC) segment level for the selected MPO regional networks. It should be mentioned these data are much broader in coverage than the National Performance Management Research Data Set, which is HERE data licensed to FHWA and made available to State DOTs and MPOs. The data were harvested for 5-minute intervals and then averaged to estimate overall AM peak period speeds for each segment. The TMC segments were matched against the model networks using an automated conflation or map-matching process. Three mid-week day AM peak period averages were computed for comparison with the model travel speeds at the TMC level. In the analysis, we stratified the data by functional class, area type, and free flow speeds when comparing the modeled and measured speeds.

The comparisons revealed that, in general, the travel demand models did not produce congested travel times that were in good agreement with independent measurements from HERE. For 4 of the 5 MPOs, the overall model travel speeds were slower than the measured travel speeds. The one MPO (MAG) that has made more extensive use of speed data actually achieved a fairly close match between the model speeds and the reported measurements.

We also found that modeled VHT can be very different from measured VHT based upon TMC segment samples. However, some MPOs matched the measured VHT fairly well without matching the travel speeds by functional class closely.

An additional comparison of travel speed data from a micro-simulation-based dynamic traffic assignment (DTA) for Central Phoenix developed in a separate project by Caliper illustrated that it is possible to match reported speeds (in this case from INRIX) with a suitably constructed and calibrated micro-simulation-based DTA model.

We also used Google data on point-to-point travel times to investigate travel times for complete trips. This analysis largely substantiated the results from the TMC analysis.

With the new availability of speed data, there is reason to believe that modelers will be able to produce regional models that do a better job of matching observed count and speed data.

## **Summary Conclusions and Recommendations**

---

This study provides cause for both concern and optimism with respect to travel forecasting models. On the one hand, there are widespread difficulties with existing models that affect their forecasting ability, and, on the other hand, it appears that available modeling techniques can be used successfully to estimate the impacts of transportation improvement projects.

Greater attention to modeling basics, to model details, and to model validation emerge as clear needs from the assessment of the state of the practice. Based upon this study, there is room for improvement in even some of the best regional models that are currently in use, and in-depth empirical investigation of models can readily identify problems to be addressed. Fortunately, most improvements that were identified are easy to implement.

Overall, the approach of utilizing more stringent criteria for traffic assignment and feedback convergence can be recommended as a good practice. Tighter traffic assignment convergence will reduce convergence error and will lead to more plausible and reliable estimates of project impacts.

The static user equilibrium model and its key assumption of equal travel times (or generalized costs) for all utilized paths between each origin and destination is a great simplification of reality. Nonetheless, it seems to pass the test of usefulness. It appears that convergent assignments can be computed to a level that yields plausible estimates of project impacts and will be largely free from spurious noise. In particular, it appears that available methods are able to discern the highway benefits of transit projects if carefully implemented.

However, estimates of project impacts will vary quite a bit with the modeling choices that are made about traffic assignment and feedback methods. Shortcuts that are taken in computing assignments and feedbacks have consequences that can be significant, rendering the shortcuts potentially quite counterproductive.

Careful scrutiny of traffic assignment procedures reveals problems that are correctable in terms of geographic accuracy, coding of turn prohibitions, incorrect capacities, insufficient or improper centroid connectors, and insufficient traffic counts by time period and direction for validation. Some problems in assignment convergence are associated with poor choices for volume-delay functions. These problems can easily be corrected.

Feedback practices need to be improved and justified. When needed, feedback should be performed for each time period in the model and should be computed to a uniform level when performing plan and project evaluation. The computing burden can be reduced significantly by beginning model runs with good estimates of congested link travel times.

Many if not all of the modeling choices modelers make have potential consequences for the answers obtained in project evaluation. Considerable professional judgment is thus an essential part of good practice. This is particularly the case in deciding which model components and types of model feedback are appropriate for specific projects.

Validation should be accorded a greater priority in the model development process. It should be disaggregate in nature, and traffic assignment models should be validated at the link level by time period and direction. A sufficient number of directional counts by time period should be obtained by functional class to be statistically valid. In addition to link volumes, measured speed data should be used as part of the model development and validation process. Otherwise, estimates of vehicle hours of travel are not likely to be very accurate. Before-and-after studies of project impacts should be performed to assess the external validity of travel demand models and their forecasts.

### ***Recommendations for FTA guidance***

Uncertainties associated with the quality of forecasts from deployed travel demand models have logically led FTA to taking a conservative point of view with respect to patronage estimates for New Starts. This study illustrates that conservatism is warranted in view of the general state of regional models and various technical issues associated with model development, application, and validation.

FTA's premise that tighter traffic assignment convergence might clean up some forecasts is fully supported by this study. Moreover, newer algorithms have been shown to be much more effective than the classic one in achieving this goal, making it realistic to suggest some minimum standards. Despite that, regional travel demand models are quite varied and do not follow a single, standard approach, making it impractical and inadvisable to suggest uniform guidance for all regions or all models. Rather than give a specific relative gap for traffic assignment convergence, it would be better to encourage MPOs to demonstrate that the gap is low enough for its intended purpose. Also, while it appears to be possible to estimate the highway congestion relief benefits of major transit projects, these travel time savings might be hard or impossible to observe in the field and absent validation of their projected magnitude, they need not be part of a conservative assessment of potential transit investments.

Rather than issue technical guidelines, FTA can exert a positive influence on modeling practice in several ways. The material in this report can be used to augment the questions and criteria already in use with respect to scrutiny of trip tables and mode choice models when regional models are used as the basis for New Starts submissions. In particular, using reasonable congested auto speeds can be a point of emphasis as can be consistent treatment of assignment and feedback convergence when comparing build and no-build scenarios. Use of link flow difference mapping can be a simple and revealing method of inspection of project impacts.

### ***Research recommendations***

Our principal research recommendation is comparison of model forecasts with before-and-after data from studies of road and transit improvement projects. Data sets collected in carefully constructed before-and-after studies can be used to assess travel demand models and develop improved methods. Without this type of research it will be hard to have much confidence in model forecasts.

The availability of travel speed data invites the question of how best to use it in model development, validation, and forecasting. This should be a fruitful area for further research.

We are confident that there will be continued research on faster means of computing travel demand models and improved algorithms for achieving model convergence for both static and dynamic traffic assignment models. Dynamic traffic simulation models have the potential to mirror traffic behavior and transit use more closely through time and that should be very helpful for transportation planning and management.

### ***Concluding remarks***

This study illustrates that most of the modeling choices that modelers make have a direct influence on the forecasts produced. Hopefully, the type of analysis performed in this study will serve as an example to modelers of the scrutiny that can be and should be directed at the many aspects of a travel demand model in its development, calibration, and validation phases. Improved methods and new data can have a very positive impact on forecasting, but impact assessment should be done with validated rather than merely asserted models. In the absence of before-and-after data on the impacts of specific projects, one cannot properly evaluate the forecasting ability of regional travel demand models. Modeling needs to focus on providing useful support for project and policy evaluation and should generate evidence of its own usefulness.



# Chapter 2

## Inventory of MPO Traffic Assignment Modeling Practices

### Introduction

---

This chapter presents the results of an inventory of the traffic assignment model procedures used in the travel demand models deployed by larger U.S. Metropolitan Planning Organizations (MPOs) and a few other transportation agencies. The information base for the inventory was model documentation available in fall 2011 supplemented by inspection of some model scripts and communication with agency modelers and consultants.

The purpose of the inventory and assessment was the identification of good practices that are in use and the selection of a small number of MPOs to work with in conducting research on traffic assignment and feedback methods relevant for benefits estimation. While some agencies have been more focused on traffic assignment and feedback convergence than others and use better practices, it was hard to find examples of uniformly good practice. It also became evident that considerable further research would be required to address the main objectives of the project as existing models did not appear to be fully capable of calculating the congestion relief benefits of transit.

The inventory included the nation's 30 largest MPOs and represented regions with a high degree of traffic congestion delay as estimated by the Texas Transportation Institute. The focus was on the properties of models that were currently in use for forecasting and not on models that were under development or enhancement. Data were obtained for nearly all 30 MPOs. No attempt was made to verify all of the information assembled, and it was clear that due to evolving methods and practices, some MPOs have changed what they do since they created their documentation or spoke with us about their practices. Nevertheless, our belief is that the aggregate portrait assembled was more than adequate to characterize the state of the practice.

Overall, the inventory provided abundant evidence of widespread deficiencies in deployed traffic assignment models and a lack of knowledge and care in the development, validation, and application of traffic assignment models. The methods used for achieving feedback convergence were generally ad hoc and also deficient. In a later section of this report, we identify many of the problems and suggest simple remedies that anyone could implement. There are also practices that require further investigation and research since they may or may not be beneficial.

Static user equilibrium (UE) traffic assignment models have numerous conceptual limitations, but their simplicity and reliability should make them useful for planning, and they will continue to be so until dynamic models are well established. Contrary to popular opinion, UE traffic assignments, when properly implemented and converged, appear to provide a consistent and useful means of evaluating some types of transportation projects. Of course, if there are gross inaccuracies in trip tables and/or other model components or if the projects involve temporal dynamics or traffic signal optimization, the static traffic assignment models will probably not be reliable. Dynamic models present virtually all of the same challenges and some additional ones

as well. The understanding of convergence issues should also help with the testing and implementation of dynamic models.

The organization of this chapter is as follows. First, we provide some background on user equilibrium traffic assignment models and convergence issues. Then we summarize the findings on the current state of the practice focusing on the algorithmic methods, volume-delay functions, and convergence metrics in use and the level of convergence achieved.

## Background on Equilibrium Traffic Assignment Models and Convergence

---

Some form of a user equilibrium traffic model is the generally accepted method for static traffic assignment models. In the larger MPOs, these models generally have multiple user classes to account for HOV facilities, trucks, and truck restrictions. Most MPOs use an equilibrium model that is computed with the Frank-Wolfe algorithm (FW) which was implemented in the Urban Transportation Planning System (UTPS) software and legacy planning packages many years ago.

The user equilibrium condition is defined by Wardrop's condition [1] that all used paths for trips between each origin-destination pair have the same minimum travel time (or generalized cost). In other words, no traveler can unilaterally switch to a shorter path and improve his or her travel time (or generalized cost). In congested networks, user equilibrium is characterized by the use of multiple paths for many O-D pairs. The Wardrop condition, while certainly not totally realistic, is appealing as it resembles a simple route choice process that one can envision for individual travelers and a plausible means of describing overall systems behavior.

An essential aspect of this problem is that the choices of travelers are dependent upon the collective route decisions of others. As more travelers utilize a given network link, the travel time on that link degrades. This volume dependence of travel times is represented in traffic assignment models with what are typically non-linear volume-delay functions.

Beckmann *et al.* [2] demonstrated, under assumptions of route costs that are the sum of their link costs and link costs being simply a (continuously differentiable, non-decreasing) function of link flows, that the traffic assignment problem could be formulated as a minimization problem with a specific objective function that has a unique link flow solution. This formulation did not immediately lead to a computational method for finding the optimal solution.

Leblanc *et al.* [3] and Nguyen [4] proposed using the Frank-Wolfe (FW) method for computing equilibrium that was implemented in UTPS and which has subsequently been used in most planning software. In the FW method, a series of all-or-nothing assignments are performed and flows are combined using weights derived from a line search that attempts to minimize the UE assignment objective function. All of the link flows from trips from all origins are updated each iteration. As a result, the order in which the origins are processed does not significantly affect the numerical results achieved. The process is repeated until some stopping criterion is met.

Note that if the minimum path travel time between each OD pair does not change, the Wardrop condition is satisfied since there are no lower time (cost) alternatives for any traveler. As a result, at equilibrium, the difference between the total cost of the current User Equilibrium (UE) solution ( $c_{UE}$ ) and the total cost of the All-or-Nothing, AON, solution ( $c_{AON}$ ) is zero and the difference is, therefore, a natural measure of convergence. Obtaining the value of the objective

function requires an extra calculation, but the cost at the AON solution (which is always available since it determines the direction of search for the next iteration) serves as a lower bound on the equilibrium solution for the current iteration.

Since the solution algorithm is iterative in nature, a stopping criterion is required. Rose *et al.* [4] lists several stopping criteria that might be used and these are shown below:

1. Change or percent change of the objective function

$$\left( \frac{z^n - z^{n-1}}{z^n} \right)$$

2. Maximum link flow change

$$\max(|x_i^n - x_i^{n-1}|)$$

3. Relative gap

$$\frac{\sum x_{UE} \cdot c(x_{UE}) - \sum x_{AON} \cdot c(x_{UE})}{\sum x_{UE} \cdot c(x_{UE})}$$

4. Average excess cost

$$\frac{\sum x_{UE} \cdot c(x_{UE}) - \sum x_{AON} \cdot c(x_{UE})}{\sum OD}$$

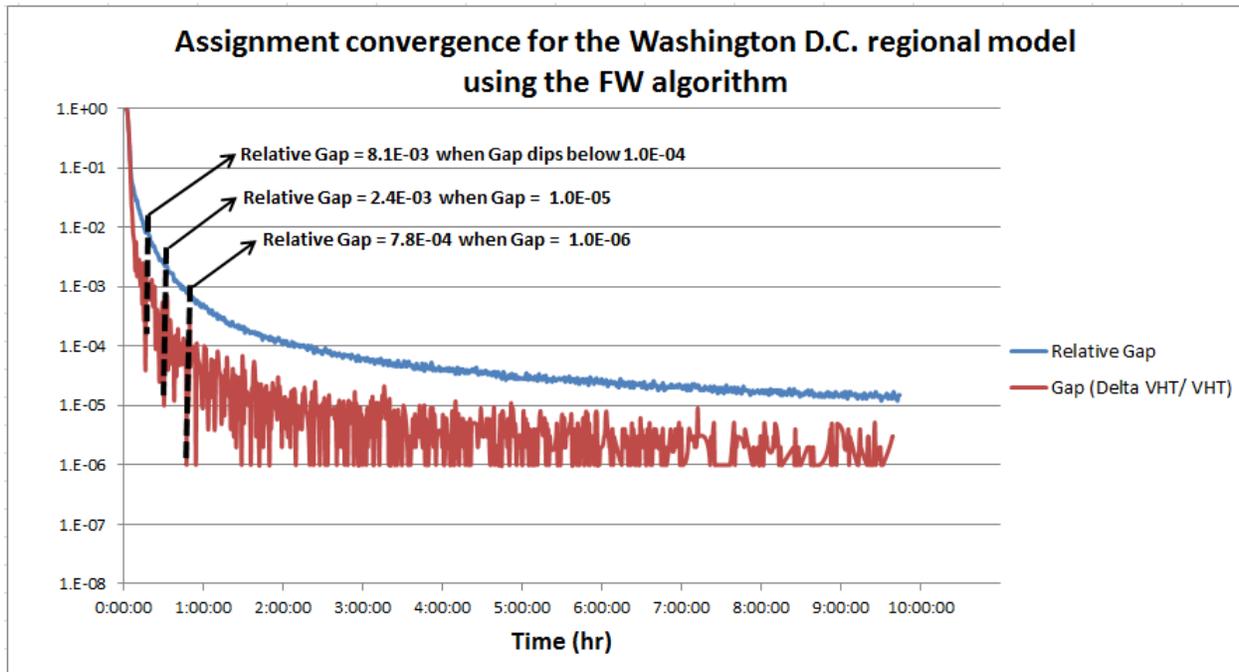
where:

- $n$  = Iteration number
- $i$  = Link index
- $z$  = Objective function
- $x_i^n$  = Flow at link  $i$ , at iteration  $n$
- $c(\cdot)$  = Volume delay function
- $OD$  = Demand

The “relative gap” is the aforementioned difference between the cost of the current UE solution and the cost of the AON solution divided by the cost of the current UE solution. This is a fairly sensitive measure of convergence and is superior to many other stopping criteria such as simple functions of the differences between assignment iterations [5]. It also has the virtue that it is comparable across scenarios, totally different assignment problems, and assignment algorithms.

The maximum link flow change between iterations measure does not indicate how far from equilibrium a solution may be. In some planning software, the “GAP” reported is completely different from the relative gap measure defined above and is computed from the percentage difference in vehicle hours travelled (VHT) from successive UE iterations without consideration of the AON solution. This measure can fluctuate wildly, leading to early termination of the assignment, and it also greatly overstates the degree of convergence obtained. To illustrate this point, we computed both measures for a large, well-calibrated regional multi-class traffic assignment problem for the greater metropolitan Washington, D.C. region. This particular problem has 2,500 zones and 57,374 links and 5 assignment classes.

Figure 2-1 Comparisons of the Relative Gap and VHT GAP



As one can see from inspecting the curves in Figure 2-1, the VHT GAP measure goes to low values very quickly and also oscillates a great deal. When the VHT GAP is .0001 (1.E-4), the relative gap is just barely over .01 (1.E-2). Similarly, when the VHT GAP first reaches .000001 (1.E-6), the relative gap is just over .001 (1.E-3). Given this behavior, using the wrong convergence measure halts the assignment process prematurely.

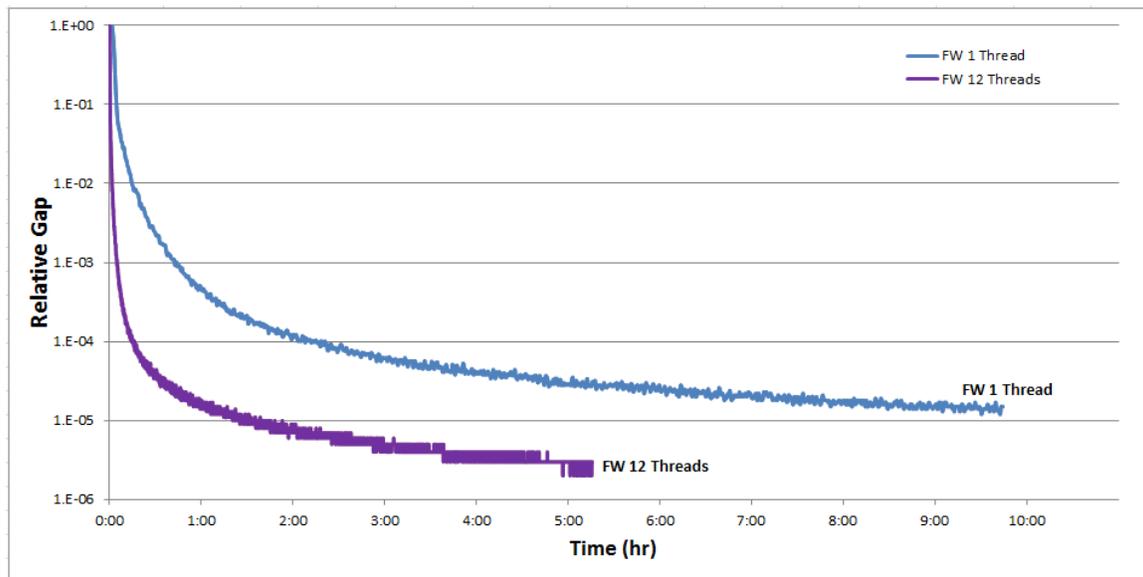
It is also important to understand that the number of iterations either by itself or as a maximum value in connection with some other measure does not by itself correspond to a particular level of convergence. The more congestion there is, as in a future forecast year, the poorer will be the convergence associated with the same number of assignment iterations. For this reason, comparisons of the future with the base case or comparisons between different scenarios will be inconsistent and potentially misleading.

Rose *et al.* [5] suggested a relative gap value of .01 in 1988 when computers were many orders of magnitude slower than they are now. Also, the consequences of poor convergence were less well understood then.

A practical problem for modelers is that the FW algorithm, while efficient early on, exhibits “tailing” with slower convergence as the number of iterations increases. Because of this, the FW algorithm is limited in its ability to obtain a tight equilibrium solution.

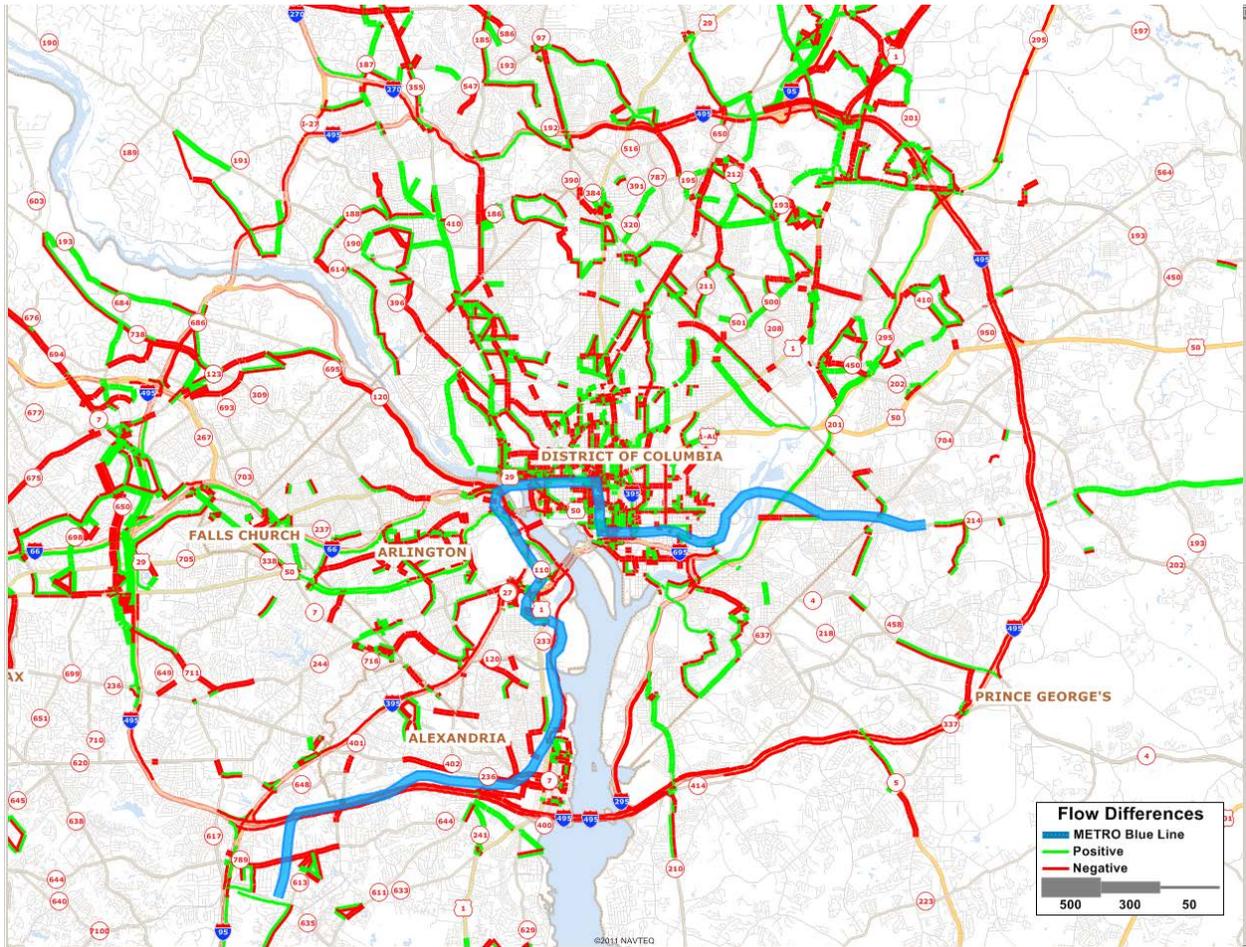
In an attempt to improve upon the rate of convergence, the FW algorithm can be multi-threaded and other, more rapidly convergent algorithms can be utilized [6]. Both the tailing of FW convergence and the effect of multi-threading are illustrated in Figure 2.2, which provides the convergence graphs for the FW algorithm running with one and with twelve threads. As can be observed, the rate of convergence slows markedly, making it impractical to get to a relative gap of .00001 with single threaded FW in a reasonable amount of time. These assignments were performed on a PC with 2 6-core processors running at 3.10 GHz. When twelve threads are utilized, there is an enormous reduction in computing time making it straightforward to achieve an order of magnitude improvement in the relative gap within the same amount of time. The FW algorithm still tails with multi-threading limiting the convergence attainable irrespective of computing time.

**Figure 2-2 DC Regional Network PM Frank-Wolfe Assignment**

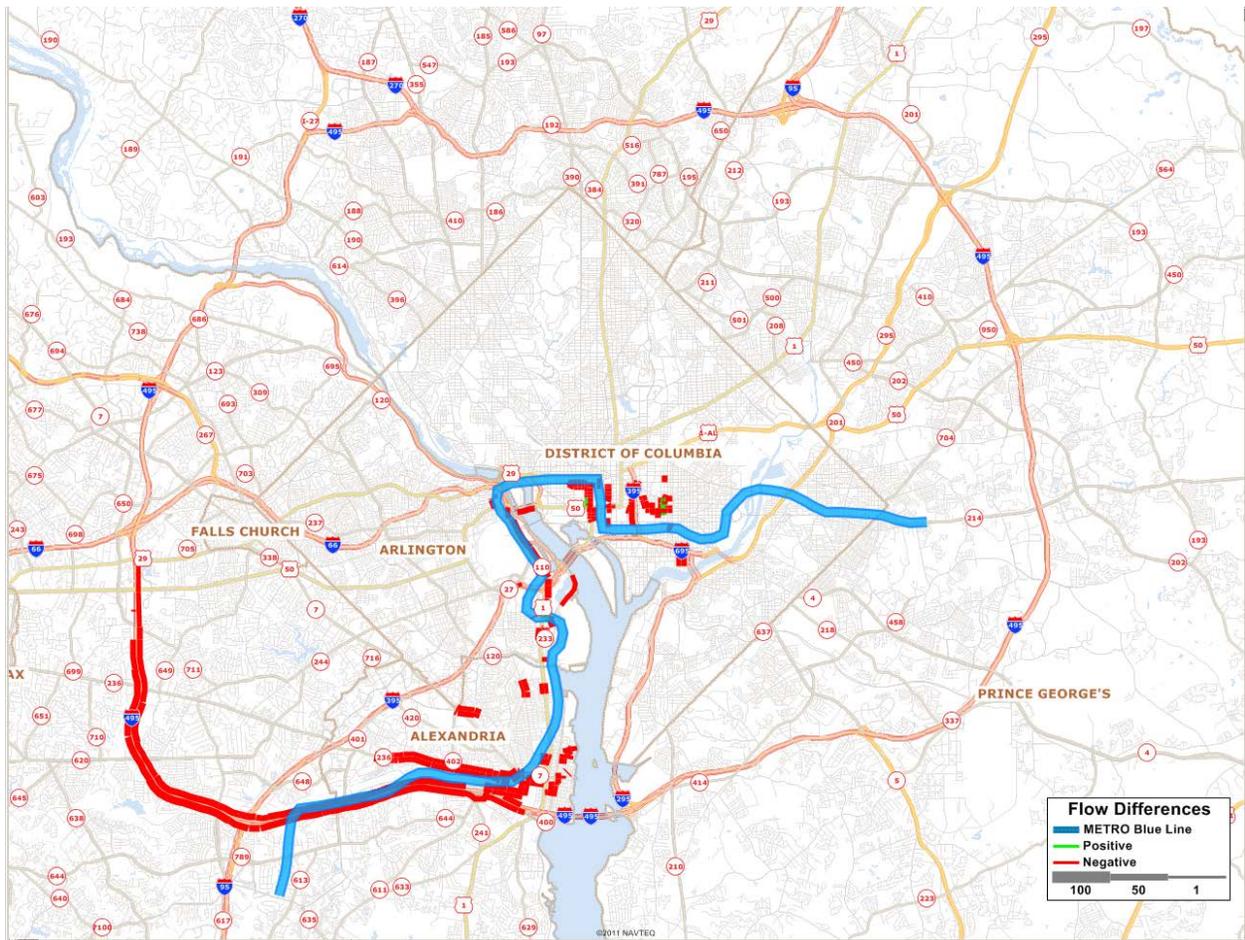


To understand **why convergence matters**, consider the example illustrated in Figures 2-3 and 2-4 that show the predicted impacts of removing 2,600 travelers from the DC regional road network because they switched to an improved transit line which is shown in blue. The impacts were assessed by rerunning the highway traffic assignment and comparing it to a prior one that had those 2,600 trips included. In Figure 2-3, we show the assignment results at the low level of convergence to a relative gap of .01, indicating in green the links that gain flow and in red the links that lose flow with the width of the lines showing the magnitude of the change. Obviously, the pattern of impacts is nonsensical and clearly erroneous. Many links gain in flow, which should not happen when trips are removed. In contrast, in Figure 2-4, which shows the traffic assignment impacts at the high convergence associated with a relative gap of .000001, the pattern of reduced highway trips is completely plausible.

Figure 2-3 Road Traffic Changes Due to Blue Line Service Improvement: Relative Gap = 0.01



**Figure 2-4 Road Traffic Changes Due to Blue Line Service Improvement: Relative Gap = 0.000001**



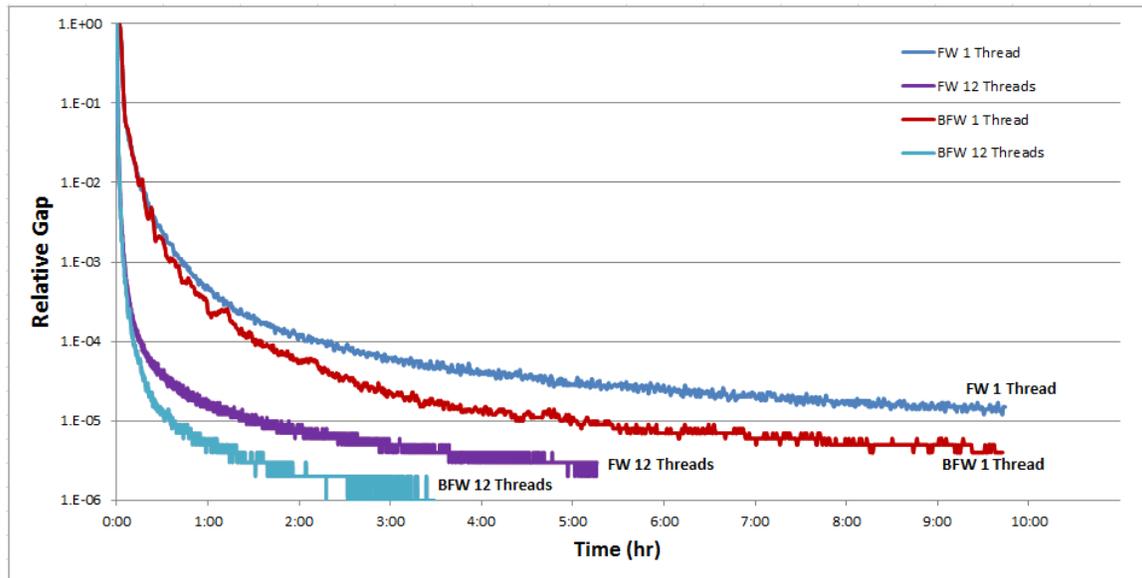
Modelers for years have had trouble explaining the seemingly random and illogical results generated by traffic assignments when evaluating projects. Typically, impacts of even minor network changes are seen far away from the changes and in corridors that should not be impacted at all. It is now evident that these strange results are the consequences of convergence error and that these artifacts disappear as the convergence levels of the traffic assignments are improved.

Researchers have been active for decades in developing and testing alternative methods to find more convergent and more rapidly convergent algorithms for the user equilibrium traffic assignment problem. Notable examples include Bar-Gera [7,8], Dial [9], and Daneva and Lindberg [10] among others. These alternative methods were seldom tested on large regional networks or on networks that included multiple user classes and turn penalties. However, there has been substantial progress in the past decade, and some of the newer methods are clearly much more rapidly convergent than their predecessors. Also, the aforementioned multi-threading coupled with continually improving computer hardware has enabled tighter and more rapid convergence to be achieved in regional planning models.

At least three types of static UE methods are now offered commercially in transportation planning packages. These include the Frank-Wolfe (FW) method that has been the workhorse for most modeling work in the past 40 years, the bi-conjugate Frank-Wolfe (BFW) algorithm, and various types of path-based methods.

The bi-conjugate descent BFW method was proposed by Daneva and Lindberg [10]. It is an extension of the FW method that finds a more efficient search direction and has significantly better convergence behavior than the FW method. In Figure 2-5, we show its performance in comparison to FW on the same network for both single-threaded and multi-threaded implementations.

**Figure 2-5 DC Regional PM Multi-Class Bi-Conjugate FW Assignments**

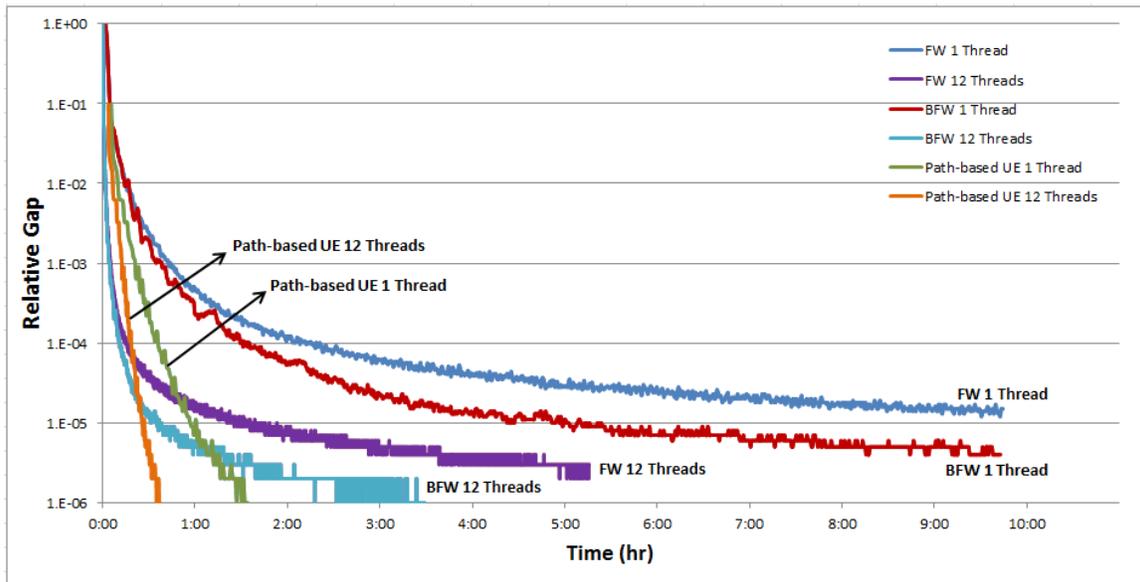


In this example, the BFW method is capable of reaching an order of magnitude lower relative gap than FW. As can be seen from the graph, the multi-threaded BFW method is more than two times faster in reaching a relative gap of .00001 than the multi-threaded FW method. It should be noted that it took a while for the advantages of the BFW method to be appreciated. The original paper was not accepted for publication, and it was only after the algorithm was implemented in commercial software and shown to be effective that a later version of the paper was finally accepted for publication [11].

It is also possible to use a path-based algorithm to solve the user equilibrium assignment problem. In doing so, flows are moved from higher cost paths to lower cost paths until the costs (or travel times) for all used paths for each origin-destination pair are virtually equal. Each significant vendor of planning software offers a type of path-based equilibrium assignment method, although these methods differ considerably from one another. From what we understand, all of the methods can reach much lower relative gaps than FW or BFW, although they may not necessarily be faster in computing time to reach a relative gap of .0001 on large congested networks.

In Figure 2-6, we show a comparison of Caliper implementations of FW, BFW, and a path-based method based on Dial's algorithm B [9]. There one can see that the path-based method can achieve much tighter convergence than the other methods although it may not always be the fastest to lesser levels of convergence such as 0.001 or 0.0001. From presentations by other vendors, it appears that similar results will hold for their path-based methods and that all of these newer methods can reach gaps of 0.000001 or lower. This makes it possible to quantify the total link flow convergence error at lesser levels of convergence. Also, the ability to utilize a warm start in which the computation of a new solution to a traffic assignment problem is computed from a saved, prior solution, can reduce the computing time for path-based methods significantly.

**Figure 2-6 DC Regional PM Multi-Class Assignment Runs with Different UE Algorithms**



Bernstein [12] has shown that UE solutions have good stability with respect to small perturbations; consequently, if a tight equilibrium solution can be generated, it should be a computationally stable method of generating forecasts. Results from a small body of tests first by Boyce *et al.* [13] and then by Slavin *et al.* [14] provide some empirical support for this conclusion. These tests also suggested that relative gaps of .0001 or lower are needed to remove significant convergence errors in link flows. This project addresses that question further in the context of transportation project evaluation with multiple MPO models.

Above we discussed the fact that inappropriate measures of convergence are self-defeating in network modeling practice. However, it must also be pointed out that there are various other modeling practices that can lead to overstated convergence. The most common of these are smoothing of flows or truncation of speeds or volume-to-capacity ratios. Imposition of a minimum speed on links will impair and impede convergence, since it wreaks havoc with the algorithms that are being used to calculate equilibrium flows. Similarly, limiting the maximum volume-to-capacity (V/C) ratios at low levels will impair convergence while overstating the gap achieved. Use of look-up tables with limited speed ranges instead of continuous functions can have the same effect as floors or ceilings on speeds or V/C ratios.

Limiting the numerical precision of flows and/or link costs will also overstate convergence. Certainly rounding of flows or costs or other adjustments would be problematic. In many cases, these practices generate incorrect solutions along with unduly optimistic relative gaps.

The relative gap is only one figure of merit, and it is worth noting that different algorithms generate different link flow solutions at the same relative gap. Based on computation of the objective function of the equilibrium assignment problem, there is evidence that the more highly convergent algorithms produce better solutions than FW at the same relative gap [14].

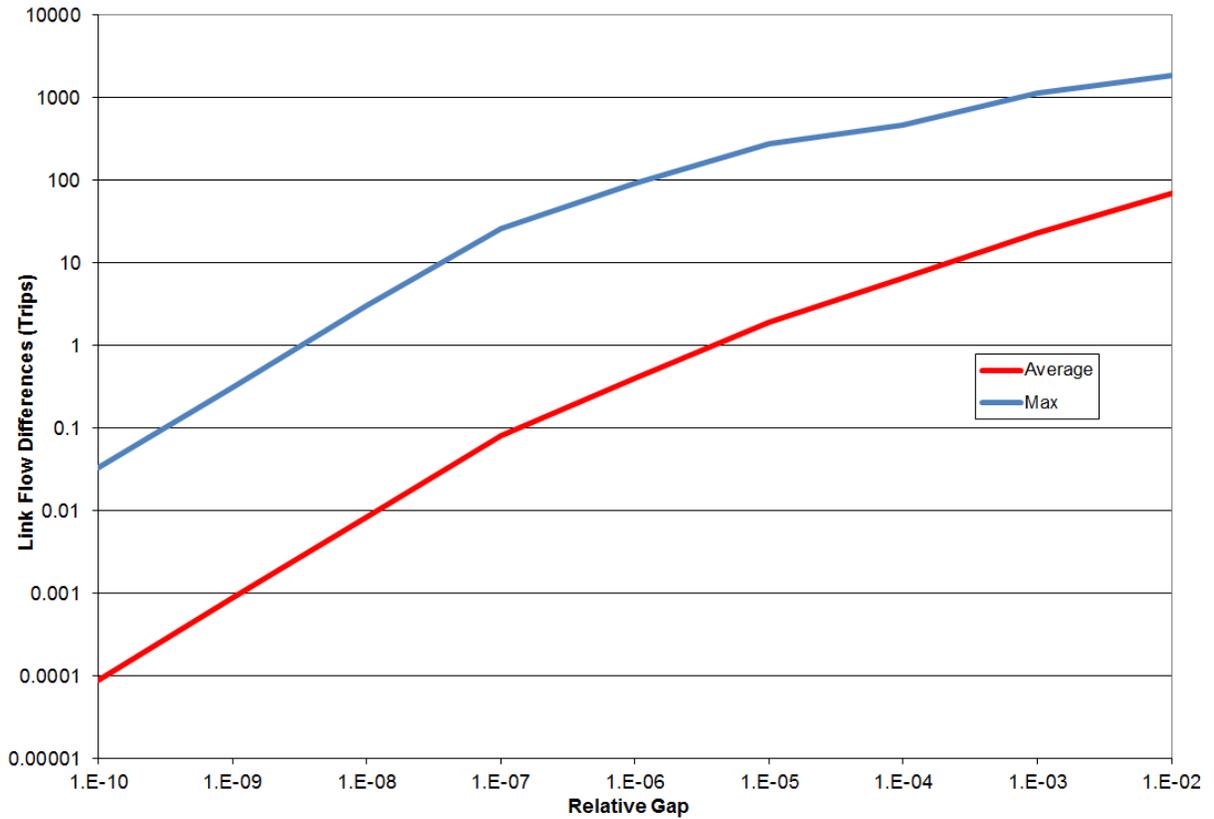
There is a great deal of confusion about select link analysis that is associated with user equilibrium traffic assignments. From a mathematical point of view, only the total link flows are guaranteed to be uniquely determined at equilibrium. This means that the reported class link flows from a multi-class assignment or the estimated route flows for even a single class assignment are not necessarily unique. Moreover, the methods used to estimate the route flows that are reported in select link analysis can be greatly misleading [15]. One way to understand this observation is that the paths saved from all the iterations of a FW assignment are not the paths that would be used at or near equilibrium; they are merely a means of estimating the equilibrium link flows. We now know that the artifacts from the unrealistic paths generated in the first few iterations of FW are never completely removed from the FW solution, and thus they will bias the select link analysis.

As illustrated by Boyce *et al.* [16], the estimated route flows from order-dependent assignment algorithms can be very peculiar and quite unreasonable. One possible improved approach is to calculate the most likely route flows using an entropy or proportionality assumption [17]. This calculation can be done with some of the newer algorithms. Proportional route flows can resolve the issue of non-uniqueness, but there is no evidence that it has any behavioral validity or that the solution has a high probability of occurrence even if it is somehow “the most probable.” The BFW algorithm is not order-dependent, and Florian and Morosan [18] have indicated that it exhibits reasonable proportionality in class flows. In any case, without good convergence, the select link analysis cannot possibly be correct.

In assessing the state of the practice, a variety of criteria apart from convergence issues come into play. Good practice requires modeling the peak periods separately and having separate off-peak models when 24 hour travel volumes need to be computed. Networks should be geographically and topologically accurate, be sufficiently dense to represent the roads that might be used to travel from one zone to another, and have correct attributes in terms of functional class, vehicle use and turn restrictions, tolls, and posted speeds. The presence of buses and trucks should also be considered in some fashion in the assignment model for large metropolitan areas.

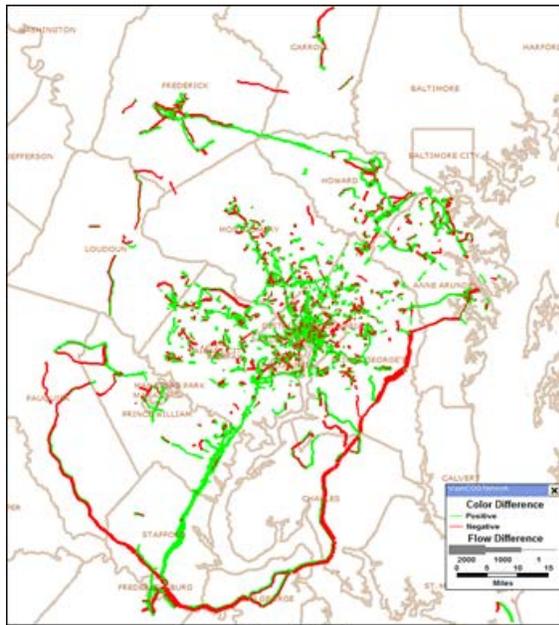
**How much convergence is enough?** This is a complex question that may not have a simple answer. The first question to examine is how different are the flows for the same problem at different convergence levels. This can be done with a chart such as that shown in Figure 2-7, which illustrates the maximum and average link flow errors as a function of convergence levels. From the chart, one can see that the largest link flow error at a gap of .001 is about 1000 vehicles for the peak period that was analyzed. To reduce the largest link flow error to 100 vehicles requires a gap of 1.E-06.

Figure 2-7 Average & Maximum Link Flow Convergence Errors

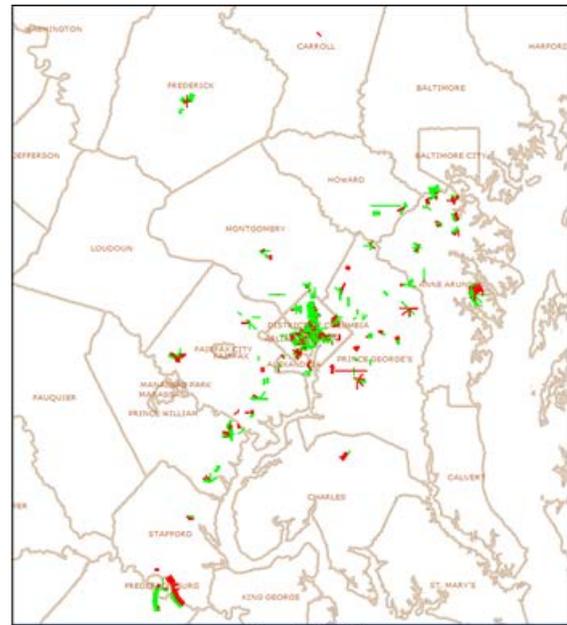


Convergence errors can also be profitably assessed through maps of network differences illustrating the differences in link flows between highly converged solutions and those that are less converged. In Figure 2-8, which follows, we show a comparison between a UE solution that was computed to a relative gap of 1.E-10, which is de facto the equilibrium solution and several other lesser convergence levels. For this network problem, a relative gap of 1.E-5 would seem to be adequate.

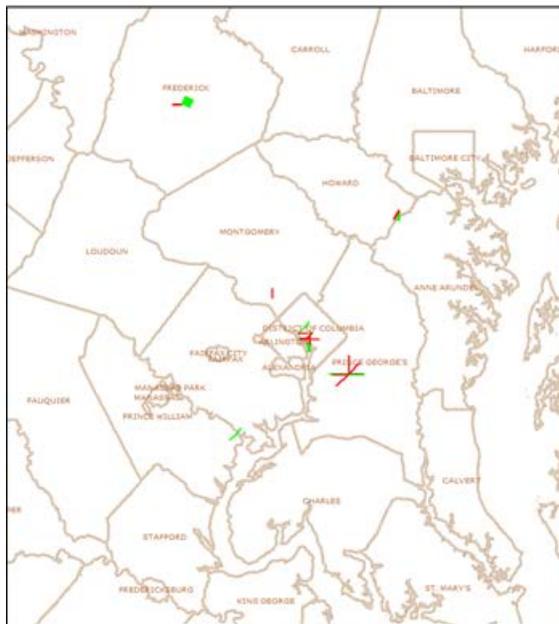
**Figure 2-8 Flow Differences from User Equilibrium at Varying Convergence Levels**



Gap 0.01



Gap 0.001



Gap 0.0001



Gap 0.00001

At the time of the MPO model inventory, it seemed that most traffic assignments should be computed to a relative gap of at least .0001 for each time period. This would help ensure that convergence error is limited and does not mask other errors. Later in this report in Chapter 7, we re-examine this issue with direct before-and-after tests of project impacts at different convergence levels.

Other aspects of assignment models are also important. The assigned flows in a base case should have plausible volume-to-capacity ratios, with no links having V/C ratios greater than 1.5 or 2. High V/C ratios are almost invariably associated with errors in network structure, insufficient centroid connectors, improper capacity estimates, and numerous other problems including problematic trip tables. A good practice is to investigate each instance of a high V/C ratio to see if it can be corrected by identifying and addressing its root cause.

Plausible V/C ratios and speeds are insufficient to validate a traffic assignment. The validity of a base case traffic assignment must be judged against external, observed data on counts and speeds. Assigned volumes should be in close agreement with link counts by time period and direction of travel. This is a more stringent and more appropriate test of the model than conformance to daily flows, screenline counts, or bi-directional flows.

If the assignment is a multi-class assignment, then validation against class counts is warranted. If there are insufficient class counts available to do so, it is questionable whether or not a multi-class assignment is appropriate. Special attention should be given to prediction of specific HOV and toll facilities and to the overall balance between freeway and arterial travel.

A second and crucial dimension of validity is plausible prediction in response to specific hypothetical and real network changes. The premise is that if the model cannot provide a reasonable answer to individual network changes, it will not be valid in predicting a large group of changes. In our prior work, we have recommended that three types of changes be tested. These are an insignificant or almost irrelevant change to the network which should have nearly no effect or only a very localized one, a small change that should have only a local effect, and a major change that should have a noticeable impact on travel patterns in at least one corridor [19].

Hypothetical tests are useful, but tests of real projects that will be or have been implemented are certainly better. In most metro areas, there is a continuing stream of changes to the road network and therefore there will typically be an opportunity to test pre-project forecasts of post-project impacts. The spatial pattern of the change needs to be examined to further verify that the impacts make sense and that there are no extraneous inexplicable changes in flows. For these short-term tests, full model feedback is neither required nor necessarily appropriate, but feedback to mode choice could be considered.

## **Current MPO Traffic Assignment Procedures**

---

We assembled data on the current traffic assignment procedures used by the nation's 30 largest MPOs (in terms of population) and several other transportation agencies. The information collected included the traffic assignment algorithm utilized, the convergence or closure criteria employed, and basic information on the number of time periods, the volume-delay functions, and the user classes employed.

The results were not encouraging with respect to the current state of the practice because we found that inadequate practices are in widespread use. Only half of the MPOs used a valid measure of assignment convergence while the other half variously used a maximum number of iterations or the VHT GAP as the closure measure. One MPO used a travel time skims difference and one used a link flow difference measure. Of the ten largest MPOs, one used only 4 iterations, one used 6 iterations, and another used 10. Typically tens or hundreds of iterations are required for reasonable convergence. Irrespective of the method employed, these are clearly deficient practices.

Of the half of the MPOs that used the relative gap, only two used a convergence value of .0001 for the AM peak period. Many used a criterion of .001, but a few used .01 or .005 instead.

With respect to algorithmic approach, Frank-Wolfe was used by most MPOs, but 5 used the bi-conjugate FW method, and a few used a path-based method in addition to FW. One MPO used an old-fashioned, non-convergent capacity restraint method, and another used a set number of fixed FW iteration step sizes which also is neither convergent nor a valid means of comparing scenarios.

Some form of Bureau of Public Records (BPR) function was used by a majority of MPOs, some of whom added operating costs and others of whom added terms for signal delay. Some varied the BPR function parameters for different functional classes as is recommended in the 2000 Highway Capacity Manual. Other volume-delay functions (VDFs) utilized included the conical, Akcelik, and logit functions. Many MPOs seemed to recognize that it is good practice to utilize VDFs that correspond to a link's performance. While some performed speed studies or analyzed different volume-delay functions, there was little supporting evidence for the functions chosen.

Most MPOs modeled 3 or more separate time periods during the day, but at least 3 had a single 24-hour model for which it is impossible to have a reasonable traffic assignment procedure. Others had peculiar periods of quite varying durations.

Most MPOs used two or more car classes to take account of HOV restrictions and most had at least one truck class associated with heavy trucks. The truck flows are often weighted with a passenger car equivalent greater than or equal to 1.5. Some MPOs preload buses on their network, but this is far from widespread.

Initially we had hoped to evaluate the geographic accuracy of the road networks in use. This proved to be rather a subjective topic and one that is more or less impenetrable unless the networks are inspected directly. Our general observation, though, was that fewer than half the MPOs use a geographically accurate network in which the geographic shape and topology of the roads are correctly represented. The amount of error this introduces could be assessed in future work.

There was little evidence that traffic assignment models were ever tested by making forecasts for specific projects. Rather, the base case models were applied to scenarios that included a wide set of future conditions masking the impact of any one particular network change.

In the model documentation and in follow-up discussions, the computational burden of computing traffic assignments was cited as a reason to take short-cuts in the traffic assignment models and in feedback procedures. It did not appear that the consequences of such short cuts were properly appreciated.

## Concluding Remarks

---

Our inventory of large MPO modeling practices gives cause for concern as it indicated that the traffic assignment modeling procedures employed are often deficient and in need of improvement. An inescapable conclusion is that there is a great deal of convergence error in many of the models. It also raises the specter of concomitant errors in the travel times that are used for trip distribution and mode choice models. It is hard to know how consequential those errors might be, but these errors could definitely have an impact on forecasts including those for major transit projects. Generally, overstated congested travel times will be associated with insufficiently converged traffic assignments as travelers will not be using their lowest cost paths. If auto travel times are overestimated, then transit patronage may be as well.

It should not be difficult for many MPOs to improve their traffic assignment procedures. Since most of the worst deficiencies could easily be remedied by simply switching to different practices that are supported by all commercial modeling packages, it seems that the most relevant gap in this regard is a knowledge gap.

This is not to imply that there are not many unanswered questions to be addressed about traffic assignment models for large MPOs. Among these are determination of best practice methods and the efficacy of static UE models to predict traffic flows and congested travel times. These are topics that will be examined closely in later chapters of this report.



# Chapter 3

## Current Practices in Computing Model Feedback

In most travel demand models, there is typically a feedback loop from the traffic assignment stage of a model back to trip distribution and mode choice. Travel speeds that are computed from the assigned link volumes are used in the next loop of the model. The goal in feeding back speeds or travel times from the traffic assignment is to achieve consistency between the times upon which the model is initially based and those that result from a consistent application of all of the component models in a multi-stage model

For a model to reach feedback convergence requires that the model components are themselves stable or convergent and that a convergent feedback methodology is employed. For it to converge to a correct or valid solution may have additional requirements. Apart from achieving consistency in model application, the behavioral motivation for computing models with feedback loops is to reflect the effects of transportation improvements on land use, trip frequencies, trip distribution, mode choice, and any other model components that are dependent upon congested travel times. Feedback convergence has also been described as supply-demand equilibration [20].

In this chapter we provide background material on feedback convergence. This is followed by an inventory of practices employed in large MPO models as gathered from the same effort discussed previously to document traffic assignment methods.

### Background on Feedback Convergence

---

For a closed-form model, it is often possible to solve the feedback convergence problem directly, generating a consistent solution for trip distribution, mode choice, and traffic assignment [21]. However, these closed-form models are not in favor with practitioners, and sequential, multi-step complex models are used instead. In advanced practice, there may be disaggregate models evaluated on synthetic populations with sequences of complicated models of tour frequency and stochastic as well as deterministic model components that are utilized. For these and other models, calculating what in mathematics is referred to as a consistent fixed-point solution may not always be possible, or if it is possible, there may be multiple and different approximate solutions. This situation has led to a certain amount of freelancing with respect to the methods employed in model feedback.

There has been a great deal of misunderstanding about feedback convergence and effective methods for achieving it. Some of this is due in part to incorrect notions being published or research findings being misinterpreted or generalized beyond a reasonable degree. One fundamental misunderstanding is the notion that feedback convergence can be judged by simply measuring the link flow differences between loops, such that when these are on the order of a few percent, the model has achieved feedback convergence. The fallacy in that reasoning is that a declining rate of change in flows does not ensure convergence to a particular limit. To see this, imagine that the vector  $F$  of link flows increases by  $F/n$  at each loop  $n$  after the

first. Then the ultimate flow vector will be computed from  $F+F/2+F/3\dots+F/n= F\sum 1/n$ . Since  $\sum 1/n$  goes to  $\infty$ , then so will the link flows. Even for a series whose values or sum has a fixed limit, evaluating only the first ten or twenty terms may be completely insufficient as an approximation to that limit.

The same reasoning would apply to other measures of feedback convergence such as trip tables or travel speeds. Small changes from loop to loop may simply present deceptive convergence as perceptively noted by Gibb [22].

Much of the early research on feedback convergence was performed with traffic assignments that were not well converged. Some of these models did not even have converged gravity trip distribution models. As a result, the conclusions reached may very well have been distorted or incorrect. Another crucial limitation of most prior work is that there was no explicit global metric used for measuring feedback convergence.

Most feedback research has been done with 4-step models characterized by gravity trip distribution models and simple or no mode choice models, rather than the complex nested logit models that are currently in use and with logsums in the trip distribution models. It was noticed, however, that various types of rounding or imprecision in model components did have some influence on the results obtained [23].

It is well-understood that simple or naïve feedback of travel times from one loop to another will not necessarily converge. This insight has come more from empirical testing than from any formal reasoning, but there is no particular reason that an arbitrary model sequence should converge with feedback as opposed to moving off in some direction or oscillating back and forth with or without a trend.

An old, influential, and somewhat misleading report on feedback was published in 1996 by the Travel Model Improvement Program [23]. It recommended the use of the 5 feedback convergence criteria that are listed below.

1. Percent Change in average speed by functional class and area-type
2. Percent of links with less than 5 percent change in assigned volume
3. Root Mean Square Error (RMSE) of assigned link volumes
4. Percent of person trips with less than 10 percent change in origin-destination flows
5. RMSE of origin-destination flows

With the exception of the last measure, none of these measures are reasonable metrics for convergence.

A natural measure of feedback convergence is the closeness of the input and output O-D travel times. Travel times are the key input to all travel demand models, and they are used to determine the spatial pattern of trip-making. Another important aspect of this measure is that the travel times for O-D pairs can be sampled and observed and can be verified by direct empirical measurement for each time period. The closeness of input and output travel time skims can be adequately measured by a RMSE statistic and possibly by other metrics.

Another measure that has been suggested is the stability of the trip table from loop to loop. Certainly if the trip tables stop changing, then the travel times and link flows will also stop changing. However, the sensitivity of the trip table to small changes in travel times may still remain.

Some form of averaging is considered the method of choice to be applied to one or more of these quantities in order to achieve feedback convergence. The particular form of averaging and the most efficient target for the averaging has generally been considered an empirical matter to be determined for a model through experimentation [21]. A form of averaging, the method of successive averages or MSA as it is usually called, is convergent in the limit (i.e., with a large enough number of iterations) to some solution because of decreasing step sizes and is widely applied. It is not clear if it will always be the most efficient method, or if it or any other heuristic solution method leaves its signature in the solution that results.

Based upon the inventory, the most common approach is use of the method of successive averages (MSA) to combine the link flows from successive model loops. The basic idea is to combine the link flows from the current feedback loop with the best estimate of link flows from the previous loops to produce the current best estimate of link flows. This is then used to compute congested link travel times using the volume delay function and these congested link times are input to calculating the shortest path travel times. Various weighting schemes might be used, but MSA weighting gives the appearance of converging reliably because of declining step sizes.

The MSA method utilizes a predetermined sequence of step sizes of the general form,

$$\alpha_n = \frac{K_1}{K_2 + n}$$

where:  $\alpha_n$  = Step size  
 $n$  = Iteration counter  
 $K_1, K_2$  = Parameters

$K_1, K_2$  must be chosen so that the following two conditions are satisfied:

$$\sum_{n=1}^{\infty} \alpha_n \rightarrow \infty$$

$$\sum_{n=1}^{\infty} \alpha_n^2 < \infty$$

One of the simplest step size sequences satisfies both conditions:

$$\alpha_n = \frac{1}{n} \quad (K_1 = 1, K_2 = 0)$$

So typically, the adjusted MSA link volumes are calculated based on the following equation:

$$MSAFlow_n = MSAFlow_{n-1} + \frac{1}{n} \cdot (Flow_n - MSAFlow_{n-1})$$

where:  $n$  = current MSA iteration number  
 $MSAFlow_n$  = calculated MSA flow at iteration  $n$   
 $Flow_n$  = resulting flow directly from trip assignment

Because the efficiency of MSA wears out, some have suggested restarting it with larger increments after a certain number of iterations. Other averaging schemes are also known for solving fixed point problems that may be applicable [24]. In practice and in some research, fixed step sizes of varying sizes are also encountered and have been deemed to be more effective than MSA averaging.

In our own prior work, we have found MSA to be preferable for some models with feedback through distribution, mode choice, and assignment [25]. It is important to note that the link flows are being averaged and not the link travel times. Averaging the times may be less desirable because it may lead to slower convergence or inconsistencies due to the fact that the average times do not correspond to any consistent set of link flows that are produced by a traffic assignment.

Given two skim matrices from two successive model loops, a percent RMSE can be calculated (using each zone-to-zone value as one observation) and a convergence value can be established. If the percent RMSE of the skim matrices of successive loops is within a specified threshold, then the feedback loop procedure can be terminated. In a Washington, DC regional model developed for Prince George's County, Caliper used .1% and lower values as thresholds for the RMSE of the skim matrices in determining when to terminate the model with feedback loops. This demonstrated that these levels of feedback convergence could be achieved with conventional methods. Note that if the model computes both peak and off-peak skims or skims by time period, feedback convergence should be achieved for each time period. This may take a different number of loops for some time periods than others.

Another school of thought is to compare the O-D matrices from successive feedback loops. Measures such as the RMSE between the O-D matrices or the sum of the absolute differences in the O-D matrices (named the Misplaced Flow) have been suggested for stopping criteria [26].

In addition to link flow averaging, trip table averaging and impedance averaging have been suggested as the most appropriate targets for achieving feedback convergence. Boyce *et al.* [26] found that trip table averaging with constant weights was the most effective approach for a model of the Albany, NY region. However, this model did not have a mode choice component, rendering the results of questionable applicability to more complex models. In past research on deployed models [25], we found that trip table averaging may aid the MSA method, but is not an effective substitute. Florian [27] has suggested that impedance averaging (i.e., skim averaging) is effective, and our inventory of practice indicates that many MPOs agree. Additional research will undoubtedly be required to assess the most efficient computational strategies for specific types of models and contexts.

A good practice when computing feedback convergence is to begin with very good estimates of congested link travel times and skims. This, in essence, is beginning the computations closer to a fixed-point solution and will, in general, reduce the number of feedback loops required.

Another very important point is that in order to achieve feedback convergence, the individual model components must be run to an appropriate level of convergence themselves. This means that the trip distribution model must be converged (if relevant) and that crude rounding or other off-model adjustments of trips must be avoided. If the individual model components are not highly converged, the feedback procedure may not converge or it may converge to the wrong solution. Also, there is some evidence that suggests that the more highly converged the traffic assignment, the fewer the number of feedback loops required to achieve the same level of

feedback convergence. Others have suggested saving time by using assignments with lesser convergence in early loops [28].

If best transit path O-D skimming is included as part of the 4-step model, the feedback convergence problem is likely to be more complex, and if the transit travel times are a function of the congested highway travel times, there may be no guarantees of convergence in all instances. Also, even if convergence can be achieved, it may take longer to reach a given level.

In the base case, validity tests should be applied to ensure that achieving feedback convergence produces a model that fits observed data more closely than a poorly converged model. Forecast tests with specific, real or hypothetical, projects should also be performed to help judge the credibility of the overall model with feedback.

The behavioral premise of feedback through trip distribution for long-range planning is that trip patterns will change in the long run in response to changes in transportation system performance. This is hypothesized to come from changes in destinations chosen for non-work trips and longer term adjustments in residential and work place location choice. While this may no doubt be true, there is little if any evidence that trip distribution or land use models are adept at predicting such changes. Yet feedback convergence will often give results that are dominated by the trip distribution models. For short-term assessment of highway projects, it can be argued that only the traffic assignment needs to be re-run or that feedback be performed only back through mode choice, holding the person trip tables constant. For FTA's purposes, this might be a conservative analysis strategy.

## **Feedback Methods in Use**

---

Based upon our investigations, we estimate that about two-thirds of the nation's 30 largest MPOs attempt some type of feedback calculation. Most of the ten largest MPOs do so. What is less encouraging is the manner in which it is performed.

While the need for feedback is generally acknowledged by many MPO modelers, we found wide variation in the methods employed and the results sought. Approximately 20 percent use naïve speed feedback, which is generally not convergent. Another 20-25% use MSA flow averaging with at least one MPO using MSA flow averaging and trip table averaging together. For the remaining MPOs that perform feedback, both speed averaging and MSA trip table averaging were about equal in frequency of occurrence.

Perhaps the most serious problem is that, of those who perform feedback loops, almost none uses an explicit, relevant, and global feedback closure metric. A global metric would include all O-D pairs and would be applied to each and every time period in the model. Surprisingly, performing feedback for each time period in the model is highly uncommon. Most feedback is done for the AM peak period or a blend of AM and PM peak periods.

The most common practice is to run 3 to 5 full model loops and accept the results, irrespective of their quality. We could find no MPO that used a global travel time skim metric, but one used travel time differences of a minute or less for most O-D pairs as a criterion. Many MPOs used link flow differences and a few used trip table stability as criteria. Closure levels such as flow difference RMSEs of no more than 3-5% were used by a handful of MPOs and a few others used stopping criteria such as 90% of all the O-D flows within 10% of the prior loop.

Using flow differences to test feedback convergence has the same problems previously discussed in using them to test traffic assignment convergence. Small changes per loop do not indicate how close or far away the model is from feedback convergence.

Another serious problem is that MPOs do not impose the feedback criterion globally, either with respect to all O-D pairs or with respect to all time periods. These omissions make the feedback tests defective and to an indeterminate degree. To be clear, a criterion that all travel times are within 5% for all but 10% of O-D pairs begs the question of what level of global feedback is actually achieved.

There is no question that flows in the AM and PM peak periods are not symmetrical, and certainly there are regions in which the PM congestion levels are the highest. Therefore, it is not sufficient to calculate feedback for only one of the peak periods or to treat them as mirror images. Using congested travel times that are a combination of AM and PM travel times is certainly not error-free even if the times are transposed, summed, and divided in half. This will introduce further errors in trip distribution and mode choice. Also, there will often be enough congestion in large regions to require that feedback be performed for one or more of the off-peak periods. So one can only conclude that forecasts will be distorted to some degree by these practices of ignoring or aggregating time periods.

More than a few MPOs had no mention of feedback loops in their model documentation. For those that do not perform feedback loops, it would be interesting to know the magnitude of the disparity between their input and output travel times.

It was mentioned previously that solving models with feedback to convergence is aided by a good starting point. This suggests that models be initiated with congested travel times from previous runs with feedback convergence or observed data or a combination thereof. In spite of this observation, it appears that more than half of MPOs use free-flow times as the initial input to their model runs. A reason given by some for this practice is the convenience of not having to store and retrieve separate congested travel times for different scenarios. That desire should be weighed, however, against the much greater computing time required for a model run.

We would hope that when models are validated, planners use the results obtained from the travel demand models being run with consistent travel times. From the available model documentation this would appear to be rarer than one might think.

From our review, the magnitudes of the trip table and link flow errors associated with different levels of feedback convergence are seldom if ever measured or reported. This would entail an assessment of the link flow differences as well as the associated VMT and VHT measurements.

Given the state of the practice, it is hard to know what feedback convergence practices are warranted and what the implications would be of implementing more formal methods and metrics. Exploration of feedback convergence issues and their consequences is fairly straightforward to do and merits the attention of those that already put so much effort into travel demand model development and application. This should include direct tests of project impacts to understand the consequences of feedback computations. In this study, we attempted to examine some of these consequences.

The computational burden of performing feedback loops is widely mentioned as a reason for using informal convergence tests. This is not surprising given that the total running time for most models is a simple multiple of the number of feedback loops run. Highly-converged traffic assignments add to this burden as does the number of user classes and the number of time periods. This often leads to computing times on the order of 50-100 times greater than that for one single class assignment. Fortunately, computers keep getting faster and improved assignment algorithms can make the necessary calculations a practical reality.

## **Concluding Remarks**

---

The insufficient attention to model feedback clearly calls into question model forecasts of future traffic conditions and transit patronage that are intended to be brought about by transportation planning. Unlike traffic assignment, there is less formal knowledge about feedback methods and issues for a variety of reasons. One reason is that there has been little empirical study of the consequences of alternative approaches and varying levels of consistency in models.

Given the state of the practice, there is ample scope for improvement in the traffic assignments and feedback practices that are in use. These topics are not only relevant to 4-step models but are just as important if not more so for disaggregate models including the latest activity models [28], all of which need good and consistent inputs on congested travel times.



# **Chapter 4:**

## **Overview of the ARC, MAG, NCTCOG, PSRC, and SANDAG Models**

In this chapter, we provide an overview of the 5 MPO models that we reviewed and worked with in the project. We focus primarily on the aspects of the models associated with traffic assignment and feedback. We necessarily worked with particular snapshots of the models due to their continuing evolution.

Given that these models were thought to be among the better examples of good practices, this overview is pertinent to understanding the state of the practice, modeling trends, and emerging practices. The diversity of the practices employed is indicative of the lack of consensus about the best way to develop the traffic assignment and feedback components of travel demand models.

During the 18-month period of the analysis, there were considerable changes in some of the models. When we began the project, we examined the Atlanta Regional Commission (ARC) and San Diego Association of Governments (SANDAG) trip-based models.

The ARC activity-based model was not deemed ready for prime time until June 2014. Thus, initially we worked with the prior trip-based model. The Maricopa Association of Governments (MAG) model was updated in January 2014 so we redid most of our analysis as a result. The North Central Texas Council of Governments (NCTCOG) model did not change during our analysis, but we converted it to TransCAD 6 and 7 to use some of the software's newer features. For SANDAG, we worked briefly with the trip-based model and then subsequently with their CT-RAMP activity-based model (ABM) which was under development and was not yet deployed. It seemed to us that it would enhance the research to include at least one ABM in our work. The Puget Sound Regional Council (PSRC) trip-based model was also in flux and was delivered to us very late in the project, which also limited our ability to test it. Lastly, the assignment portion of the ARC ABM was also provided to us late in the project. We also attempted to fit in some examination of this model although the time that we had to work with it was quite limited. Once again we caution that our descriptions may not apply to the current versions of each of these models.

In this chapter, we describe each of the MPO models with a focus on the details of their traffic assignment inputs, method, and outputs. We have prepared comparison charts to help keep track of the model characteristics and how similar or dissimilar they are. Please note that unless explicitly differentiated, the characteristics described apply to both the trip-based and activity-based models of SANDAG. For ARC, we describe only the activity-based model since the trip-based model is no longer in use.

## Model Information Summary Tables

Summary tables for each model follow. These indicate the salient characteristics of each model with respect to traffic assignment and feedback methods employed.

**Table 4-1 ARC ABM Model Information Summary**

Aspect	Attributes	Information
Software	Version	CUBE/Voyager & CT-RAMP
Size of Model	Links, Nodes	74,110 links, 26,907 nodes
Size of Model	Number of TAZs	5,981
Assignment	Time Periods	5 periods –EA 3 - 6 AM, AM 6 – 10AM, MD 10 – 3PM, PM 3 – 7PM, EV 7PM – 3AM
Assignment	Assignment Method	Bi-conjugate Frank Wolfe
Assignment	Convergence Test	0.0001 relative gap, 200 Max iterations specified
Assignment	User Classes	6: SOV, HOV2, HOV3+, Commercial, Medium Truck, Heavy Truck
Assignment	VDF Functions	$T_0 (1 + \alpha * V/C + \gamma [(V/C)]^\beta)$ For $V/C < 1$ , $\beta$ is a large number (6-9), For $V/C > 1$ , $\beta=3$ $\alpha$ , $\beta$ and $\gamma$ vary by functional class and whether $V/C < 1$ or $> 1$
Assignment	Value of Time	Auto: \$25/hr, Commercial: \$35/hr
Assignment	PCE values	PCEs for of 1.5 for medium trucks and 2 for heavy trucks
Assignment	Exclusion Sets	SOV on HOV lanes, trucks with O or D inside I-285 prohibited from highway links in perimeter
Assignment	Turn Prohibitions and/or Penalties	None
Assignment	Operating Costs	Autos: 13.85 cents/mi, Trucks: 49.33 cents/mi
Assignment	Tolls/HOT Lanes	Matrices for Toll and non-Toll trips, I-85 HOT Lane
Assignment	Capacities	Vary by Area Type and Facility Type, values based on a lookup table. Area Types based on population and employment density lookup
Assignment	Volume Preloads	None
Feedback	Number of Loops	Variable based on convergence criteria below
Feedback	Closure Criteria	%RMSE difference between feedback link volumes $< 5\%$
Feedback	Skims updated	All time period skims updated after assignment (EA, AM, MD, PM, EV)
Feedback	Flow/Skims/Trip Adjustment	MSA on the link flows
Air Quality	Post-processing	None noted

**Table 4-2 MAG Model Information Summary**

Aspect	Attribute	Information
Software	Version	TransCAD 5.0
Size of Model	Links, Nodes	29,109 Links and 19,523 Nodes
Size of Model	Number of TAZs	3022
Assignment	Time Periods	4 periods—AM 6 – 9AM, PM 2-6 PM, MD 9AM-2PM, and NT 6PM – 6AM
Assignment	Assignment Method	Frank Wolfe, later bi-conjugate Frank Wolfe
Assignment	Convergence Test	0.0001 relative gap, 1000 max iterations specified
Assignment	User Classes	5: LOV, HOV, Heavy Trucks, Medium Trucks and Other Trucks
Assignment	VDF Function	Custom VDF; all_rd3.vdf
Assignment	Value of Time	None specified since no toll links in network
Assignment	Are there varying PCE values	No
Assignment	Exclusion Sets	Yes
Assignment	Turn Prohibitions/ and/or Penalties	LinkID-to-LinkID prohibitions
Assignment	Operating Costs	A link impedance is specified in the VDF as 1.4 min/mile and added to link time after multiplying by link length
Assignment	Tolls/HOT Lanes	None
Assignment	Capacities	Based on Facility Types and Area Types. Facility Types vary from Freeways to Arterials. Area Types vary from CBD to Rural. Approximate ranges of capacities by facility type are below: Freeways: 1,800-2,100, HOV: 1,300-1,500, Expressways: 800-1,000, Arterials: 700-900, Collectors: 450-600, Ramps: 1,000-1,300, Centroids: Uncapacitated
Assignment	Volume Preloads	None
Feedback	Number of Loops	Maximum of 10
Feedback	Closure Criteria	Flow %RMSE and Trip Matrix %RMSE within 3.8% between feedback loops
Feedback	Skims Updated	PM and MD road skims
Feedback	Flow/Skims/Trip Adjustment	PM and MD link flows averaged via MSA procedure
Air Quality	Post-processing	None noted

**Table 4-3 NCTCOG Model Information Summary**

Aspect	Attributes	Information
Software	Version	TransCAD 5.0
Size of Model	Links, Nodes	42,036 Links and 25,848 Nodes
Size of Model	Number of TAZs	5386
Assignment	Time Periods	Three periods--AM 6:30 to 9:00; PM: 3 to 6:30, Off Peak 9AM-3PM, 6:30PM-6AM
Assignment	Assignment Method	Frank Wolfe User Equilibrium
Assignment	Convergence Test	0.0001, 1000 Max iterations specified
Assignment	User Classes	4: Drive Alone, Shared Ride HOV, Shared Ride No HOV, and TRUCK
Assignment	VDF Function	Custom VDF that includes a volume-dependent approach delay at intersections and intersection delay to link congestion.
Assignment	Value of Time	Varies by class, \$14.00/hr for the Non-truck classes and \$17.00/hr for the truck classes, in 2007 dollars with future CPI factors
Assignment	PCE values	None
Assignment	Exclusion Sets	Yes
Assignment	Turn Prohibitions and/or Penalties	None
Assignment	Operating Costs	Operating costs of 15 cents/mile.
Assignment	Tolls/HOT Lanes	Monetary tolls are present on about 150 links. The tolls are the same for all vehicle classes.
Assignment	Capacity	Separate link and intersection capacities. Link capacity is based on LOS E, functional class and area type. 2300 is used for freeways, 700-900 for arterials, 425-600 for collectors, 1250-1700 for freeway ramps, 650-1000 for frontage roads, and 2000-2300 for HOV. Freeways adjusted for weaving sections based on HCM using median v/c and Length. Area types used but not for freeways.
Assignment	Volume Preloads	None
Feedback	Number of Loops	User selected from 3-12. A typical run has 5 loops, but some special runs can go up to 12 looks using the criteria below.
Feedback	Closure Criteria	Skim RMSE <= 1%, Max change in skim cells < 10%, Link Volume RMSE <= 2%. The maximum link volume change by facility type divided by the one-lane link capacity should be less than the following criteria : ≤ 15% - Freeways, ≤ 20% – Major Arterials, ≤ 25% – Minor Arterials, ≤ 25% – Collectors, ≤ 25% – Ramps, ≤ 50% – Frontage Roads
Feedback	Skims Updated	AM and OP.
Feedback	Flow/Skims/Trip Adjustment	Skims are averaged after assignment. A weight of 0.25 is used for previous average skims and 0.75 is used for the current loop skim.
Air Quality	Post-processing	None

**Table 4-4 PSRC Trip-based Model Information Summary**

Aspect	Attribute	Information
Software	Version	EMME/3
Size of Model	Links, Nodes	34,748 links, 24,375 nodes
Size of Model	Number of TAZs	3,874
Assignment	Time Periods	4 periods—AM 6-9AM, MD 9AM – 3PM, PM 3– 6PM, EV 6 – 10PM, NT10PM – 6AM
Assignment	Assignment Method	Path-Based User Equilibrium
Assignment	Convergence Test	0.0001 Relative Gap
Assignment	User Classes	11: HBW SOV (4 income classes) Non-Work SOV, HOV2, HOV3+, Van, Light, Medium, & HDV Trucks
Assignment	VDF Function	Custom VDF with BPR elements. Arterials VDFs include for signal delay. Ferry link VDFs account for ferry frequency and vehicle capacity of ferries.
Assignment	Value of Time	Different VOTs by class and purpose. Between \$12-\$42/hr. for the HBW SOV classes. \$20-48/hr. for the non-work SOV and HOV classes. \$50 - \$63/hr. for the truck classes
Assignment	PCE values	PCEs for medium and heavy duty trucks
Assignment	Exclusion Sets	SOV, HOV, and truck exclusions
Assignment	Turn Prohibitions and/or Penalties	Link ID-to-Link ID prohibitions
Assignment	Operating Costs	None used
Assignment	Tolls/HOT	Apart from ferries, only 2 links in the network have link tolls. These tolls vary by vehicle class (Non-truck, light truck, medium truck and heavy truck have different tolls). All the ferry links have fares input as tolls.
Assignment	Capacities	Based on facility type and speed limits, approximate ranges by facility type are as follows: Freeways and Expressways: 1800-2100, Arterials and Collectors: 500-1100, Ramps: 1000-1400, Centroid Connectors: 1000
Assignment	Volume Preloads	Car equivalent bus flows are preloaded
Feedback	Number of Loops	4 + final
Feedback	Closure Criteria	None. Five feedback iterations are performed.
Feedback	Skims Updated	skims are updated for every time period (AM, MD, PM, EV, NT
Feedback	Flow/Skims/Trip Adjustment	Skims are averaged after each loop
Air quality	Post-processing	No adjustment noted in documentation

**Table 4-5 SANDAG Trip-based Model Information Summary**

Aspect	Attributes	Information
Software	Version	TransCAD 5.0
Size of Model	Links, Nodes	28,877 Links and 21,429 Nodes
Size of Model	Number of TAZs	4682
Assignment	Time Periods	3 periods--AM, MD, and PM
Assignment	Assignment Method	Bi-conjugate Frank Wolfe
Assignment	Convergence Test	0.001 relative gap, maximum iterations 1000
Assignment	User Classes	14 classes (6 of them truck)
Assignment	VDF Function	Logit-based volume delay function in the trip-based model
Assignment	Value of Time	Varies by class. \$30/hr. for auto and \$43.2/hr. for truck
Assignment	PCE values	Yes. PCE > 1 for the six truck classes
Assignment	Exclusion Sets	Yes
Assignment	Turn Prohibitions and/or Penalties	Link Type-to-Link Type and link ID-to-link ID prohibitions and penalties
Assignment	Operating Costs	Yes, on all links equal to 15c/mile.
Assignment	Tolls/HOT Lanes	Monetary tolls are present on 70 links. These tolls are different for light (base toll), medium (1.03*base toll) and heavy vehicles (2.33*base toll)
Assignment	Capacities	Mid-link capacity: Use Caltrans 1900-2100 for freeways, 2000 for HOV, $In * 1800 - 300 - 200$ ( $m < 2$ ) for urban facilities, $In = \#$ of mid-block lanes, $m =$ median code (0 or 1 signifies no median). Intersection Capacity is based on HCM. Looks like LOS D for HOV, LOS E for freeway
Assignment	Volume Preloads	Car equivalent bus flows are preloaded
Feedback	Number of Loops	4
Feedback	Convergence Test	None. Fixed number of loops.
Feedback	Skims Updated	All 3 time periods are updated
Feedback	Flow/Skims/Trip Adjustment	Simple averaging of skims after each loop
Air Quality	Post-processing	An automated adjustment procedure has been developed to adjust future year traffic volumes to compensate for calibration errors. This procedure was discontinued in the ABM model.

**Table 4-6 SANDAG ABM Model Information Summary**

Aspect	Attributes	Information
Software	Version	TransCAD 6.0
Size of Model	Links, Nodes	55,382 directed links and 22,222 nodes
Size of Model	Number of TAZs	4996
Assignment	Time Periods, Times	5 time periods --Early AM 3-6AM, AM 6-9AM, MD 9AM-3:30 PM, PM 3:30-7PM, EV 7PM-3AM
Assignment	Assignment Method	Bi-conjugate FW
Assignment	Convergence Test	0.0005 relative gap, specified max iterations 1000
Assignment	User Classes	14 classes (6 of them truck)
Assignment	VDF Function	Customized Tucson-based delay function in the activity-based model
Assignment	Value of Time	Varies by class. \$30/hr. for auto and \$43.2/hr. for truck
Assignment	PCE values	Yes PCE > 1 for the six truck classes
Assignment	Exclusion Sets	Yes, for all the classes
Assignment	Turn Penalty Information	Link Type-to-Link Type and link ID-to-link ID prohibitions and penalties
Assignment	Operating Costs	Yes, 15c/mile on all links
Assignment	Tolls/HOT	Monetary tolls on 70 links. These tolls are different for light (base toll), medium (1.03*base toll) and heavy-duty vehicles (2.33*base toll)
Assignment	Capacities	Mid-link capacity: Use Caltrans 1900-2100 for freeways, 1600 for HOV, $I_n * 1800 - 300 - 200$ ( $m < 2$ ) for urban facilities, $I_n = \#$ of mid-block lanes, $m =$ median code (0 or 1 signifies no median). Intersection Capacity is based on HCM. Looks like LOS D for HOV, LOS E for freeway
Assignment	Volume Preloads	Car equivalent bus flows are preloaded
Feedback	Number of Loops	3 plus one final assignment outside of loop
Feedback	Closure Criteria	None. Fixed number of loops as specified above.
Feedback	Skims Updated	All 5 time periods
Feedback	Flow/Skims/Trip Adjustment	MSA on link flows
Air quality	Post-processing	An automated adjustment procedure has been developed to adjust future year traffic volumes to compensate for calibration errors

In the remainder of this chapter, we describe further details of the models deployed and review the inputs and traffic assignment formulations utilized. Descriptions of the models include the type of model, the trip purposes, and modes modeled. The formulations of the traffic assignment model in terms of network attributes, centroid connectors, volume-delay functions, and current practices are described and are essential background for the further testing that is described in later sections of this report.

## MPO Model Formulations

---

The five MPOs models reflect a mix of advanced four-step models and initial deployments of activity-based models. Of the five, ARC has completely switched to an ABM. MAG, SANDAG, and PSRC are in the process of ABM development. NCTCOG has not yet initiated a move to an ABM for travel demand forecasting.

### *ARC*

ARC now uses an activity-based model for their planning and forecasting activities. This model uses the CT-RAMP ABM formulation which is the same general activity-based model that is under development at SANDAG. The ARC ABM model replaces an earlier trip-based model that we reviewed earlier in the project.

### *MAG*

MAG uses a trip-based model for its current forecasting activities and it has an ABM model under development that is based on CT-RAMP. The MAG trip-based model uses a destination choice model for trip distribution and a nested logit model for mode choice.

### *NCTCOG*

NCTCOG uses a trip-based model with three basic trip purposes and a gravity model for trip distribution. The mode choice model distinguishes trips by different transit modes as well as walk trips.

### *PSRC*

PSRC uses a trip-based model with 7 trip purposes and a gravity trip distribution model. It also has a DAYSIM ABM under development.

### *SANDAG*

The SANDAG trip-based model has 10 trip purposes and uses a gravity model for trip distribution. The CT-RAMP ABM is under development but is sufficiently far along that we were able to run it for the purposes of this research project.

## ***Trip purposes***

The person trip purposes represented in the trip-based models are described below in the Table below. As one can see, they vary quite a bit in the number of purposes modeled.

**Table 4-7 Model Trip Purposes**

<b>MPO Model</b>	<b>Trip purposes</b>
<b>MAG</b>	Home-based work, Home-based other, Home-based school, Home-based university, Home-based shopping, Non home-based work, Non home-based other, ASU students, and Airport trips
<b>NCTCOG</b>	Home-based work, Home-based non-work and Non home-based.
<b>PSRC</b>	Home-based work, Home-based college, Home-based school, Home-based shop, Home-based other, Non home-based work and non home-based other
<b>SANDAG trip-based</b>	Home-based work, Home-based college, Home-based education, Home-based shop, Home-based other, Serve passenger, Work-based other, Other-other, Airport, Visitor

In the ARC CT-RAMP ABM model, there are mandatory work and school tours, maintenance tours for escorting travelers, shopping, and other “maintenance” activities, and 3 categories of discretionary tours for social purposes, eating, out, and “other” discretionary activities. Although we did not inspect it in detail, the SANDAG CT-RAMP ABM implementation appears to be quite similar.

### ***Travel modes***

The table below describes the transit and non-motorized modes used in each of the models. The trip-based models all include auto and shared ride auto modes and various types of commercial vehicle trips. The non-auto modes are listed below.

**Table 4-8 Non-Auto Travel Modes**

<b>MPO Model</b>	<b>Transit Modes</b>	<b>Non-motorized Modes</b>
<b>ARC ABM</b>	Walk all, Walk premium, KNR all, KNR premium, PNR all, PNR premium,	Walk, Bike
<b>MAG</b>	Access modes: Walk, Park-n-Ride, Kiss-n-Ride Transit modes: Local Bus, Express Bus, Rapid Bus, Urban Rail, Commuter Rail	Walk, Bike
<b>NCTCOG</b>	Transit modes based on 5 different agencies: APM, DART, DCTA, FWTA and RAIL	Walk
<b>PSRC</b>	Transit access modes: Walk only. Drive access trips are not directly part of transit assignment as the trip is broken down into the drive part which is assigned to the highway network and the trip from the park and ride lot which is treated as a walk access trip. For walk access trips, transit modes are bus, rail, and ferry.	Walk, Bike
<b>SANDAG (both trip-based and ABM)</b>	Transit access types: Walk, Drive, Drop-off For each form of access, transit modes: Local Bus, Express Bus, Rapid Bus, Light Rail, Commuter Rail	Walk, Bike

## **Traffic Assignment Problem Characteristics**

We now turn our attention to reviewing the key aspects of the traffic assignment components of each model. This includes a description of the network characteristics, inputs to the assignment procedures, volume-delay functions, assignment procedures and convergence criteria, and basic assignment outputs including volume-to-capacity ratios and travel speeds.

### ***Network size & software***

Reflecting the trend of smaller sized and thus more numerous travel analysis zones, most of the MPOs use nearly 4,000 or more zones. The specific number of TAZ's, the number of network links and nodes, and the software used are tabulated below.

**Table 4-9 Model Network Size and Software**

<b>MPO Model</b>	<b>Description</b>
<b>ARC</b>	74,110 links, 26,907 nodes, 5,981 TAZs in CUBE/voyager and CT RAMP
<b>MAG</b>	29,109 links, 19,523 nodes, 3,022 TAZs in TransCAD 5.0
<b>NCTCOG</b>	42,036 links, 25,848 nodes, 5,386 TAZs in TransCAD 5.0
<b>PSRC</b>	34,748 links, 24,375 nodes, 3,874 TAZs in EMME/3
<b>SANDAG trip-based</b>	28,877 links, 21,429 nodes, 4,682 TAZs in TransCAD 5.0
<b>SANDAG ABM</b>	55,382 links, 22,222 nodes, 4,996 TAZs in TransCAD 6.0 and CT-RAMP

### ***Geographic network representation***

We assessed the geography of the base-year networks by performing a variety of comparisons with different data sources. We used the HERE geography that Caliper licenses, and also made use of other data sources that were available including aerial imagery.

While the GIS revolution is still not fully realized in MPO planning, the 5 MPOs all had accurate GIS line layers that they could relate to their model networks. Some had only recently switched to accurate networks from stick networks. In general, the networks did not include all streets. Rather, they covered main roads including major arterials.

### ***Turn prohibitions and penalties***

Use of turn prohibitions where they exist is a good practice, but one that is not common in large MPO models. Failure to respect prohibitions will lead to inappropriate shortest path calculations and would be expected to be harmful in the computation of travel time skims and equilibrium traffic assignments.

Turn penalties are link-to-link movements that are assessed additional travel time. Use of fixed turn penalties in static user equilibrium models is more of an open question, but may be very helpful in some models. Fixed penalties that are independent of turning movement volumes would seem to be a potential source of bias. Dynamic, volume-dependent turn penalties would seem more logical but they are most appropriate in dynamic assignment models rather than in models with long, multi-hour peak periods.

Some modelers use penalties to penalize specific movements. For example, SANDAG uses penalties to prevent certain ramp-to-ramp travel paths. This practice may be potentially helpful but needs research substantiation. In reality, many of these coded penalties may not be necessary since trips might not use these link sequences even if there is heavy congestion.

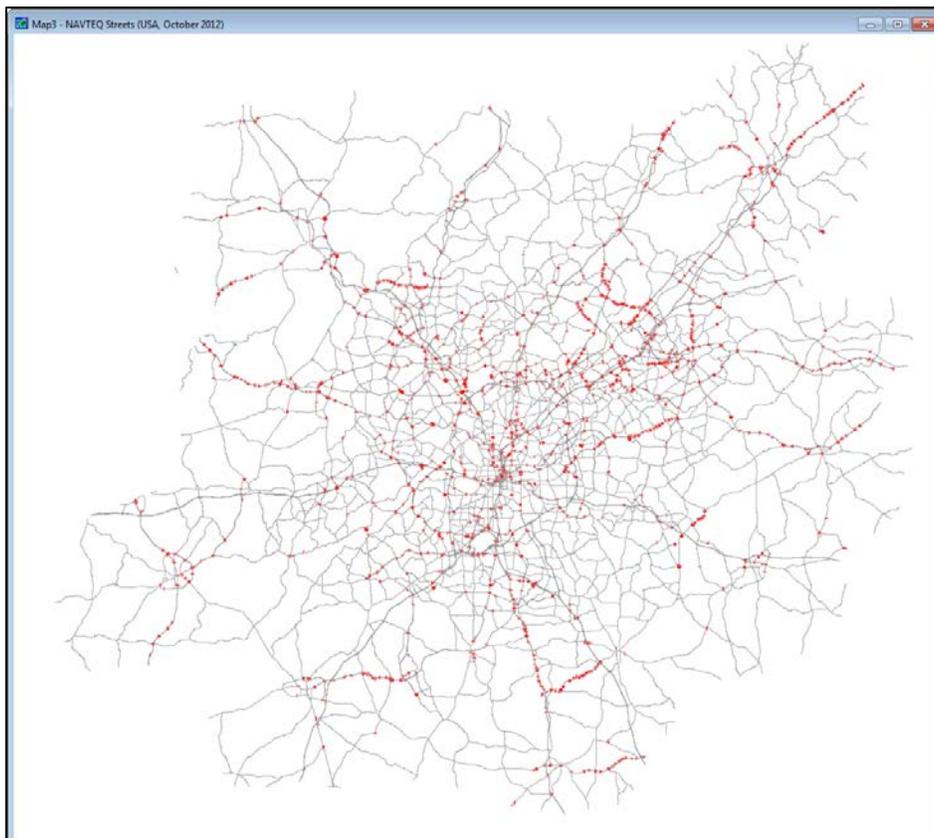
In the table below, we describe the use of turn prohibitions and penalties in the 5 MPO models. We also examined the HERE data to identify the presence of turn prohibitions in each region.

**Table 4-10 Use of Turn Prohibitions and Turn Penalties**

MPO Model	Description of Turn Prohibitions and Penalties
<b>ARC</b>	Does not use either prohibitions or penalties. HERE maps show many left turn prohibitions in the region.
<b>MAG</b>	Uses turn prohibitions, mostly in agreement with HERE maps.
<b>NCTCOG</b>	Does not use either prohibitions or penalties. HERE maps show many left turn prohibitions in region.
<b>PSRC</b>	Uses turn prohibitions. Some that are indicated by HERE maps are missing.
<b>SANDAG</b>	Uses both, prohibitions mostly in agreement with HERE maps and penalties

According to HERE (formerly NAVTEQ) data, there are over 9,000 turn prohibitions present in the Atlanta region (shown below on the map in red), but none are present in the model network. These include both prohibited left turns as well as some prohibited movements on freeways.

**Figure 4-1 HERE Turn Prohibitions in the ARC Region**

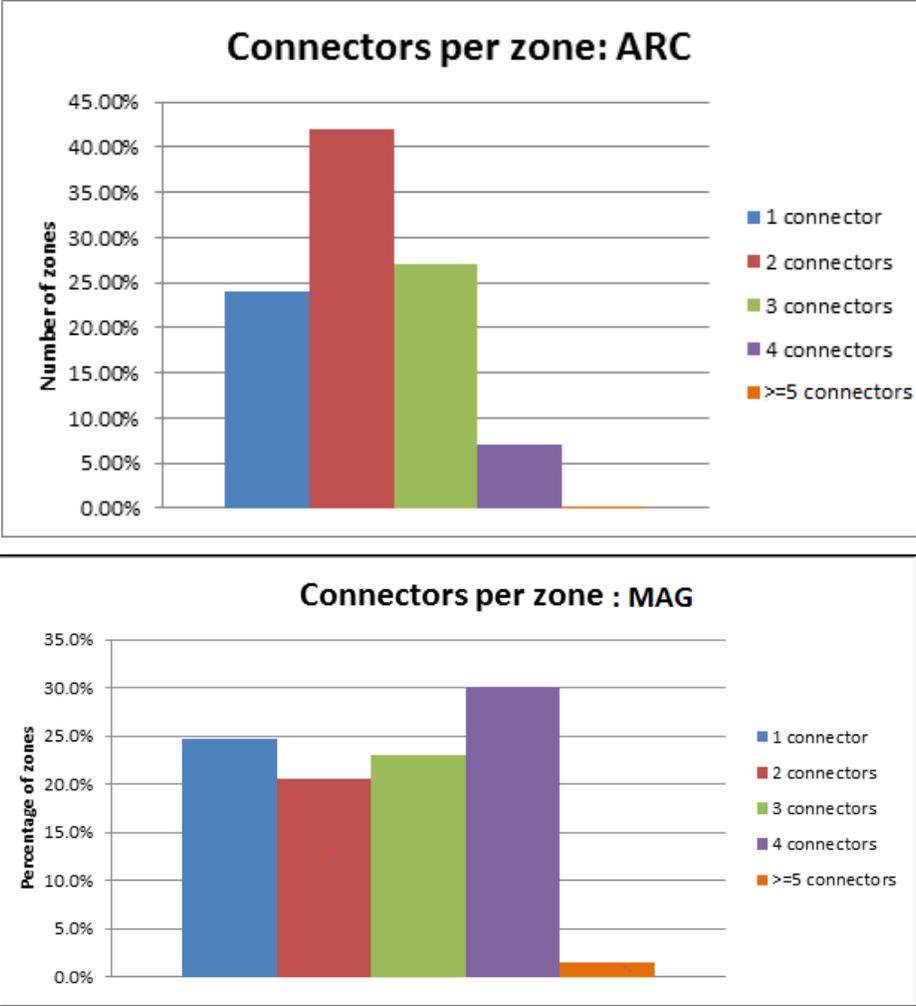


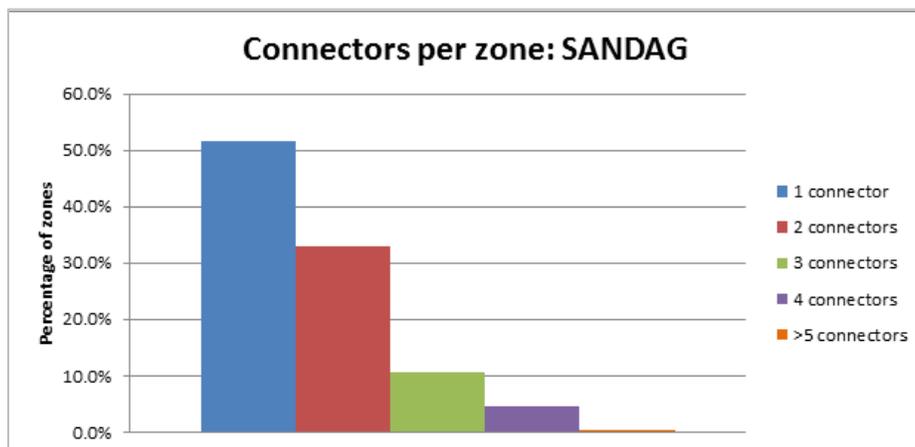
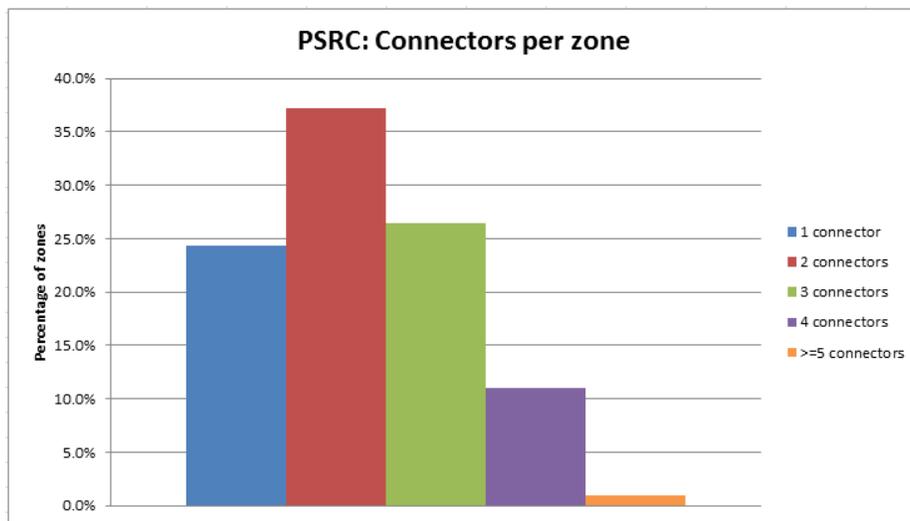
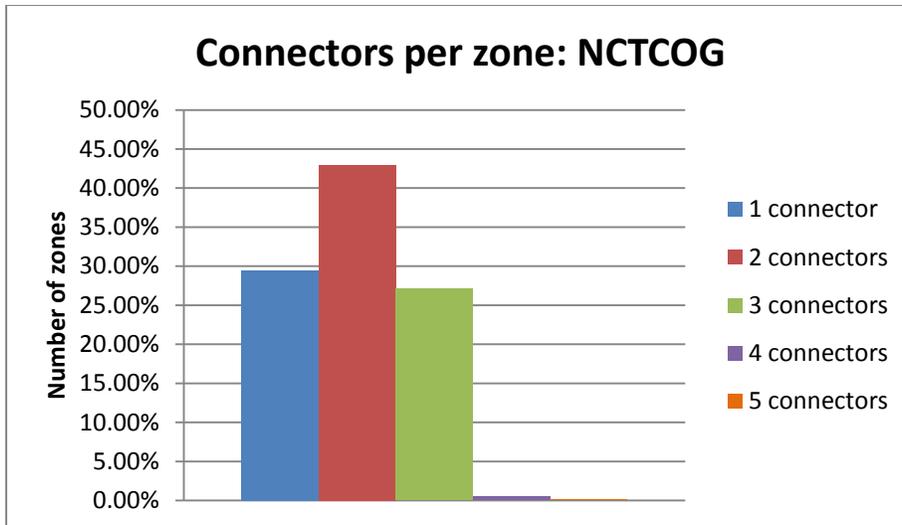
While the geometry of HERE network is more detailed and would, therefore, require many more prohibitions due to dualized road segments, many of those turn prohibitions such as prohibited left turns are present in the regional network.

**Centroid connectors**

For each MPO, we plotted histograms to illustrate the percentage distribution of the number and length of centroid connectors. For all the MPOs except MAG, over half the zones have just 1 or 2 connectors, which would not be regarded as the best practice.

**Figure 4-2 Centroid Connectors per Zone for Each MPO**

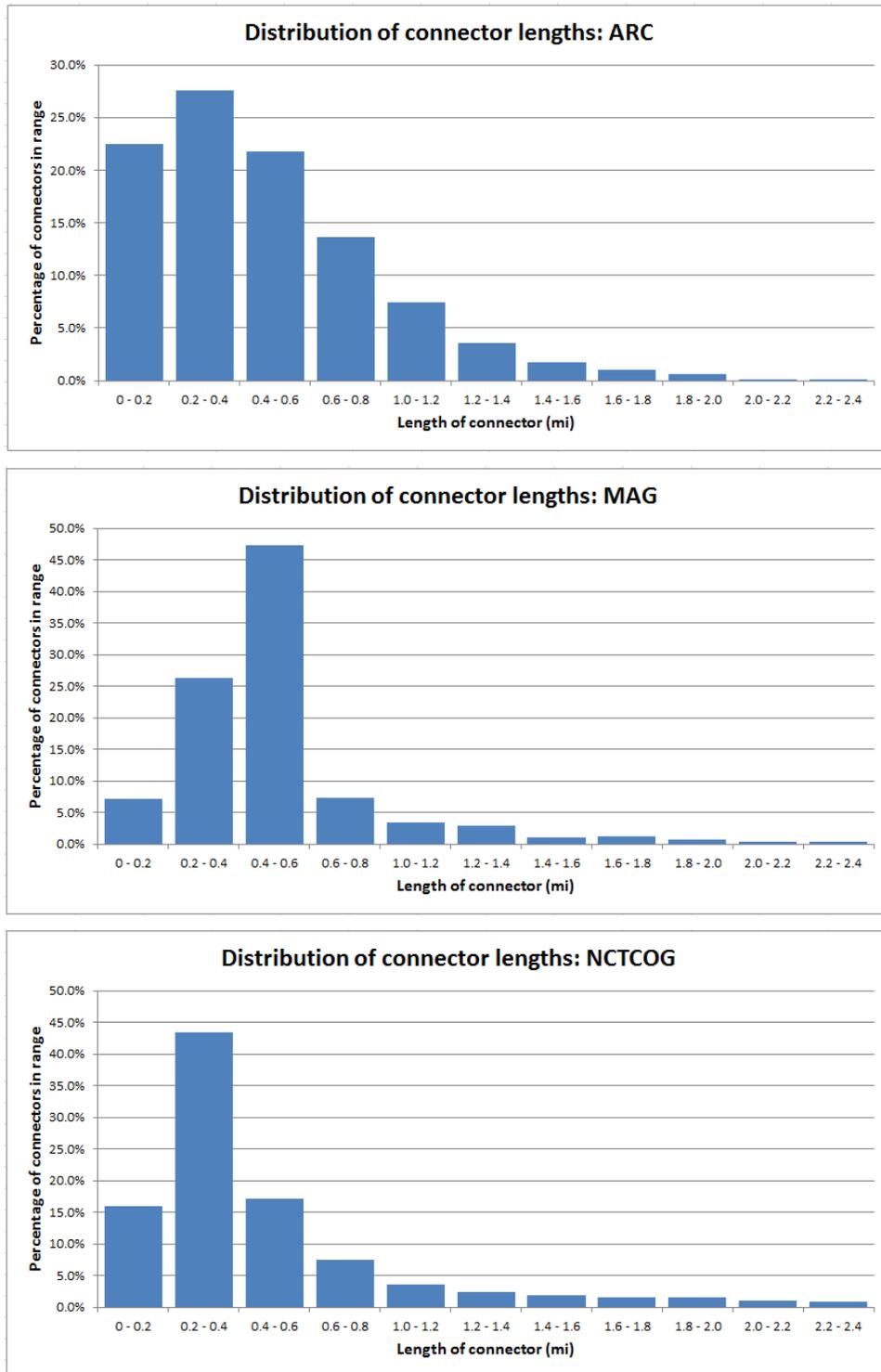


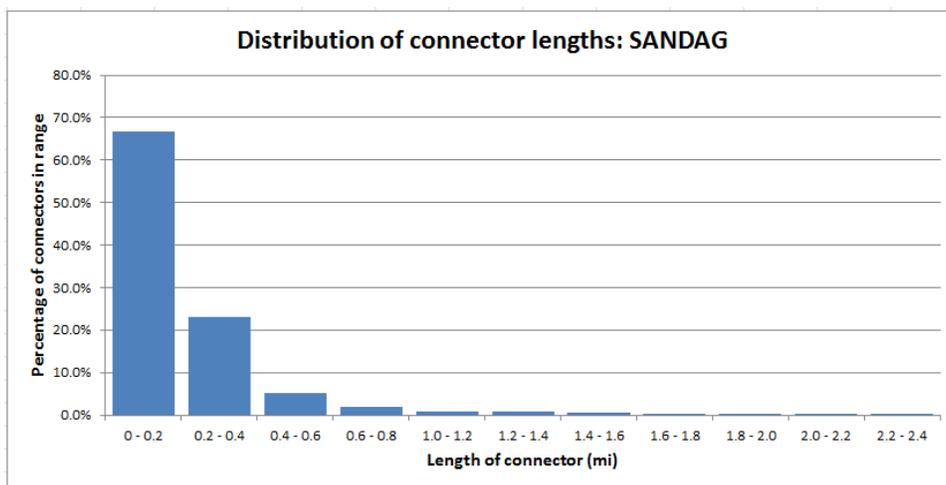
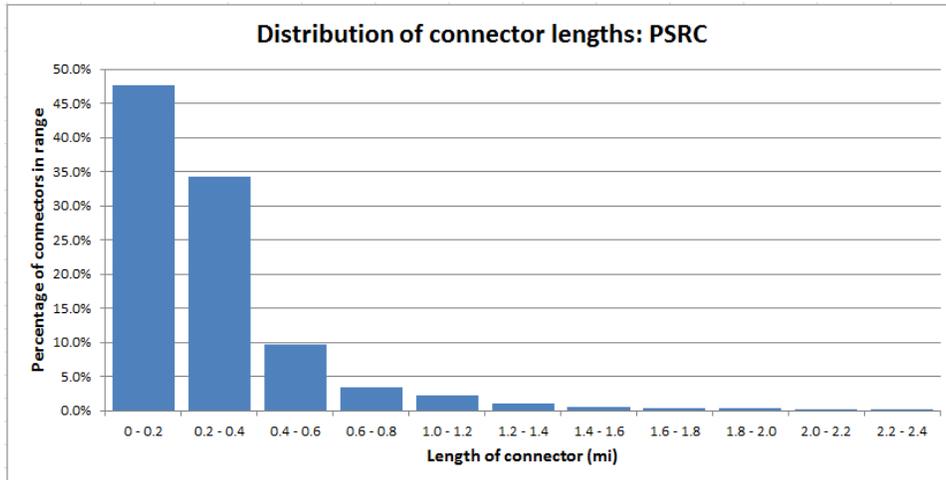


In general, we were surprised that so few centroid connectors were used in each of the models. Generally speaking, we would expect 3 or more connectors to be used more often than not.

In the figure that follows, we present histograms for the centroid connector lengths. It is generally thought that centroid connectors should be short, which typically would be associated with the use of numerous small TAZs and dense network representations.

**Figure 4-3 Distribution of Centroid Connector Lengths**





*Characterization of centroid connections in the MPO models*

Ideally, centroid connectors should connect to the lowest link classes so that flows do not overload the arterials and freeways for which calibration and/or validation is performed and for which predictions are desired. Similarly, count locations used for evaluative purposes should not be on links that are directly loaded with traffic from centroid connectors. As part of our review of modeling practices, we examined the centroid connector linkages in the 5 MPO models and offer the observations below.

**ARC:** For the most part, centroid connectors are linked to the rest of the network via collectors. Some lead onto arterials and frontage roads. Many of the non-freeway count locations are on links that are directly connected to centroids. The connectors have speeds between 7-14 mph.

**MAG:** A large part of the MAG urban network is gridded and most centroids within the grid have connectors in all directions (which is good practice). However, this also means most of the arterial links which the MPO uses as count locations are on links that are directly attached to a centroid connector. Centroids in the MAG network are primarily connected to collectors and arterials and some are connected to frontage roads. Connector speeds vary between 11 mph and 17 mph.

**NCTCOG:** The centroids in the NCTCOG network are primarily attached to collectors and arterials. However, there are a few instances of connectors linking to ramps. Many of the non-freeway counts are on links adjacent to centroid connectors. The peak-period speed for each connector is assumed to be 23 mph. The off-peak speed for each connector is assumed to be 39 mph.

**PSRC:** The centroids are connected to collectors and arterials, some of which are major arterials. The PSRC count data provided to Caliper was only on freeways, so the count locations are not on links directly connected to centroids. The connectors have speeds that vary between 3 mph and 70 mph.

**SANDAG (both ABM and Trip-based Networks):** Centroids are connected to collectors and arterials and many to frontage roads as well. The count data provided by the MPO was almost entirely on the freeway system. Among the few arterial counts, there are some on links attached to centroid connectors. The connectors have speeds that vary between 20 mph and 45 mph.

In planning networks, centroids are commonly connected to intersection nodes or are connected midblock, which involves splitting the link with an extra node. ARC and MAG use midblock connections. NCTCOG and SANDAG have many connections to intersection nodes. PSRC has some connections at intersections, but most appear to be midblock. Curiously, the two MPOs that use volume-delay functions that include node delay (SANDAG and NCTCOG) have many centroids directly connected to intersections. SANDAG's more recent networks have been updated to avoid centroid connections to intersection nodes.

### ***Area types***

Using area types is a shortcut method for selecting or modifying capacities or speeds for individual links. Generally it is reasoned that links of specific functional classes will have different capacities and/or speeds in areas of differing characteristics. For example, freeways in dense urban areas often have lower speed limits, more closely spaced exit and entrance ramps, and lower speeds on those ramps. Consequently, freeway links in dense areas would have lower capacities than those in low density areas. A similar argument can be made with respect to major arterials in central business districts.

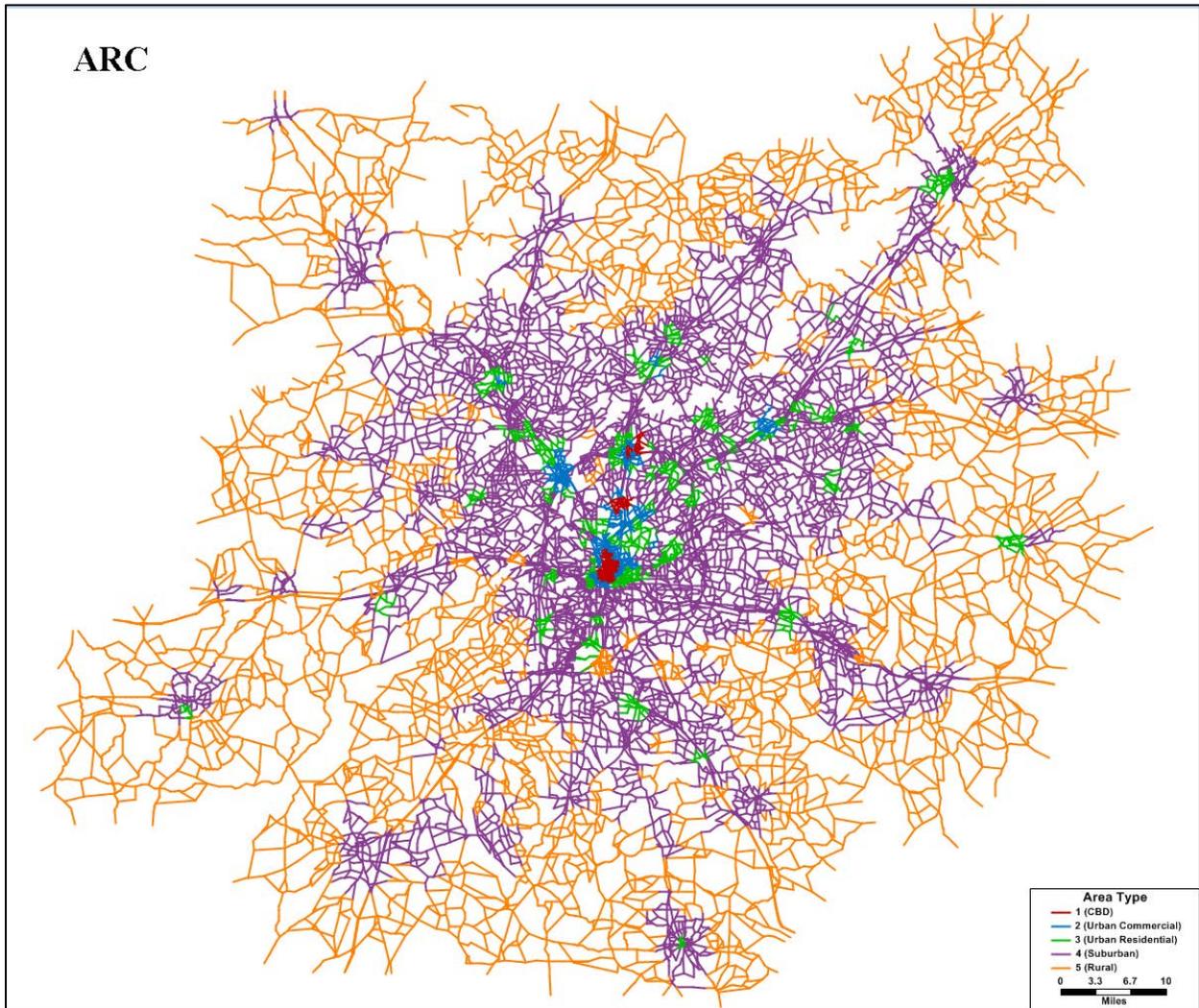
We mapped the area types for the 3 MPOs that employ them: ARC, MAG and NCTCOG. SANDAG and PSRC don't use area types. A cursory inspection of the maps suggests that there is considerable variation in the methods used to arrive at area types. The different character of the map for MAG comes from an elaborate process that they have developed and which has been described in the 2013 TRB Planning Applications Conference presentation titled:

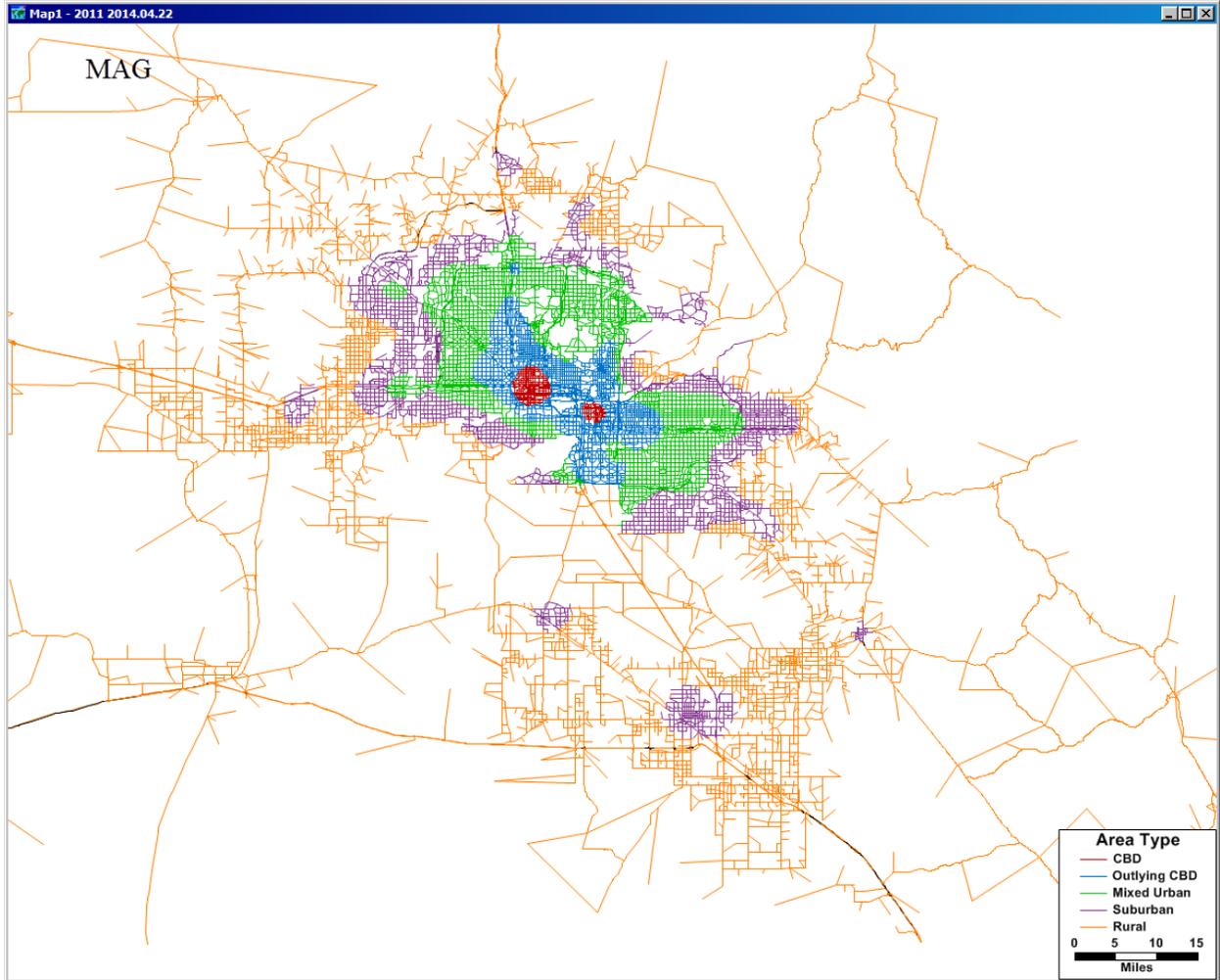
“Determine and Assign Area Type for Network Links Using GIS Technology”

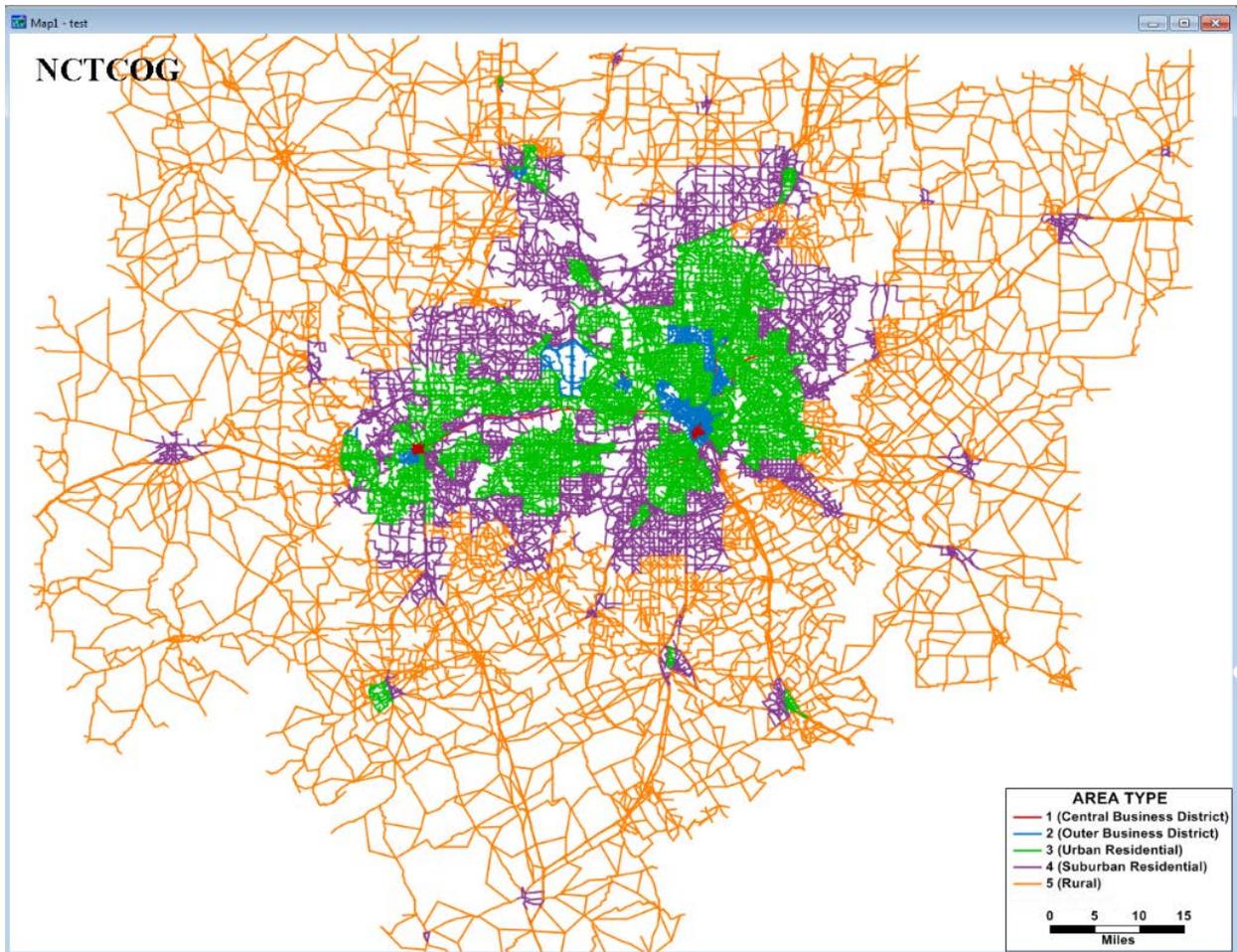
by Petya Maneva, Maricopa Association of Governments

[http://trbappcon.org/2013conf/presentations/246\\_4%20-%20246\\_Maneva\\_Area\\_type.ppt](http://trbappcon.org/2013conf/presentations/246_4%20-%20246_Maneva_Area_type.ppt)

Figure 4-4 Area Type Maps







These maps are suggestive of a rather broad categorization in setting link capacities, although the methods and assumptions employed are probably different in each case. The alternative would be a more fine-grained approach in choosing capacities for each link based upon its characteristics, which might include functional class, road geometry, signal density, and other variables.

### **AM trip characteristics**

In this section, we summarize information about the modeled AM travel demand (PM for MAG) and the separate user classes assigned. All of the summary table entries pertain to the AM peak period of each MPO model. We also tabulate the distribution of O-D pair trip volumes for all classes combined.

#### **ARC ABM**

ARC assigns 10 user classes and maintains a distinction between classes that pay tolls and those that do not. They also distinguish commercial vehicles and trucks and further separate out trucks that either use or do not use the I-285 Bypass.

**Table 4-11 ARC AM Trip Characteristics**

ARC Classes	AM Vehicle Trip Demand
All classes combined	3,664,165
SOV Free	2,435,877
SOV Toll	36,993
HOV-2 person Free	473,846
HOV-2 person Toll	2,482
HOV-3+ Free	202,582
HOV-3+ Toll	124
Commercial	364,054
Medium Truck	86,351
Heavy Truck (No I-285 Bypass)	32,321
Heavy Truck (I-285 Bypass)	29,533

The distribution of trips by origin to destination cell volume is tabulated below along with the percentage of intra-zonal trips. Reflecting the ABM approach, many cells have integer trip values.

**Table 4-12 ARC Combined Trip Matrix Statistics**

% intra-zonal trips = 5.77

Cell value from	Cell value to	# of OD pairs	% of total assigned trips
0.0001	0.001	10,528,241	0.12
0.001	0.01	12,052,611	1.18
0.01	0.1	4,572,789	3.38
0.1	1	768,021	7.04
1	10	1,116,498	58.86
10	100	43,157	24.71
100	1,000	904	4.52
1,000	10,000	3	0.17

The cells with fractional trips reflect internal to external (I-E) and external to external (E-E) trips as well as truck trips which are typically estimated by models that are not part of the ABM.

*MAG PM demand*

MAG assigns 5 user classes distinguishing HOV from SOV and has 3 truck classes. The volume of trips by class is given in Table 4-13 below.

**Table 4-13 MAG PM Trip Statistics**

MAG Classes	PM Vehicle Trip Demand
All classes combined	3,838,062
SOV	3,223,872
HOV	111,839
Light truck	33,205
Medium truck	63,915
Heavy truck	405,231

**Table 4-14 MAG Combined PM Trip Matrix Statistics**

% intra-zonal trips = 7.58

Cell value from	Cell value to	# of OD pairs	% of total assigned trips
0.0001	0.001	917,441	14.85
0.001	0.01	1,472,503	23.83
0.01	0.1	1,943,913	31.46
0.1	1	1,358,175	21.98
1	10	425,886	6.89
10	100	57,385	0.93
100	1,000	31,46	0.05
1,000	10,000	32	0

*NCTCOG AM trip demand*

The NCTCOG model assigns 4 user classes. There is only one truck class and the percentage of truck trips is only 2 percent.

**Table 4-15 NCTCOG AM Trip Statistics**

NCTCOG Classes	AM Vehicle Trip Demand
All classes (combined)	3,214,156
Drive-Alone	2,538,596
Shared-ride No HOV	346,599
Shared-ride HOV	263,055
Truck	65,906

**Table 4-16 NCTCOG Combined AM Trip Matrix Statistics**

% intra-zonal trips = 7.20

Cell value from	Cell value to	# of interchanges	% of total assigned trips
0.0001	0.001	3,967,938	0.06
0.001	0.01	9,620,485	1.23
0.01	0.1	8,308,110	8.98
0.1	1	3,028,227	27.71
1	10	450,786	34.86
10	100	30,298	21.14
100	1,000	1,000	5.81
1,000	10,000	4	0.21

A higher percentage of trips come from cells with fractional trips which is typically attributed to the use of gravity trip distribution models combined with aggregate logit mode share models.

*PSRC AM trip demand*

The PSRC model has 11 user classes distinguishing SOV trips by four income classes, each of which has a different value of time. This facilitates toll analysis but only to the degree that income and the value of time are closely aligned.

**Table 4-17 PSRC AM Trip Statistics**

PSRC Classes	AM Vehicle Trip Demand
All classes (combined)	1,372,320
Non-HBW SOV	482,451
HOV 2 person	176,469
HOV 3 or more persons	96,459
Vanpool	1,449
HBW Income 1 SOV	52,925
HBW Income 2 SOV	118,135
HBW Income 3 SOV	151,322
HBW Income 4 SOV	216,718
Light Truck	31,086
Medium Truck	20,961
Heavy Truck	24,339

**Table 4-18 PSRC Combined AM Trip Matrix Statistics**

% intra-zonal trips = 1.61

Cell value from	Cell value to	# of interchanges	% of total assigned trips
0.0001	0.001	0	0.00
0.001	0.01	0	0.00
0.01	0.1	0	0.00
0.1	1	59,079	2.44
1	10	731,889	83.23
10	100	9,235	12.73
100	1,000	117	1.60
1,000	10,000	0	0.00

PSRC has an extremely low percentage of intra-zonal trips and has no cells with fractional trips. The latter is a reflection of a built-in rounding procedure that the EMME software applies automatically prior to traffic assignment.

*SANDAG AM trip demand*

The SANDAG traffic assignment has 14 user classes, the largest number among the 5 MPO models. Toll payers and non-toll payers are distinguished as separate user classes. In the base case, there are an insignificant number of shared ride toll payers. Presumably these classes are present for estimating future use of tolled facilities by shared-ride travelers.

**Table 4-19 SANDAG AM Trip Statistics**

SANDAG Trip-based Classes	AM Vehicle Trip Demand
All classes (combined)	1,817,301
SOV General Purpose	1,367,921
SOV Pay	6,546
Shared Ride 2-person General Purpose	269,801
Shared Ride 2-person HOV	10,420
Shared Ride 2-person Pay	0.45
Shared Ride 3-person General Purpose	134,474
Shared Ride 3-person HOV	4,748
Shared Ride 3-person Pay	0.21
Light heavy-duty non-toll truck	10,520
Medium heavy duty non-toll truck	6,747
Heavy heavy-duty non-toll truck	4,395
Light heavy-duty toll truck	769
Medium heavy-duty toll truck	594
Heavy heavy-duty toll truck	361

**Table 4-20 SANDAG Trip-based Combined AM Trip Matrix Statistics**

Cell value from	Cell value to	# of interchanges	% of total assigned trips
0.0001	0.001	8,370,079	0.19
0.001	0.01	6,076,168	1.10
0.01	0.1	1,666,610	2.61
0.1	1	472,295	9.41
1	10	740,923	69.54
10	100	13,845	14.80
100	1,000	199	1.96
1,000	10,000	3	0.40

The AM trip statistics differ between the trip-based model and the ABM that is under development. The ABM trip statistics are given below.

**Table 4-21 SANDAG ABM AM Trip Statistics**

SANDAG ABM Classes	AM Demand
All classes (combined)	1,833,464
SOV General Purpose	1,362,342
SOV Pay	10,165
Shared Ride 2-person General Purpose	277,993
Shared Ride 2-person HOV	14,957
Shared Ride 2-person Pay	319
Shared Ride 3-person General Purpose	134,094
Shared Ride 3-person HOV	6,949
Shared Ride 3-person Pay	146
Light heavy-duty non-toll truck	11,751
Medium heavy duty non-toll truck	8,062
Heavy heavy-duty non-toll truck	4,635
Light heavy-duty toll truck	975
Medium heavy-duty toll truck	735
Heavy heavy-duty toll truck	336

**Table 4-22 SANDAG ABM Combined Trip Matrix Statistics**

% intra-zonal trips = 1.63

Cell value from	Cell value to	# of interchanges	% of total assigned trips
0.0001	0.001	8,184,677	0.18
0.001	0.01	6,184,691	1.16
0.01	0.1	2,019,834	3.10
0.1	1	467,570	9.09
1	10	777,816	71.51
10	100	12,876	13.17
100	1,000	130	1.38
1,000	10,000	4	0.43

The percentage of intra-zonal trips seems particularly small for the PSRC and SANDAG models, perhaps reflecting missing truck trips that are often of short length. Typically urban truck trips are quite short because of the trip chaining that characterizes urban pickup and delivery operations.

### **Capacities**

A key input to a user equilibrium macroscopic traffic assignment is the capacity of each link in the model network. The link capacity is a fundamental determinant of the volume-delay relationship.

In reality, the maximum or jam capacity of a link will depend on a variety of factors, many of which might not be considered in planning models. Various Highway Capacity Manual Level of Service (LOS) procedures detail these factors, and some MPOs attempt to take these factors into account in their volume delay functions. Noted below for each MPO is the approach used to determine network link capacities.

**Table 4-23 MPO Model Link Capacities**

MPO Model	Capacity Determination
<b>ARC</b>	Varying by area type and facility type, values based on a lookup table. Area Types based on population and employment density lookup, Centroids: Uncapacitated
<b>MAG</b>	Based on functional class and area type-Ranges of capacities by facility type are Freeways: 1,800-2,100, HOV: 1,300-1,500, Expressways: 800-1,000, Arterials: 700-900, Collectors: 450-600, Ramps: 1,000-1,300, Centroids: Uncapacitated
<b>NCTCOG</b>	Separate link and intersection capacity. Link capacity is based on LOS E and is based on lookup table for functional class and area type. 2300 is used for freeways, 700-900 for arterials, 425-600 for collectors, 1250-1700 for freeway ramps, 650-1000 for frontage roads, and 2000-2300 for HOV. Centroids: 100,000
<b>PSRC</b>	Based on facility type and speed limits, entered link by link. Freeways and Expressways: 1800-2100, Arterials and Collectors: 500-1100, Ramps: 1000-1400, Centroids: Uncapacitated
<b>SANDAG</b>	Mid-link capacity: Uses Caltrans 1900-2100 for freeways, 1600 for HOV, lanes * 1500 for urban facilities with median, lanes * 1300 for urban facilities without median, lanes = # of mid-block lanes. Intersection Capacity based on HCM, LOS D for HOV, LOS E for freeway Centroids:999,999

### ***PCEs for vehicle classes***

Large and heavy vehicles have a disproportionate impact on traffic flow relative to passenger cars. It is considered good practice to use passenger car equivalents to take account of these effects. ARC uses PCEs for trucks; 1.5 for the medium truck category and 2 for the heavy truck categories. PSRC has the same practice. SANDAG uses PCEs ranging from 1.3 to 2.5 for its six truck classes. MAG and NCTCOG do not weight truck volumes with PCEs.

### ***Transit preloads***

PSRC and SANDAG calculate car-equivalent transit flows as a preload for the highway assignment. ARC, MAG and NCTCOG do not however, and this may lead to an underestimate of congestion in certain locations.

### ***Assignment generalized cost impedance functions***

Each MPO assignment model, with the exception of MAG, is a generalized cost user equilibrium model. The total impedance of a link is comprised of its volume-dependent congested travel time and any operating cost and/ or toll that is utilized. With the exception of PSRC and MAG, all of the models use vehicle operating costs.

These operating costs are all specified in terms of a cost per mile. Therefore, the link cost varies with the length of each network link and does not depend on traffic flow. Only ARC uses a vehicle operating cost is different for cars and trucks. In the NCTCOG and SANDAG (both trip-based and ABM) models, there is a single value of operating cost used for all vehicles in the assignment. In the MAG model, there is a distance-based link impedance term added they state is “used for path selection” and which has the same value for all vehicle types.

Despite their widespread use, we believe that there is neither a theoretical or empirical reason for including vehicle operating costs in traffic assignment models. This point will be discussed in the next chapter.

### ***Values of time***

The various models use quite different values of time. These are listed in the following Table.

**Table 4-24 MPO Model Values of Time**

<b>MPO Model</b>	<b>Value of Time</b>
<b>ARC</b>	Auto: \$25/hr, Truck: \$35/hr
<b>MAG</b>	No tolls or VOT, but a link impedance term is added of 1.4 minutes/mile
<b>NCTCOG</b>	Auto: \$14/hr, Truck: \$17/hr
<b>PSRC</b>	DA Non-HBW: \$20/hr HOV2: ~\$38/hr HOV3+: \$48/hr Vanpool: ~\$128/hr DA HBW Income 1: \$12/hr DA HBW Income 2: ~\$22/hr DA HBW Income 3: ~\$33/hr DA HBW Income 4: ~\$42/hr Light Truck: ~\$50/hr Medium Truck: ~\$57/hr, Heavy Truck: ~\$63/hr
<b>SANDAG</b>	Auto and light truck: \$30/hr Medium Truck: \$30.60/hr Heavy Truck: \$43.20/hr

The wide variation in the value of time suggests that this is an area for further investigation for at least some of the MPO models. We did not investigate how these particular values of time were derived.

### ***Volume-delay functions***

The volume-delay function is a crucial component of a user equilibrium traffic assignment. It computes the delay that is added to the free flow speeds as a result of link traffic volume.

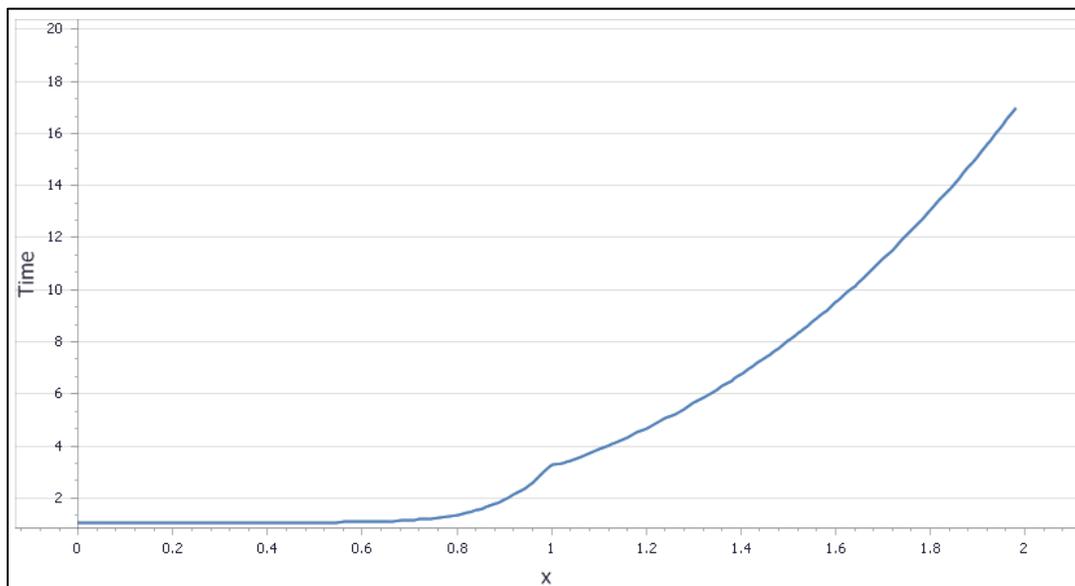
The subject of a great deal of research, one finds varying opinions about the most appropriate volume-delay functions (VDFs) for traffic assignment models. Historically, the Bureau of Public Roads (BPR) curves were used and remain popular. Indeed in our inventory of MPO models, we found that many MPOs use the BPR VDF with the standard coefficients of .15 and 4 for all types of links. A more enlightened approach and one endorsed by the Highway Capacity Manual for planning applications uses different BPR coefficients for different types of roads.

Many modelers favor other specific VDF formulations as is evidenced by those employed in the 5 MPO models. In this section we compare the VDF curves for the highway, arterial, and collector classes from each MPO wherever possible. Some MPOs, such as PSRC, do not designate a collector class.

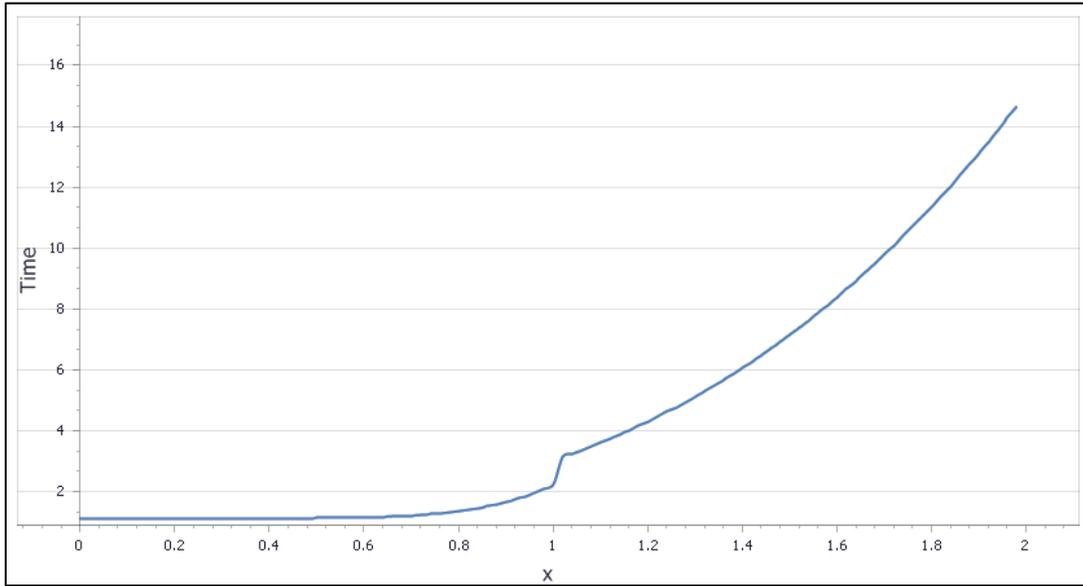
We begin with the ARC model that we examined. The ARC volume-delay curve (provided to us at the time we began analysis of their ABM model) has one function for volume-to-capacity (V/C) ratios less than 1.0 and a different function for V/C ratios greater than 1.0. This causes a sharp inflection point, which is less than ideal and affects convergence to lower relative gaps. It should be mentioned that ARC realized that their practice was problematic and corrected it late last year.

Below are plots of the ARC VDFs for various road classes. These are very gentle growth curves that would not greatly deter travel on links with V/C ratios greater than one.

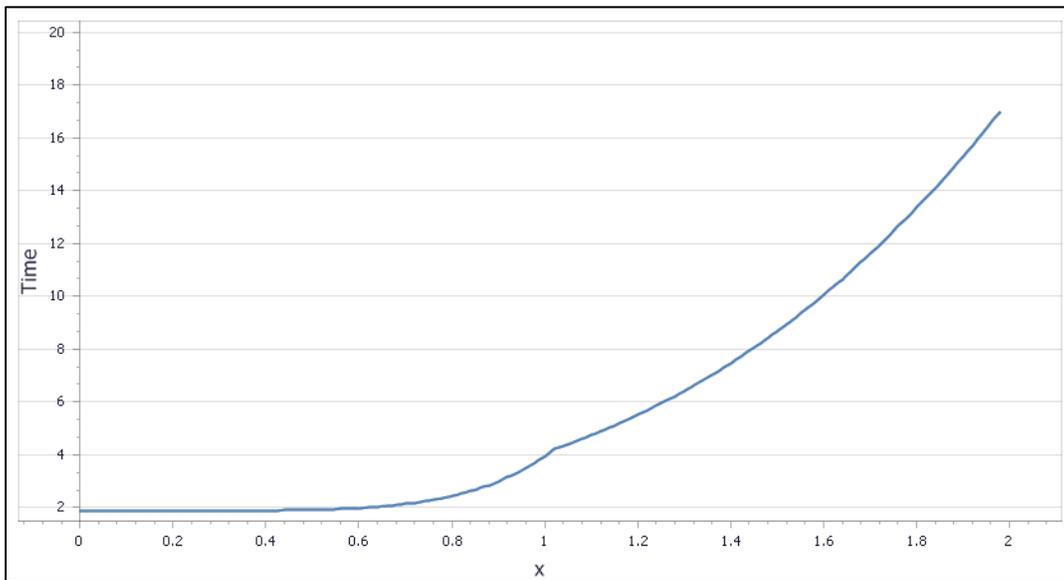
**Figure 4-5 ARC Freeway Volume-Delay Function**



**Figure 4-6 ARC Arterial Volume-Delay Function**



**Figure 4-7 ARC Collector Volume-Delay Function**



The MAG volume-delay curves use the BPR function and also seem rather gentle around  $V/C=1$ . Since the values of alpha and beta used depend on link type as well as area type, in some cases the model assigns the same value of beta to arterials, collectors and ramps within an area type, which is again less than ideal. The MAG alpha and beta coefficients were estimated in 2010.

Figure 4-8 MAG Rural Freeway Volume-Delay Function

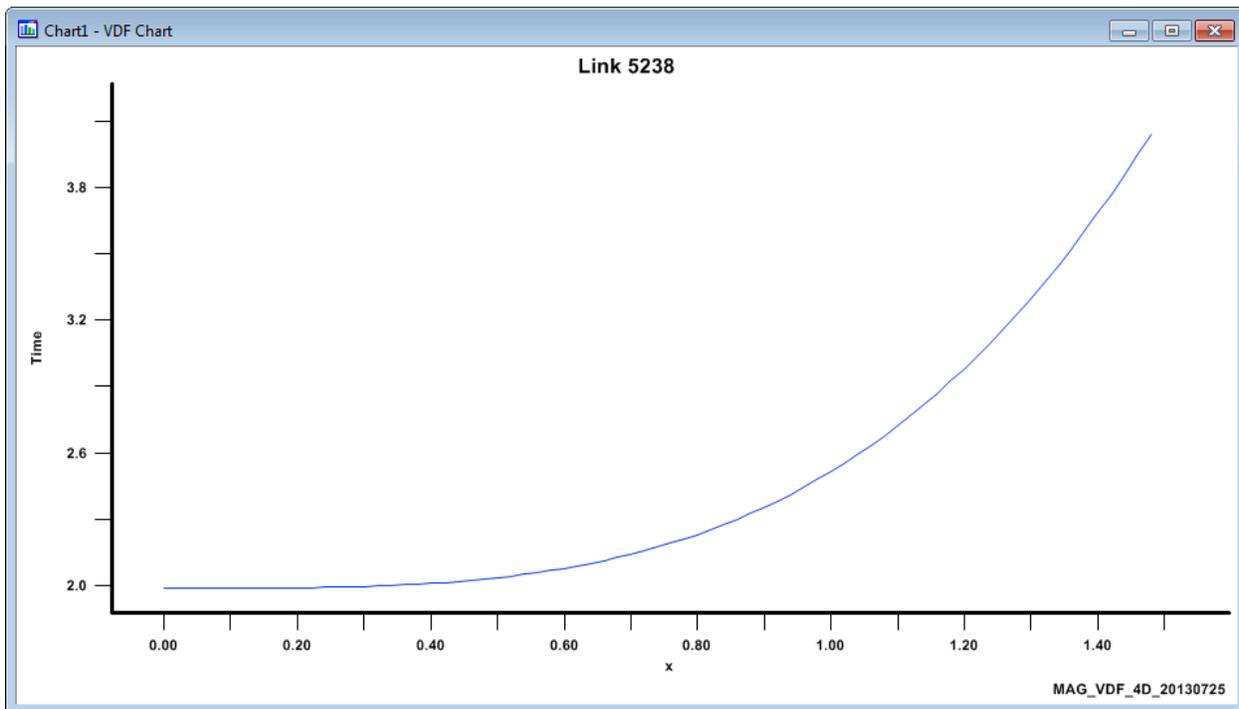
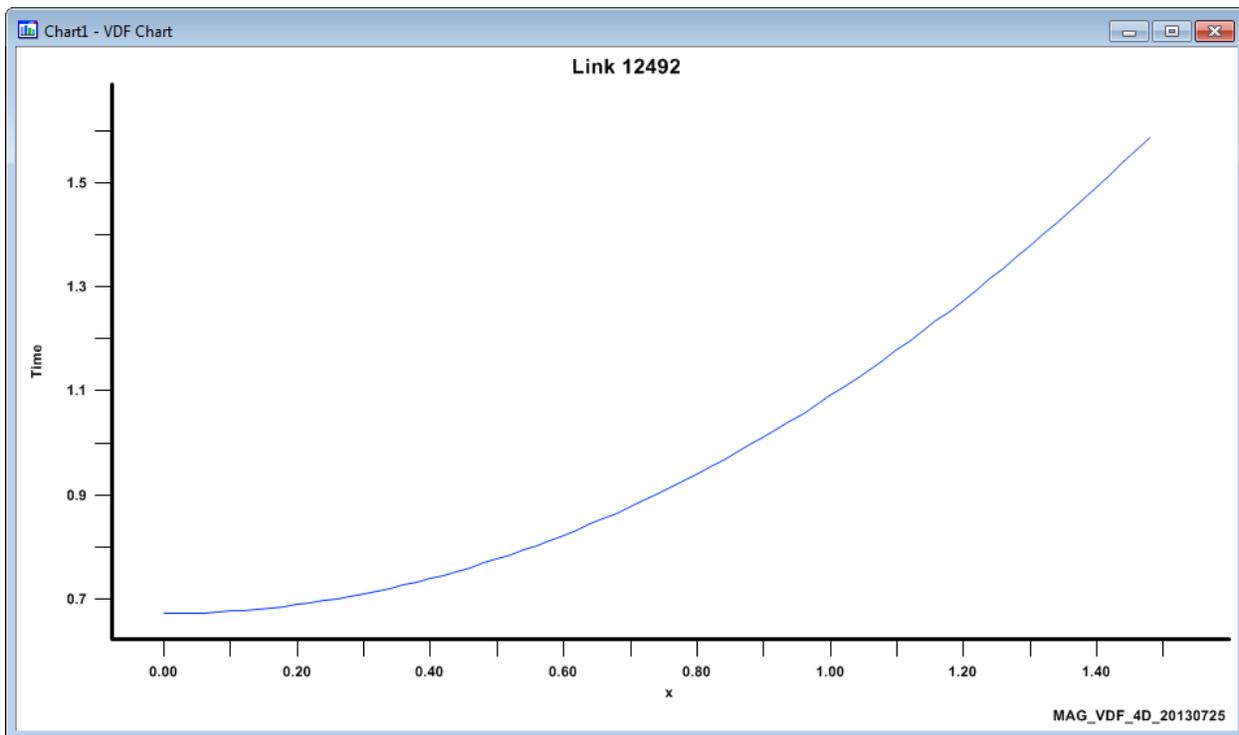
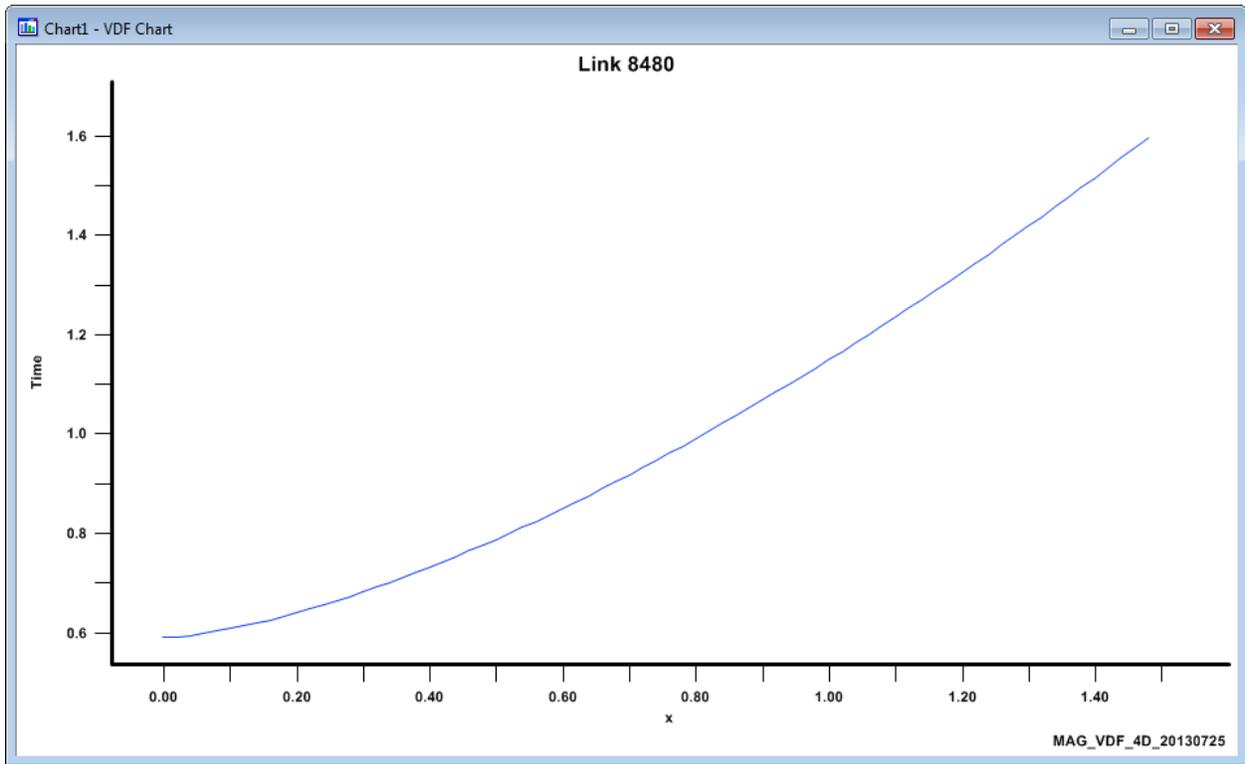


Figure 4-9 MAG Outlying CBD Arterial Volume-Delay Function

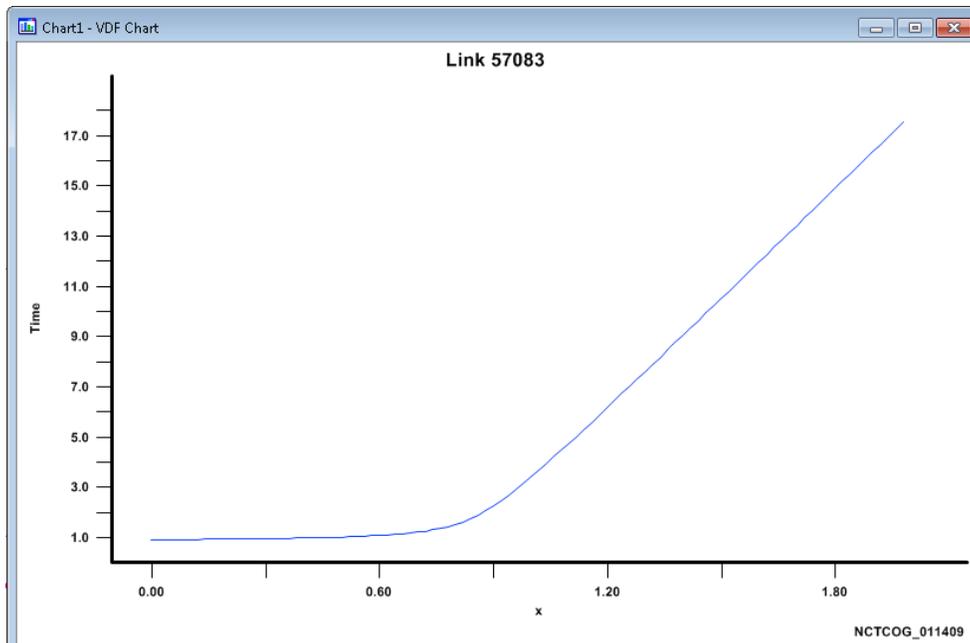


**Figure 4-10 MAG CBD Collector Volume-Delay Function**

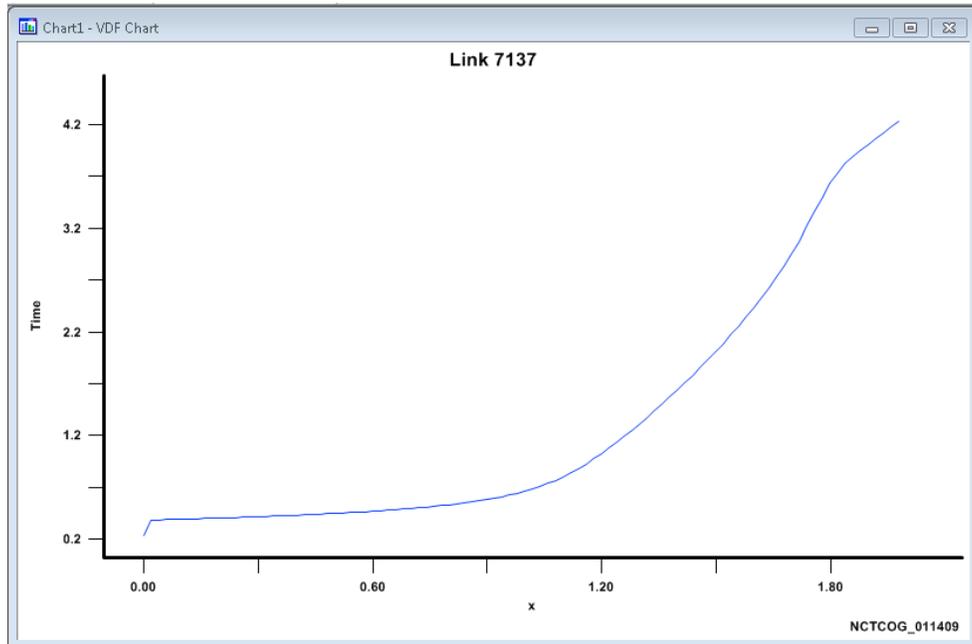


NCTCOG uses a compound volume-delay function with a conical VDF for highways estimated from empirical data and an added delay function for signalized intersections. Thus for highways, the curve is smooth, but for lower link classes with signals there are inflection points as a result of the node delay component.

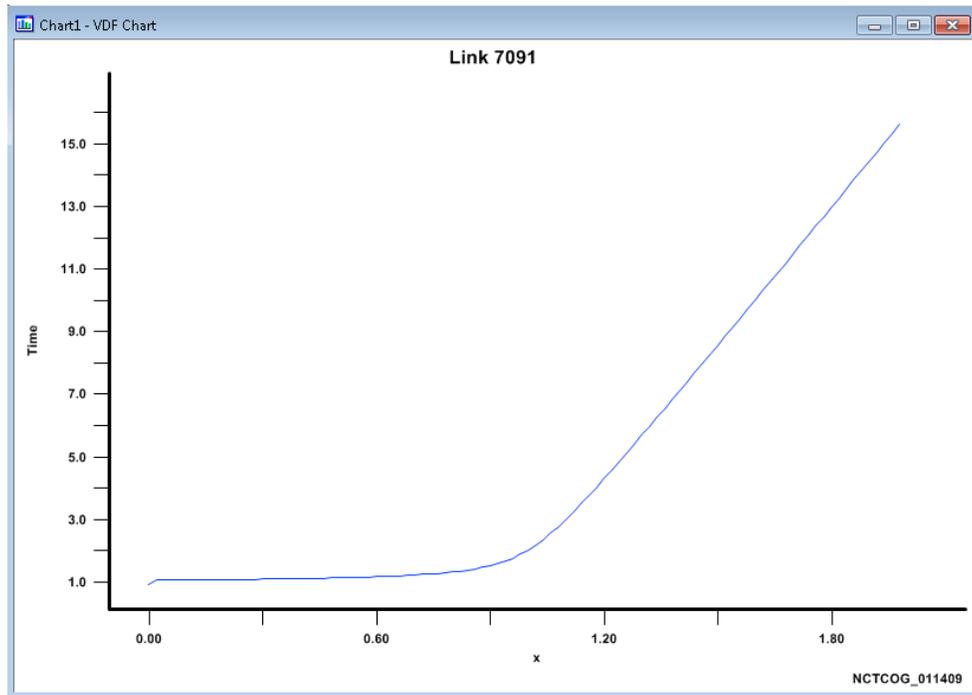
**Figure 4-11 NCTCOG Freeway Volume-Delay Function**



**Figure 4-12 NCTCOG Arterial Volume-Delay Function**

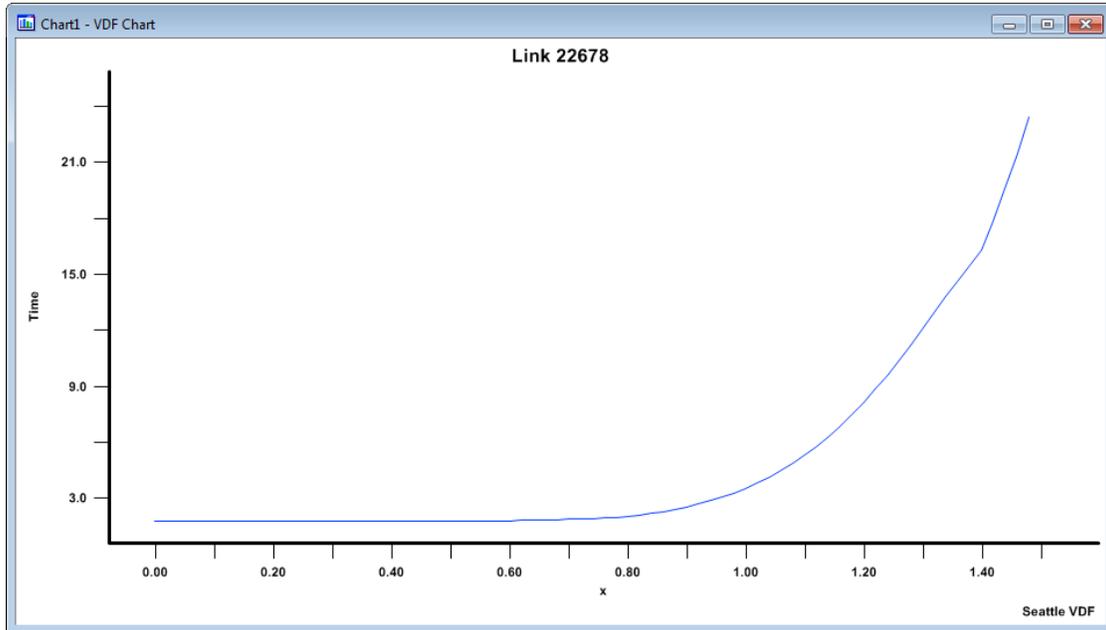


**Figure 4-13 NCTCOG Collector Volume-Delay Function**

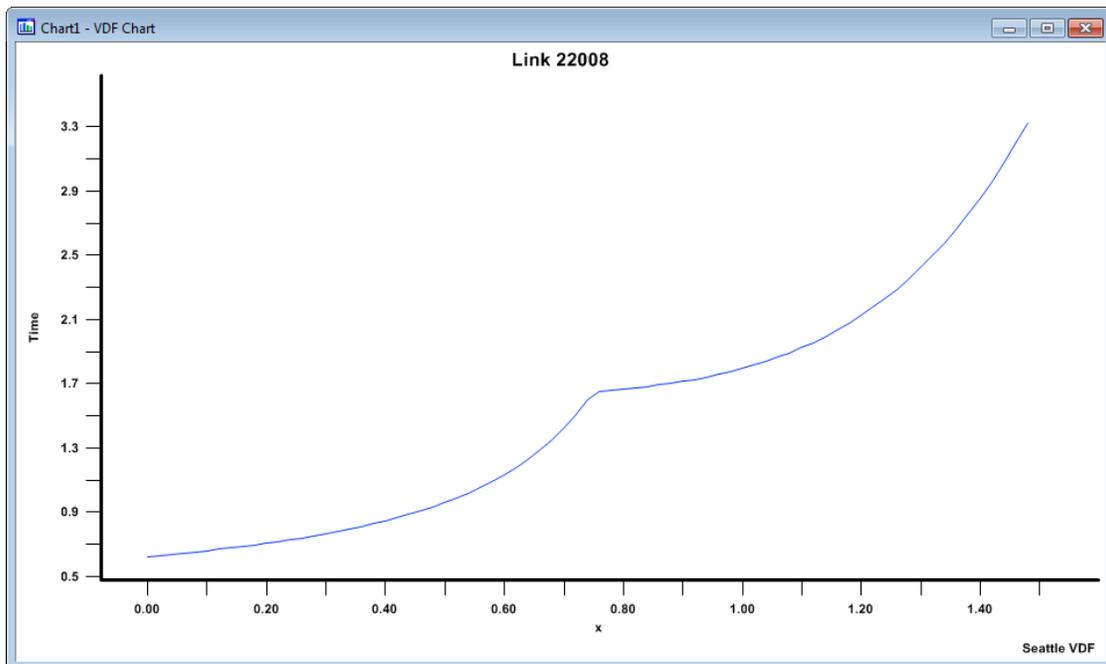


PSRC does not use area types to determine speeds or capacities. The model VDF combines a BPR term with an additional term. For freeways and expressways this term is said to be a penalty for unreliability. The term has a different form for urban and rural arterials, where it is used to represent intersection delay on links. The kink in the arterial VDF is peculiar.

**Figure 4-14 PSRC Freeway Volume-Delay Function**

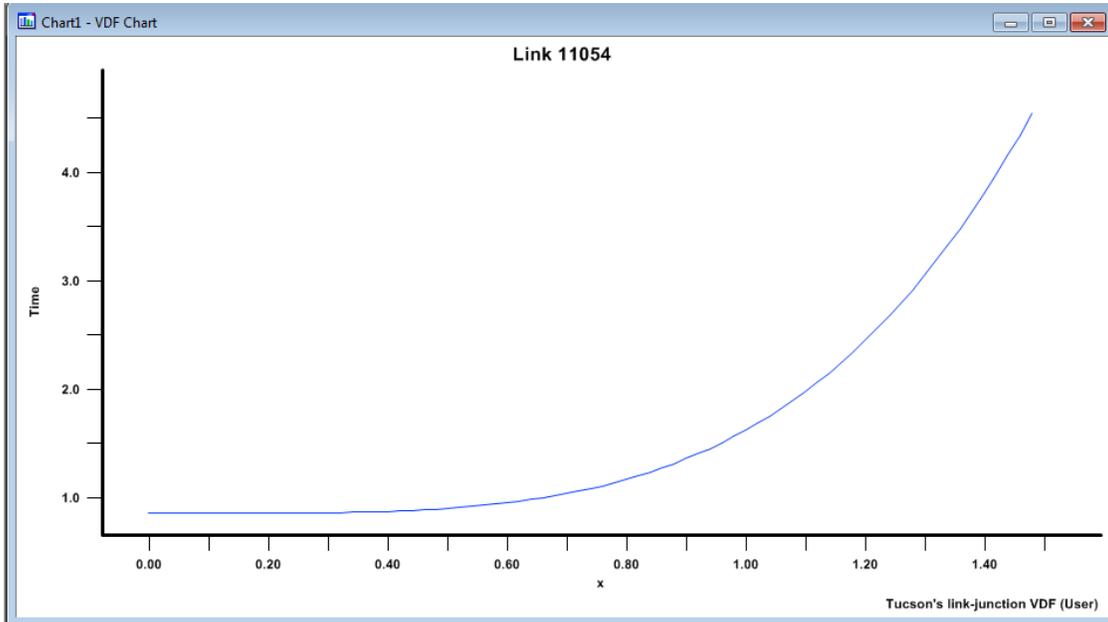


**Figure 4-15 PSRC Arterial Volume-Delay Function**



The SANDAG VDF combines a simple BPR function with an intersection delay term. As can be seen below, all of the VDF plots show fairly gentle increases in delay around  $V/C = 1$ .

**Figure 4-16 SANDAG Freeway Volume-Delay Function**



**Figure 4-17 SANDAG Arterial Volume-Delay Function**

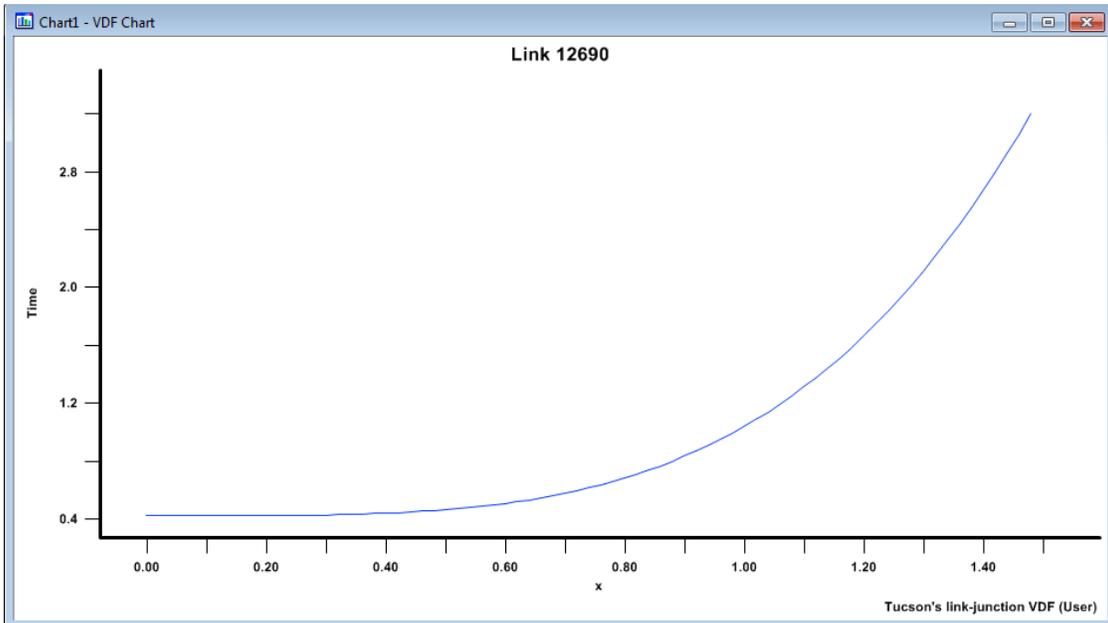
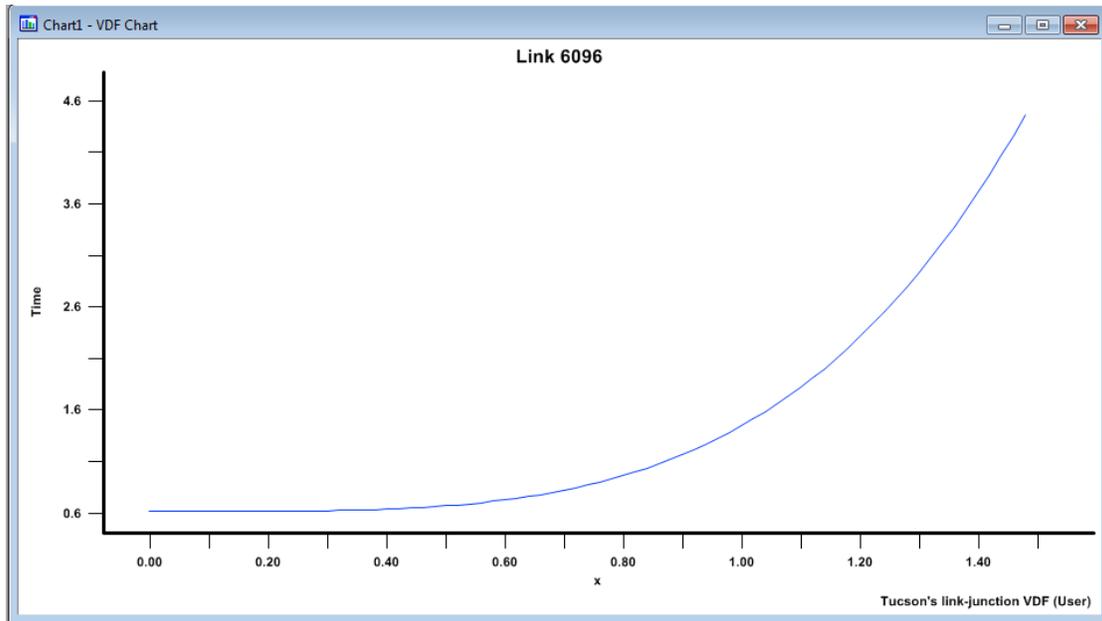


Figure 4-18 SANDAG Collector Volume-Delay Function



Overall, we were a bit surprised at the VDF functions used in the MPO models. In general, we would have expected steeper and smoother curves.

## MPO Base Model Traffic Assignments

We performed several preliminary traffic assignment runs with the MPO models. We established that we were able to run the models with the existing volume-delay functions and convergence levels currently in use by each MPO and with the same or a similar algorithm. It should be mentioned that we made slight changes to the VDF functions of two models. For ARC, we used a modified version of the VDF in which we applied the same function that was used for all v/c ranges rather than separate functions for v/c ranges less than and greater than 1.0. For NCTCOG, the VDF was not continuous at the volume=0 point. If the volume was zero the travel time was set to be free-flow time, but if there was any volume assigned, a delay function was applied. These changes were made to avoid distracting results which would not be of great interest to the research.

As indicated in the Table below, at the time we began our study, MAG and NCTCOG used the Frank-Wolfe algorithm (FW), ARC and SANDAG used the bi-conjugate Frank-Wolfe algorithm (BFW), and PSRC used a path-based algorithm [29]. We mimicked the assignments closely in TransCAD 7. These assignments were performed on a 3.2 GHz, 6 physical core i7 PC with hyper-threading disabled and 24GB of available memory. A summary table of results follows below.

**Table 4-25 MPO Base Period Traffic Assignments**

MPO	ARC	MAG	NCTCOG	PSRC	SANDAG ABM	SANDAG trip-based
<b>METHOD</b>	BFW	FW	FW	Path-based	BFW	BFW
<b>TIME PERIOD</b>	AM	PM	AM	AM	AM	AM
<b>CONVERGENCE (Relative Gap)</b>	1e-4	1e-4	1e-4	1e-4	5e-4	1e-3
<b>NUMBER OF ITERATIONS</b>	80	110	235	10	26	16
<b>COMPUTATIONAL TIME</b>	1 h 4 min	20 min	1 h 33 min	28 min	35 min	20 min
<b>TOTAL VMT</b>	40,264,910	29,357,089	35,211,735	13,122,321	16,927,509	15,730,400
<b>TOTAL VHT</b>	1,244,615	889,780	1,089,345	447,169	490,231	443,496

For all the models, the run times to achieve the specified relative gaps are modest. The disparity in run times is quite noticeable across MPOs and varies, in part, due to differences in the algorithm employed, the number of zones, the volume delay functions utilized, and the overall level of congestion. However, there is some rough consistency between area size in terms of the total number of AM trips and the assigned VMT and VHT.

### ***Trip speeds***

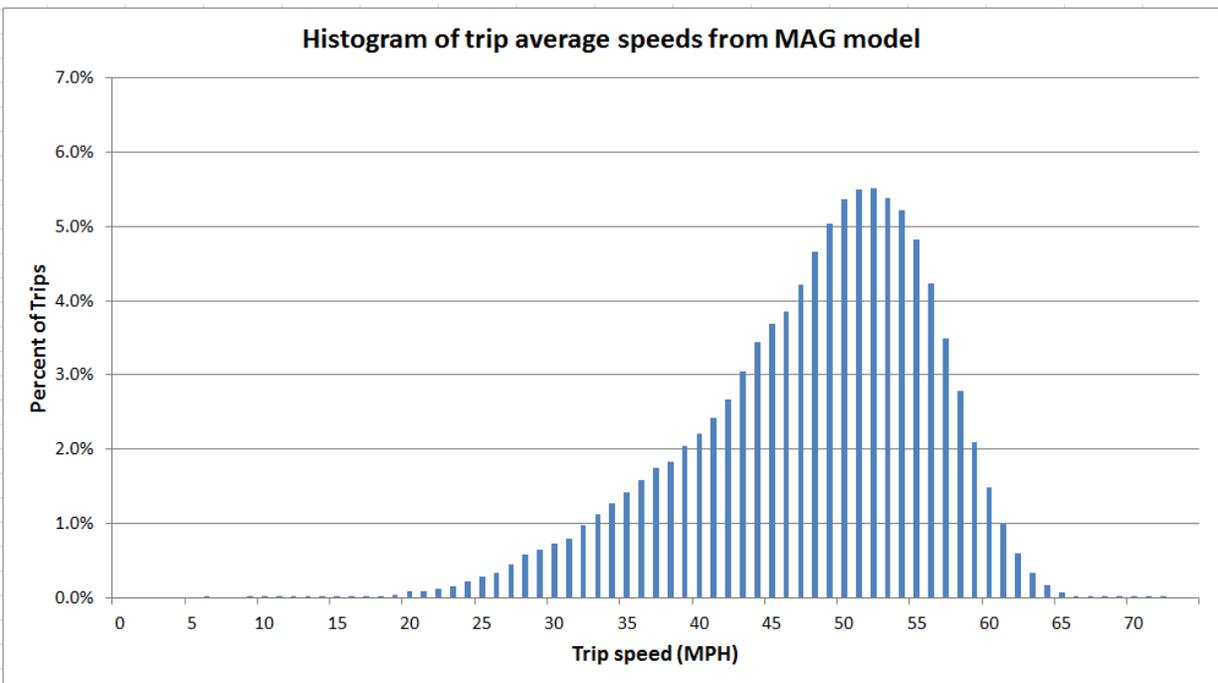
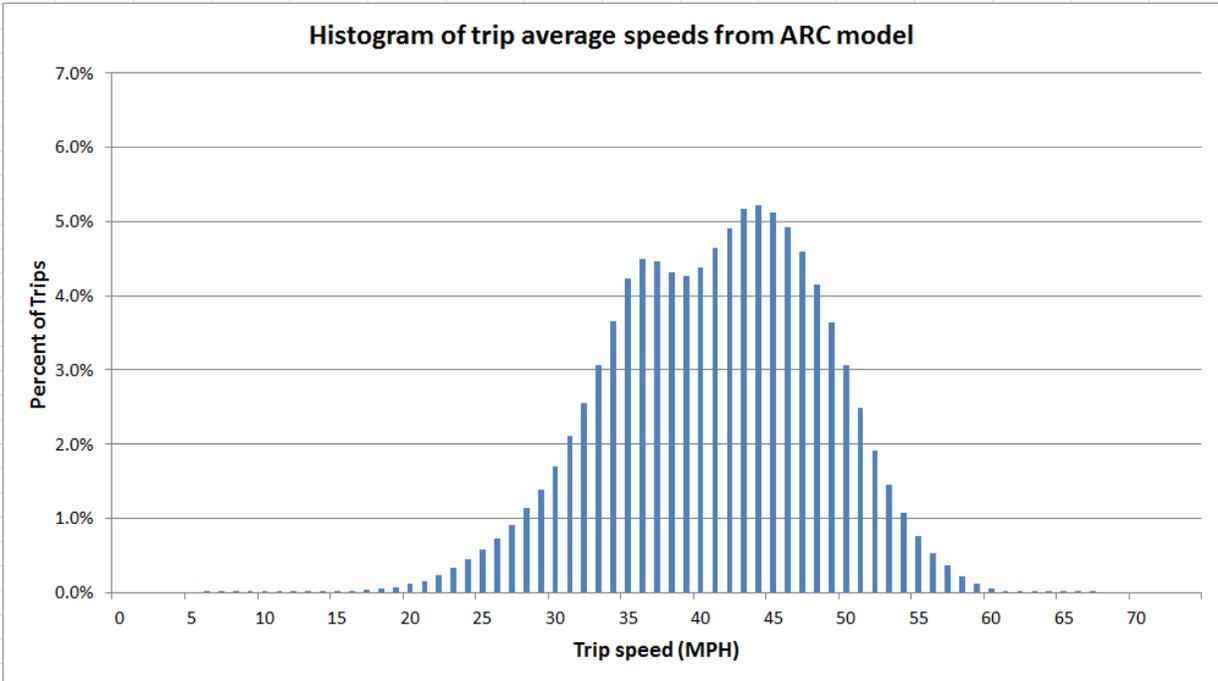
The ratio of VMT to VHT gives the average speed of travel as calculated with each model. All of the model averages fall within a fairly narrow range as indicated below.

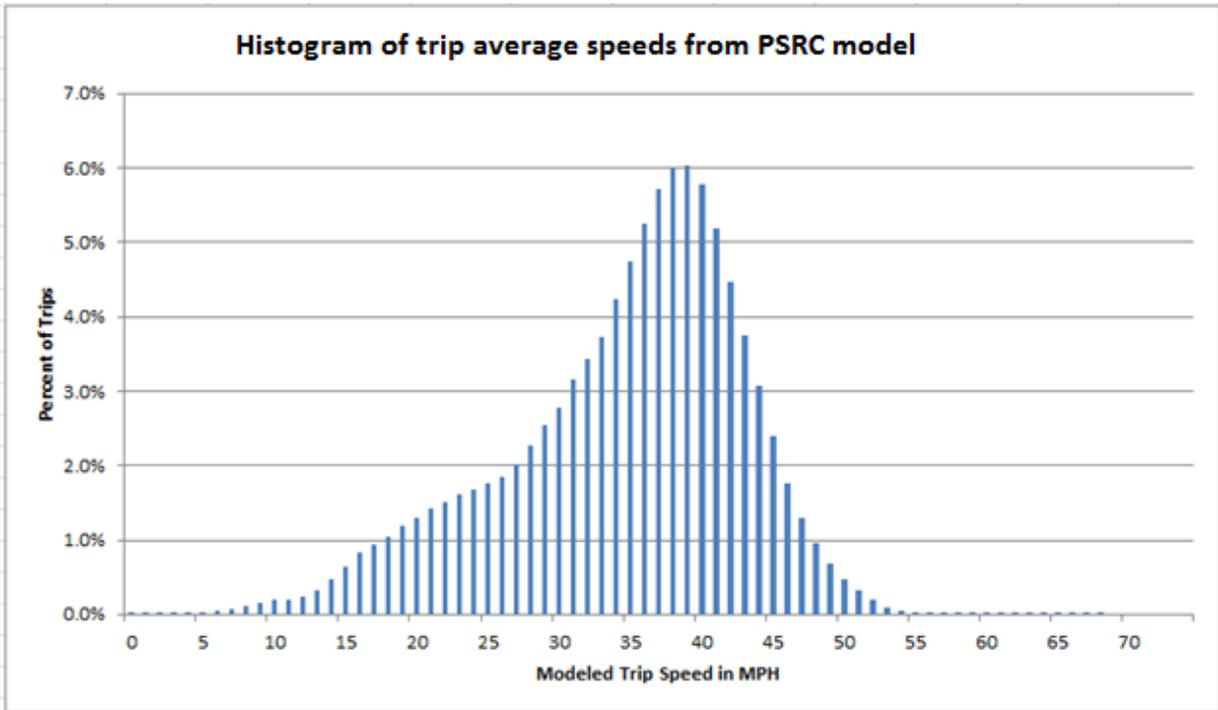
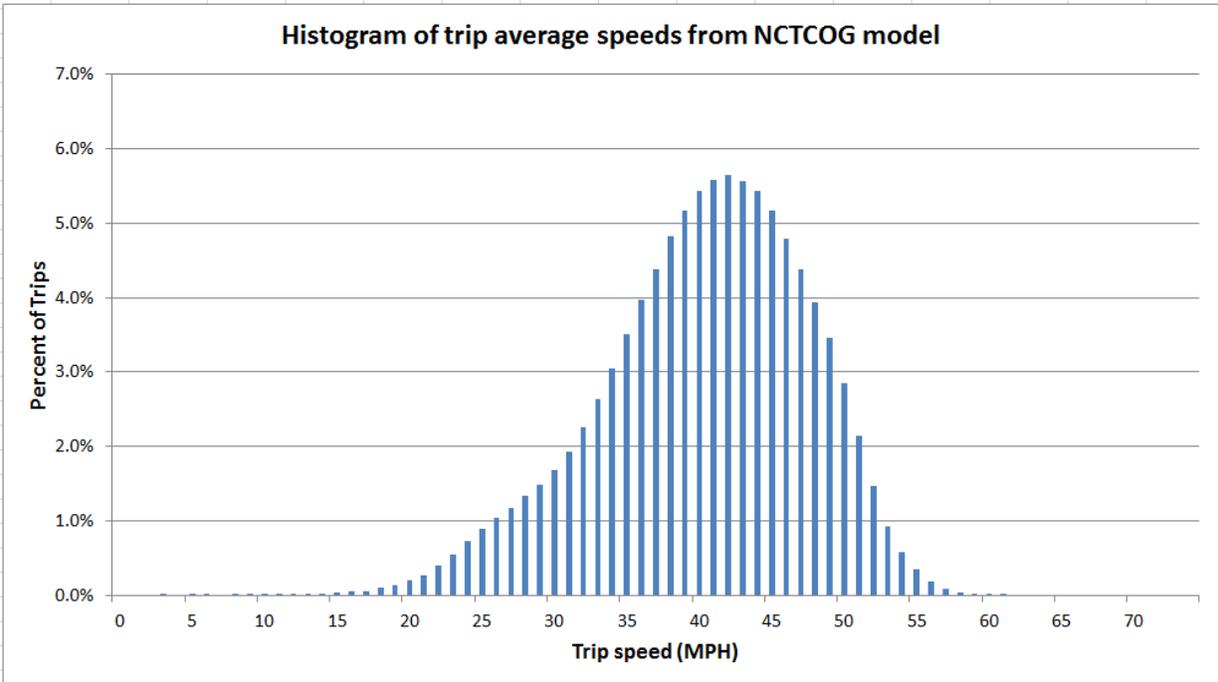
**Table 4-26 Average Travel Speeds**

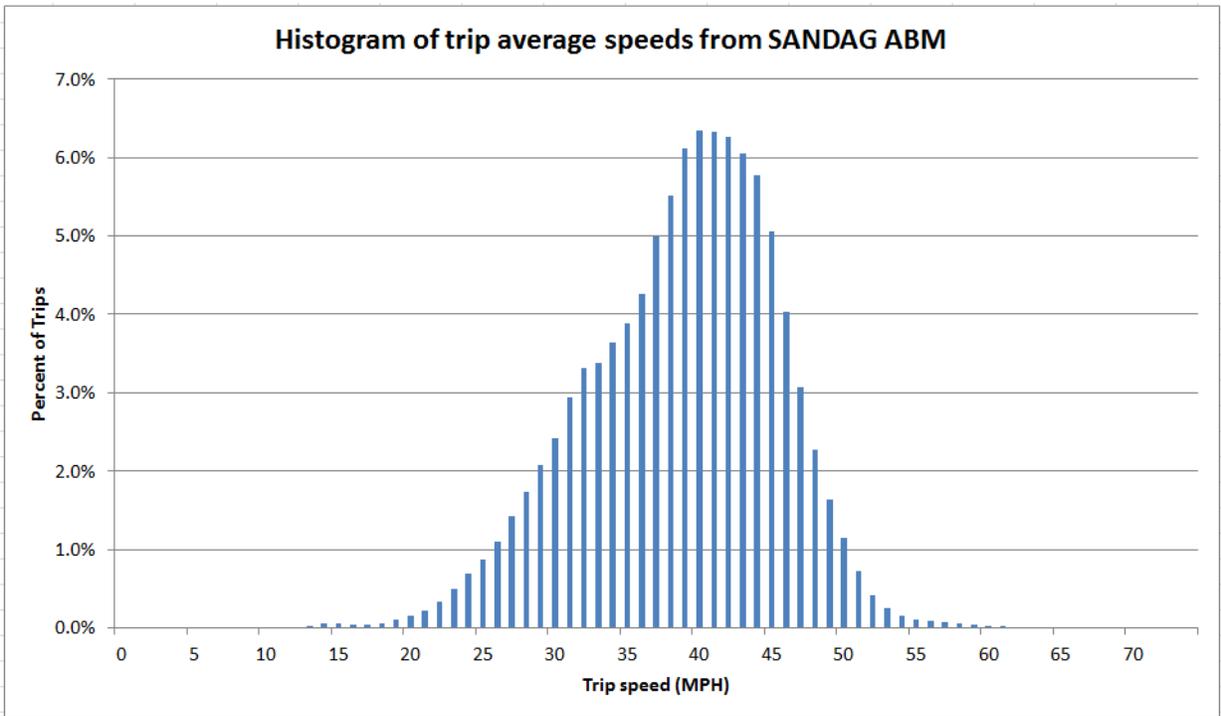
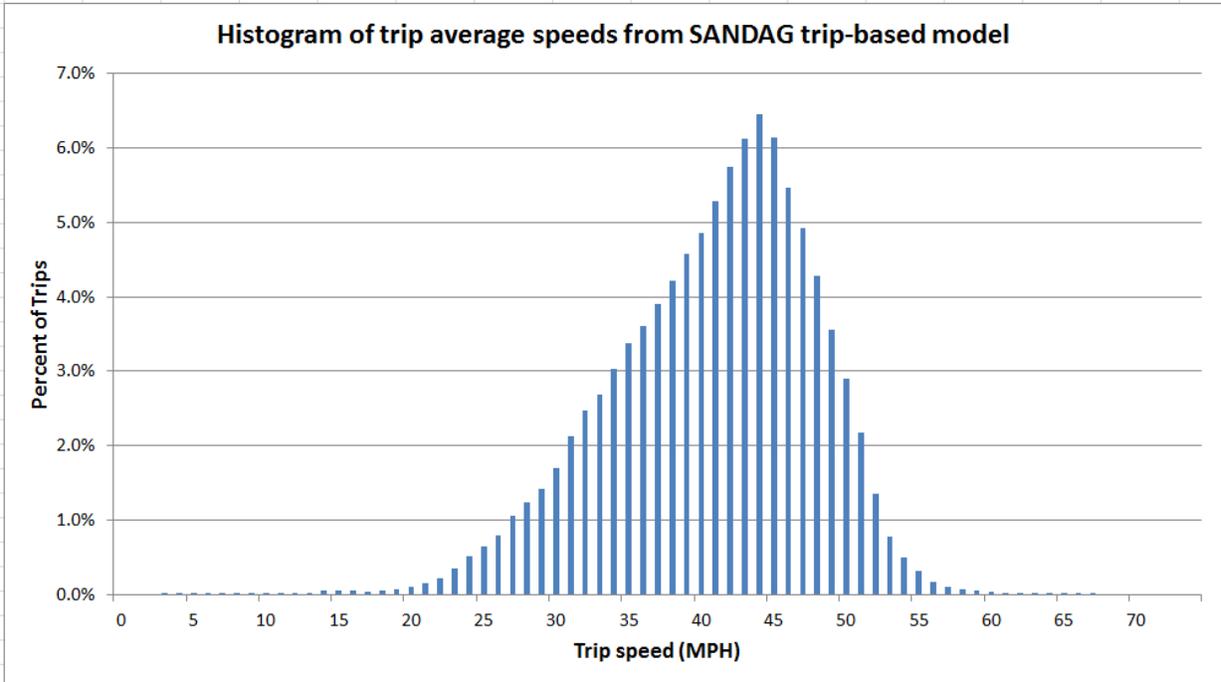
MPO	ARC	MAG	NCTCOG	PSRC	SANDAG ABM	SANDAG trip-based
VMT/VHT	32.4	33	29.8	29.3	34.5	35.5

Lastly, we tabulated the distribution of congested trip speeds in the loaded networks across all OD pairs. The speeds were calculated by dividing the OD path distance by the OD path trip time.

**Figure 4-19 MPO Model Speed Histograms**







## Concluding Remarks

---

As this chapter illustrates, the 5 MPO models present a wide range of differences in traffic assignment modeling practices and procedures. Given that these models were among the better ones deployed in the U.S. in 2011, it suggests that there was rather little consensus with respect to appropriate modeling approaches at least when it comes to the details of an equilibrium assignment.

During our study all of the modeling procedures were in flux, and it is not likely that the descriptions are still pertinent in many respects. Nevertheless, this snapshot gives a sense of current practices and their diversity. While some differences might be partially attributed to varying regional planning problems and priorities, it is rather more likely the models simply reflect different modeling simplifications and methodological choices.

The characterizations of modeling practice presented in this chapter were intended primarily as background information, which is needed to understand and assess some of the more detailed analysis that follows. Nevertheless, there is no question that the straightforward characterization and comparison of the MPO modeling practices reveals shortcomings of various sorts. While it was not our charter to provide guidance for all aspects of traffic assignment modeling, it seems that there are many areas for improvement and considerable scope for broadening knowledge about good methods.

Also, while it might be evident to those that construct traffic assignment models how many moving parts are involved in a deployed model, those that manage planning activities might be surprised at the wide array of details that require attention, measurement, and assessment. The failure to pay attention to the details or allocate sufficient resources for certain aspects of traffic assignment models can easily compromise the utility of model forecasts and the plans that are based upon them.

The models for the most part reflect some consideration of convergence issues. The tighter relative gaps and the use of more rapidly convergent algorithms reflect recognition of recent research and some penetration to practice. Having said that, we catalogued a variety of modeling aspects, some of which are very basic, that could be improved. The descriptions in this chapter are intended to provide a backdrop for more in-depth analysis of the traffic assignment methods to be presented next.



# Chapter 5

## Traffic Assignment Models and Tests

In this chapter, we present the results of tests of the traffic assignment models in use at some point in the past few years by the 5 MPOs examining convergence issues and model validation. We also present the results of some experiments that we conducted on the MPO models and variants thereof. As noted previously, all of the traffic assignments are user equilibrium methods, all use some form of generalized costs, and all have multiple user classes, but apart from that there are numerous differences in methodological approach. Also, we reiterate that the models tested have been in flux, and our descriptions of them may no longer apply.

It is generally understood that traffic assignment convergence can be and is likely to be a problem-dependent matter. In other words, achieving good convergence may be of quite varying difficulty in different areas with differing congestion levels and differing volume-delay functions. Also, the specific UE algorithm utilized will typically exert a strong influence on the level of convergence that can be achieved.

In the research literature there has been a preoccupation with the question of which algorithms converge the most rapidly. However, almost all of the comparisons that have been made have used small networks with, only one or two user classes and often with fabricated trip tables. Also, the literature includes vast implementation variations, is plagued with false or invalid comparisons of methods, and is generally lacking the details that would be required to reproduce any of the results. As such both researchers and practitioners may have only a poor or biased assessment of methodological alternatives. For working modelers, theoretical best performance is not necessarily of great or much consequence. Rather, traffic assignment methods need to do the job required and to do so in manageable computing time.

In prior research performed for FTA and in other studies, convergence issues have been identified as leading to incorrect and sometimes counterintuitive guidance in project evaluation. In this research, we examine these issues in the broader context of multiple and more complex models that are in use and are more representative than those used in prior work. We are not attempting to indicate which methods and approaches are best, but rather to understand current practices and their utility.

Through our experiments, we have been able to establish 1) that tight traffic assignment convergence is achievable for all MPO models 2) that we can quantify how tight convergence reduces the magnitude of convergence error and 3) that tight convergence by itself does not necessarily yield a good or useful model of traffic behavior. The latter requires external validation of the model both in its ability to match base case ground counts and the ability to predict the effects of transportation improvement projects.

In search of validation, we attempted to compare the traffic assignment results with directional traffic counts by time period and direction. To do this we acquired the traffic counts that the MPOs use for validation and also some other counts that were available to us. In later chapters, we perform project impact evaluations, and we examine the congested travel times produced by the traffic assignment models and compare them to measurements made in the field.

## Traffic Assignment Runs

We performed numerous traffic assignment runs with our versions of the MPO models. We established that we were able to run the models with the existing volume-delay functions currently in use by each MPO with slight changes to the ARC and NCTCOG model VDFs as discussed in the previous chapter. Each assignment was run to a relative gap of 1.E-4 using the bi-conjugate Frank Wolfe algorithm. This algorithm is found in all the major software packages and is more efficient than the original FW algorithm utilized in the past.

These assignments were performed with TransCAD 7 on a 3.2 GHz, 6 physical core i7 PC with 24GB of RAM running 64-bit Windows 7 and hyperthreading turned off. A summary table of results follows below.

**Table 5-1 MPO Assignments to 1.E-4 Relative Gap with Bi-conjugate FW Algorithm on a 6 Core Computer**

MPO	ARC	MAG	NCTCOG	PSRC	SANDAG ABM	SANDAG trip-based
<b>METHOD</b>	BFW	BFW	BFW	BFW	BFW	BFW
<b>TIME PERIOD</b>	AM	PM	AM	AM	AM	AM
<b>CONVERGENCE</b>	1.E-4	1.E-4	1.E-4	1.E-4	1.E-4	1.E-4
<b>NUMBER OF ITERATIONS</b>	80	51	153	66	45	39
<b>COMPUTATIONAL TIME</b>	1 h 4 min	8 min 22 s	1 h 2 min	1 h 24 min	1 h 1 min	48 min
<b>TOTAL VMT</b>	40,264,910	29,356,528	35,209,830	13,122,656	16,934,816	15,727,276
<b>TOTAL VHT</b>	1,244,615	889,645	1,089,180	447,006	490,625	443,313

As indicated in Table 5-1, we were able to achieve relative gaps of 1.E-4(.0001) in modest amounts of running time. There was, however, significant variation in the computing time required. With the fewest number of zones by far, a lower number of vehicle classes, and perhaps the least congestion, the MAG model takes the least amount of time.

Long running times are often cited as the reason for using models that are not tightly converged. However, with the bi-conjugate FW method the running times are modest and can also be easily further reduced through multi-threading. To illustrate this point, we performed the same assignments on a computer similar to the one described above but with double the number of cores.

A summary table of results follows:

**Table 5-2 Assignments to 1.E-4 Relative Gap with Bi-conjugate FW Algorithm on a 12 Core Computer**

MPO	ARC	MAG	NCTCOG	PSRC	SANDAG ABM	SANDAG trip-based
<b>METHOD</b>	BFW	BFW	BFW	BFW	BFW	BFW
<b>TIME PERIOD</b>	AM	PM	AM	AM	AM	AM
<b>CONVERGENCE</b>	1.E-4	1.E-4	1.E-4	1.E-4	1.E-4	1.E-4
<b>NUMBER OF ITERATIONS</b>	80	51	153	66	45	39
<b>COMPUTATIONAL TIME</b>	32 min	7 min 19 s	31 min	40 min	35 min	26 min
<b>TOTAL VMT</b>	40,264,910	29,356,528	35,209,830	13,122,656	16,934,816	15,727,035
<b>TOTAL VHT</b>	1,244,615	889,645	1,089,180	447,006	490,625	443,486

As one can see, for all of the MPO models except the MAG model, the run times were cut roughly in half. These run times are even less burdensome and could be improved upon further using computers with even more cores and possibly with hyperthreading turned on.

We made some additional runs with tighter gaps, but found that, in general, the MPO models were unable to converge to much lower relative gaps with the Bi-conjugate FW algorithm in a reasonable amount of time or at all. Consequently, we used a path-based algorithm to compare performance metrics at 1.E-6 and lower gaps. The path-based method is the one in TransCAD and is based upon Dial's algorithm B [7].

To reach two orders of magnitude tighter convergence definitely results in an increase in computing time as indicated below.

**Table 5-3 Assignments to 1.E-6 Relative Gap with a Path-based User Equilibrium (PUE) Algorithm on a 6 Core Computer (Cold start)**

MPO	ARC	MAG	NCTCOG	PSRC	SANDAG ABM	SANDAG trip-based
<b>METHOD</b>	PUE	PUE	PUE	PUE	PUE	PUE
<b>TIME PERIOD</b>	AM	PM	AM	AM	AM	AM
<b>CONVERGENCE</b>	1.E-6	1.E-6	1.E-6	1.E-6	1.E-6	1.E-6
<b>NUMBER OF ITERATIONS</b>	49	23	55	39	23	19
<b>COMPUTATIONAL TIME</b>	2 h 10 min	14 min 5 s	2 h 18 min	1 h 6 min	3 h 8 min	2 h 21 min
<b>TOTAL VMT</b>	39,946,163	29,347,072	35,193,601	13,121,905	16,608,922	15,551,491
<b>TOTAL VHT</b>	1,241,580	889,457	1,088,717	447,018	478,199	437,941

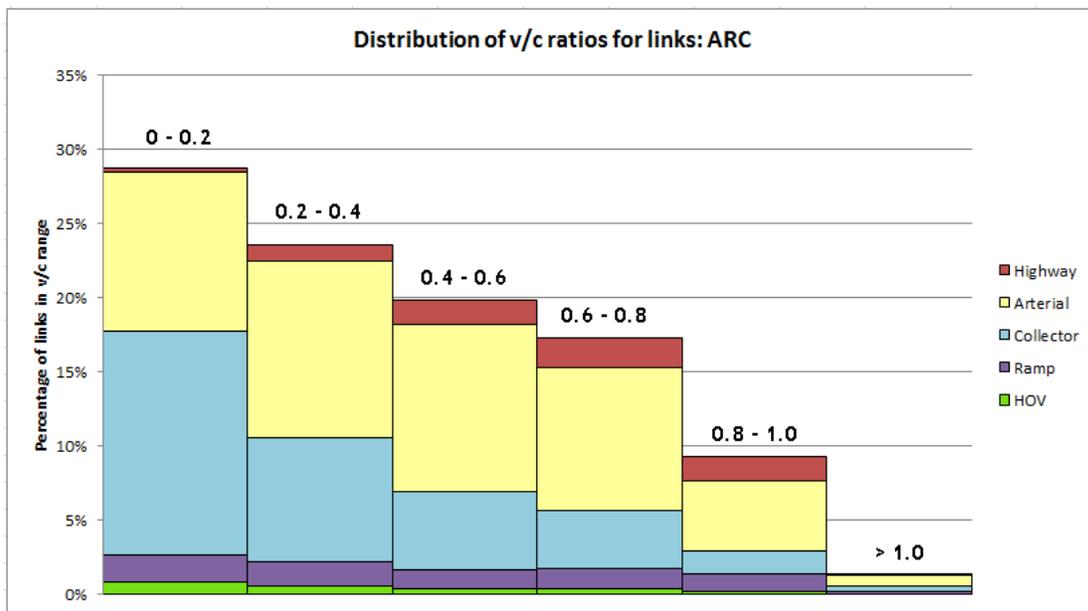
However, these run times can be reduced considerably through the use of more cores and with a warm start from prior solutions. The warm start solution is particularly effective since the largest run time expenditure is only made once rather than over and over again. In this project, we used the path-based method to generate solutions with much tighter relative gaps than possible with the bi-conjugate algorithm.

### ***Volume-to-capacity ratios***

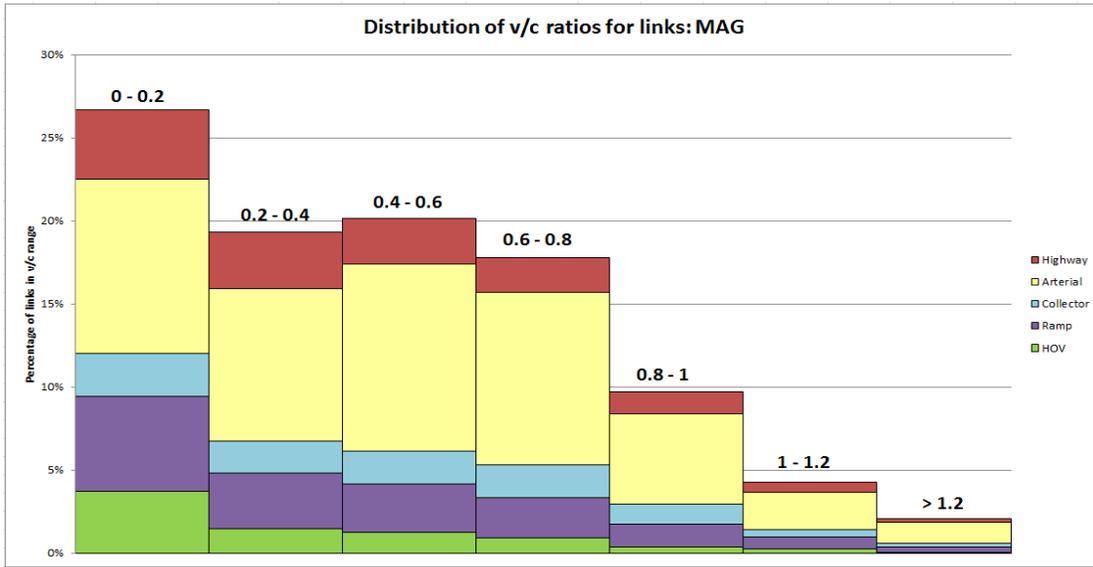
In assessing any traffic assignment, it is prudent to examine the volume-to-capacity ratios for the solution. In the real world, volumes cannot exceed jam capacities and the presence of links with high V/C ratios in the base case scenario should be investigated. This was done with the results of the assignments from the last feedback loop performed.

In the Figures that follow, we present histograms of the distribution of V/C ratios for each model indicating the percentages in each V/C bin by functional class. Overall the V/C ratios seem reasonable for each model.

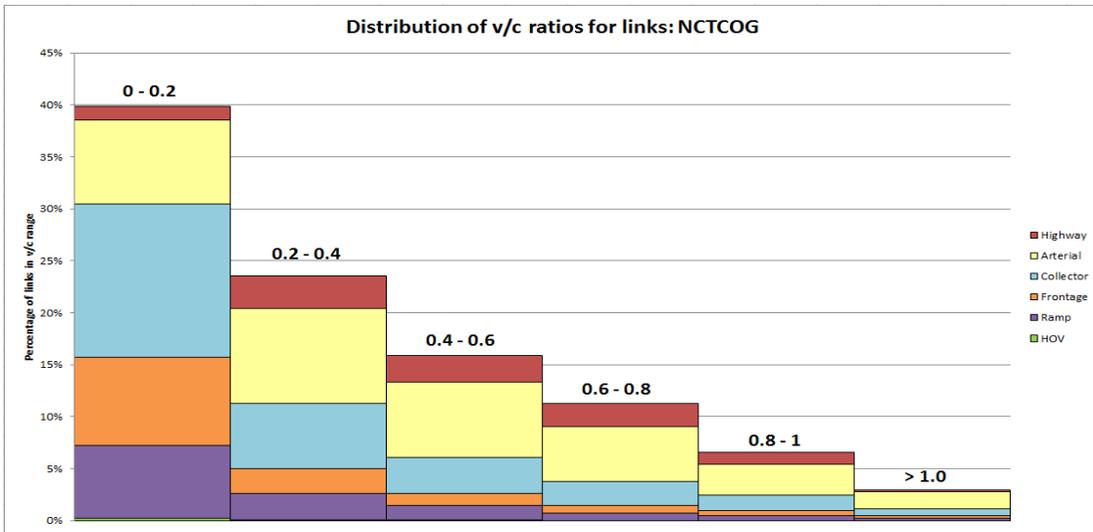
**Figure 5-1 V/C Ratios for the ARC Assignment by Functional Class**



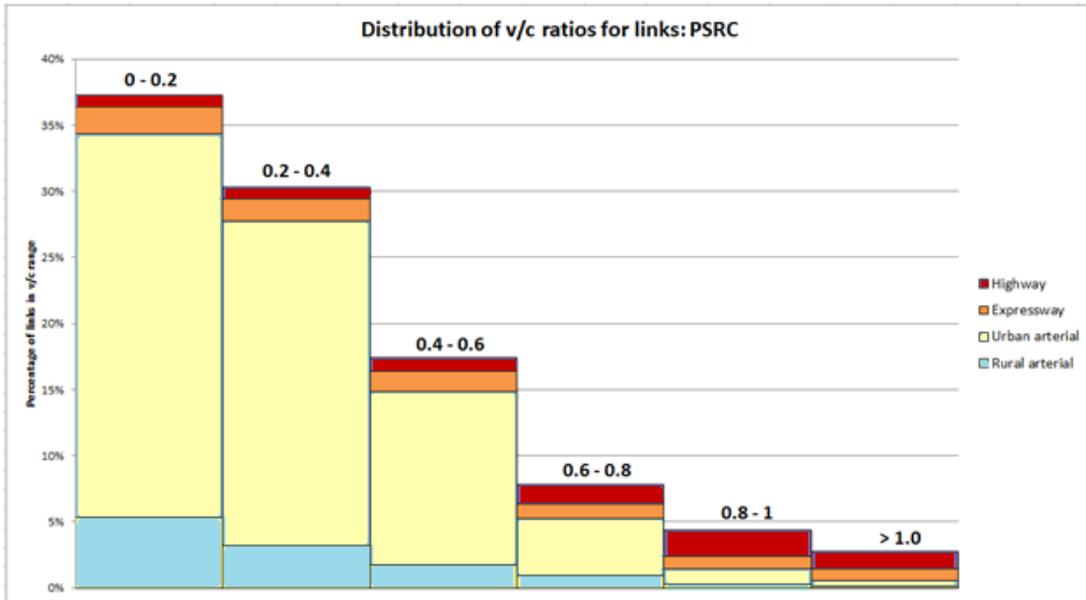
**Figure 5-2 V/C Ratios for the MAG Assignment by Functional Class**



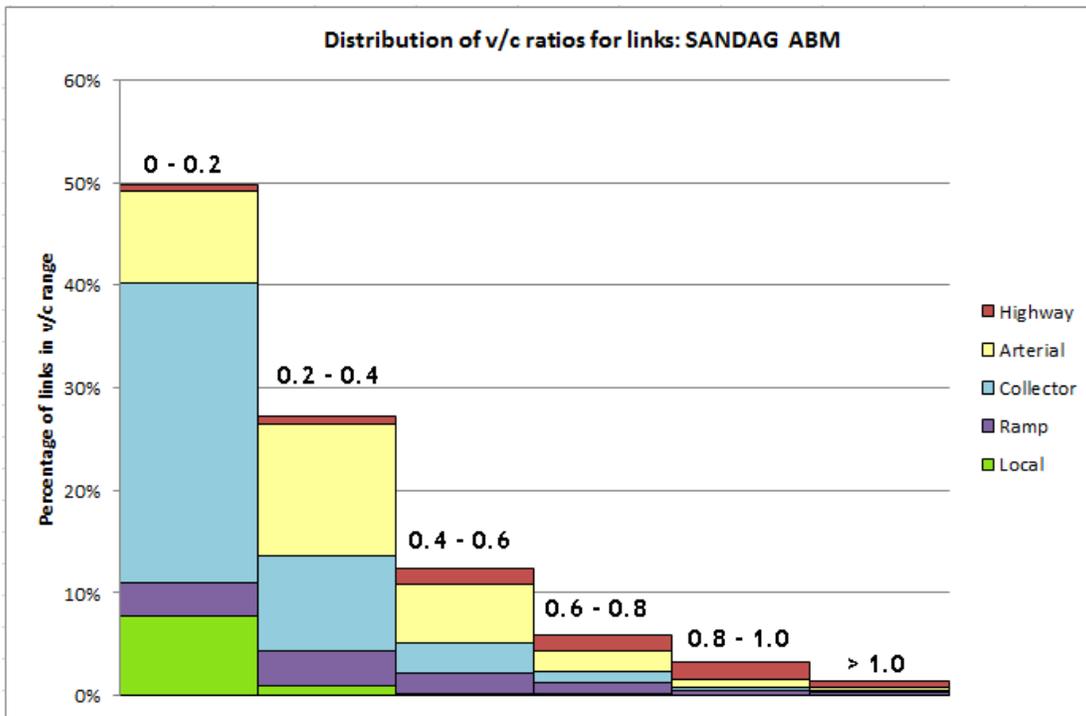
**Figure 5-3 V/C Ratios for the NCTCOG Assignment by Functional Class**



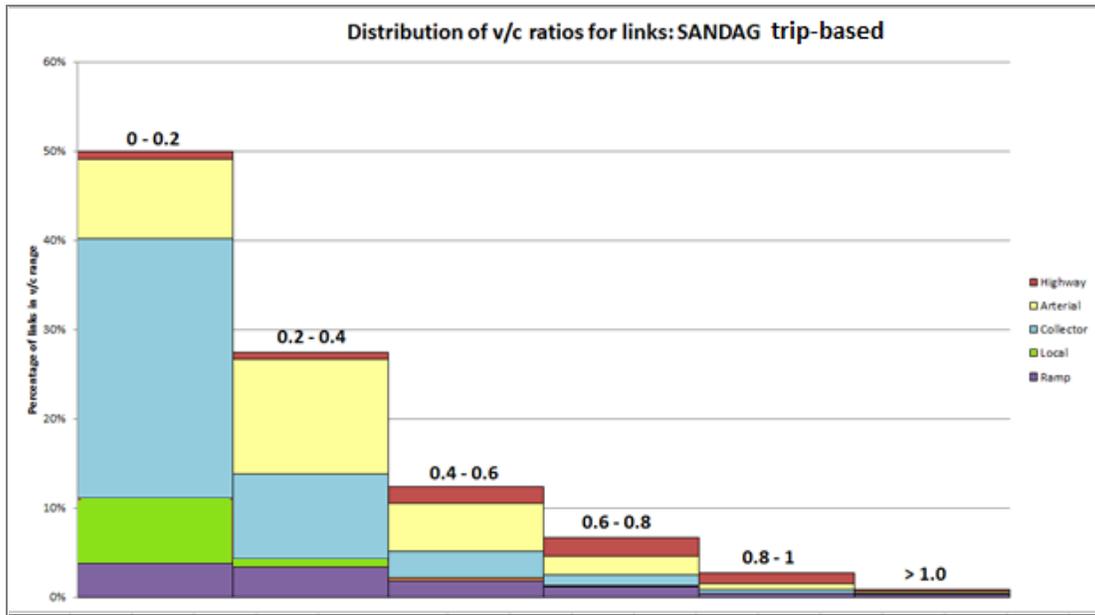
**Figure 5-4 V/C Ratios for the PSRC Assignment by Functional Class**



**Figure 5-5 V/C Ratios for the SANDAG ABM Assignment by Functional Class**



**Figure 5-6 V/C Ratios for the SANDAG Trip-based Model Assignment by Functional Class**



As indicated in the histograms, all of the models have some links with volumes that exceed capacities. This is not uncommon in planning models, but there should be very few links in the base case model where this occurs, especially if capacities are chosen properly.

Inspection of which types of links have volumes that exceed capacities indicates that this varies amongst the MPO models. In some of the models, it appears that the arterials are overloaded, and in others the freeways dominate the links with V/Cs greater than 1. This might suggest further attention to the freeway and arterial balance in each network model.

### **Zero flow link analysis**

It is generally a good practice to examine links that receive no flow in an assignment. This can be a good way to identify errors in the network and other difficulties with assignment models. While it is perfectly reasonable for there to be some unused centroid connectors, there should be some flow on all the links in major road classes. We scrutinized each assigned MPO AM network to see if this was an issue. For the most part, it appeared that nearly all highway links carried flow.

**Table 5-4 Links with Zero Assigned Flows in the ARC Base AM assignment**

Link type	Number with zero flow
Highway	0
Major arterial	0
Minor arterial	34
Collector	117
Entrance ramp	26
Exit ramp	27
System to system ramp	34
Freeway HOT	21
Arterial HOV	23

In the ARC model, it was a positive that there were no highway or major arterial links without traffic. The freeway HOT lanes that are not used are in the outbound direction during the AM commute, so it isn't unusual that they aren't used. The arterial HOV links that aren't used are in a part of the network (17th Street) that is practically free-flowing and it is just slightly faster to use the main arterial in the absence of congestion.

In the MAG model, all highway links were utilized but some arterials were not. This might be due to the grid network in Phoenix. We also noticed a number of unused links connected to ramps. These ramp links represent extra capacity at turn movements. During periods of lower congestion, the assignment may not put any flow on these links.

**Table 5-5 Links with Zero Assigned Flows in the MAG Base PM assignment**

Link type	Number with zero flow
Highway	0
Arterial	123
Collector	127
Ramp	611
HOV	20

The HOV links with no flow in the MAG base assignment were primarily HOV connectors, i.e., entry and exit points from the general purpose to the HOV lanes but the MPO uses the same functional class as HOV lanes for these links.

In the NCTCOG model, there were a great many collector links that do not receive flow. We are not sure why that is the case.

**Table 5-6 Links with Zero Assigned Flows in the NCTCOG Base AM assignment**

Link type	Number with zero flow
Highway	0
Major arterial	9
Minor arterial	62
Collector	2519
Frontage road	683
Ramp	265
HOV	1

Most of the links in the PSRC AM network carry flow, but some arterials do not.

**Table 5-7 Links with zero assigned flows in the PSRC Base AM assignment**

Link type	Number with zero flow
Highway	0
Expressway	2
Urban Arterial	102
Rural Arterial	42

**Table 5-8 Links with Zero Assigned Flows in the SANDAG ABM Base AM assignment**

Link type	Number with zero flow
Highway	0
Major arterial	0
Minor arterial	9
Collector	172
Ramp	73
HOV	23
Local	66

**Table 5-9 Links with Zero Assigned Flows in the SANDAG Trip-based AM Base Assignment**

Link type	Number with zero flow
Highway	0
Major arterial	0
Minor arterial	17
Collector	201
Ramp	101
HOV	23
Local	81

For both the SANDAG ABM and the trip-based models the HOV links with zero flow in the base AM assignments are along two major corridors. For one of the corridors (on I-15 between SR-163 and SR-56), the unused HOV lanes are in the NB direction, which is also the outbound direction for the AM commute and hence is plausible as offering no benefit to HOV users over the general purpose lanes. However, on the second corridor (on SR-54 between I-805 and SR-125) the unused HOV lanes are both in the EB and WB direction, which does seem unusual. SANDAG has noted that these links are probably reversible lanes that are designed to be “turned” off and report out zero flow during certain time periods.

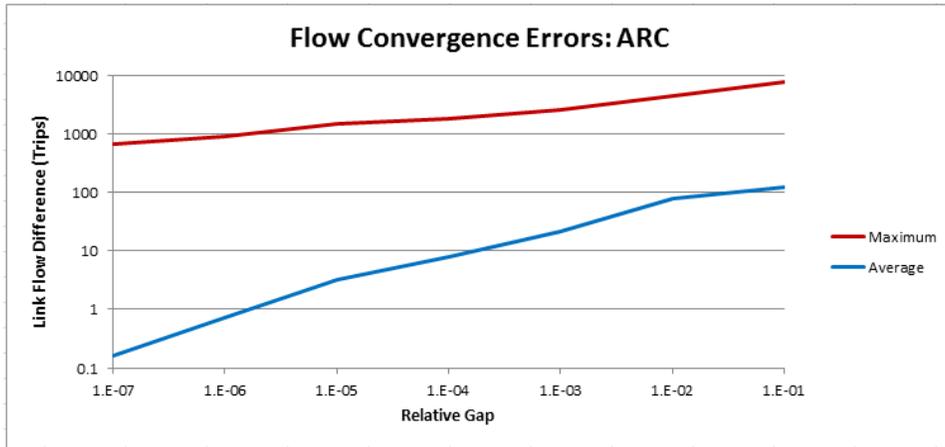
## Convergence Error Analysis

---

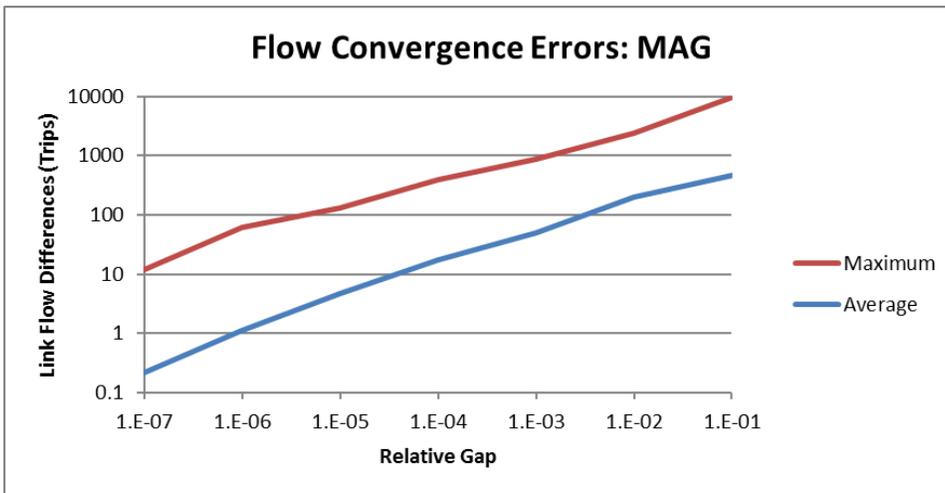
To form the basis for the analysis of assignment convergence error, we computed each MPO AM period assignment to a relative gap of 1.E-8, except for the PSRC model, which we computed to a gap of 1.E-7 using the path-based algorithm discussed before. Using these tightly converged assignments, we performed comparisons with lesser converged assignments for each MPO model. This permits the construction of convergence error graphs for each MPO peak period traffic assignment that are shown in the Figures that follow. This is a novel analysis of a type that has rarely, if ever, been performed with deployed MPO models.

The graphs show the absolute value of the maximum link flow errors and the average absolute value of the errors. This provides a better picture of the results than if positive and negative errors cancel each other out.

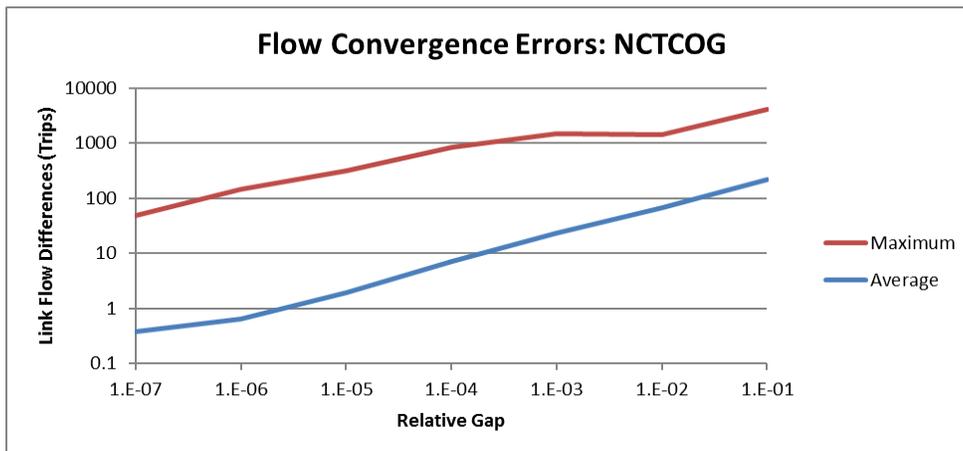
**Figure 5-7 Flow Convergence Errors in the ARC AM Model**



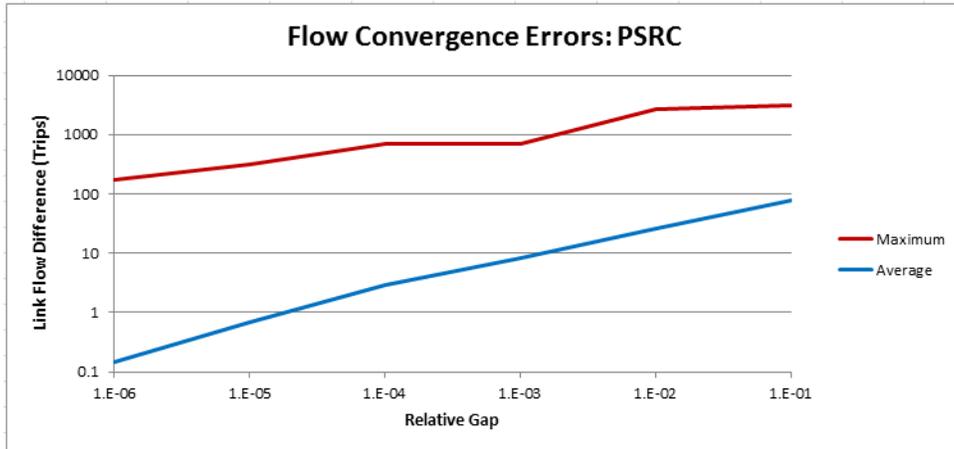
**Figure 5-8 Flow Convergence Errors in the MAG AM Model**



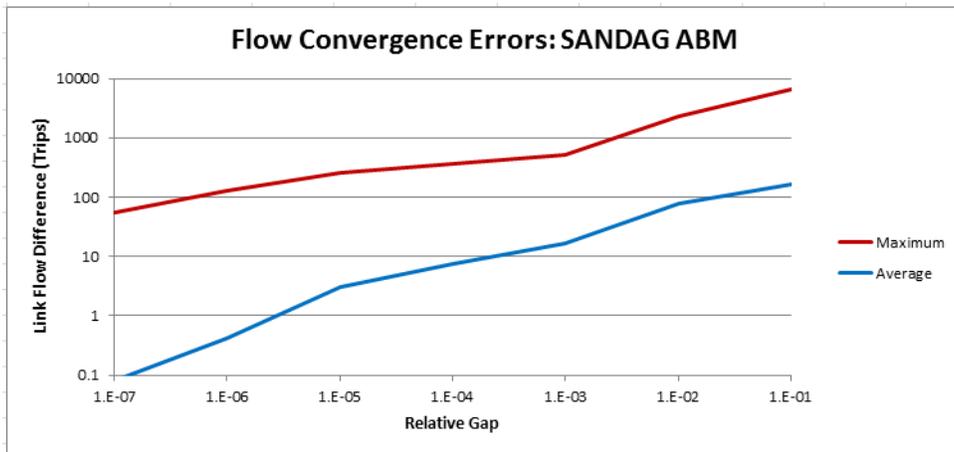
**Figure 5-9 Flow Convergence Errors in the NCTCOG AM Model**



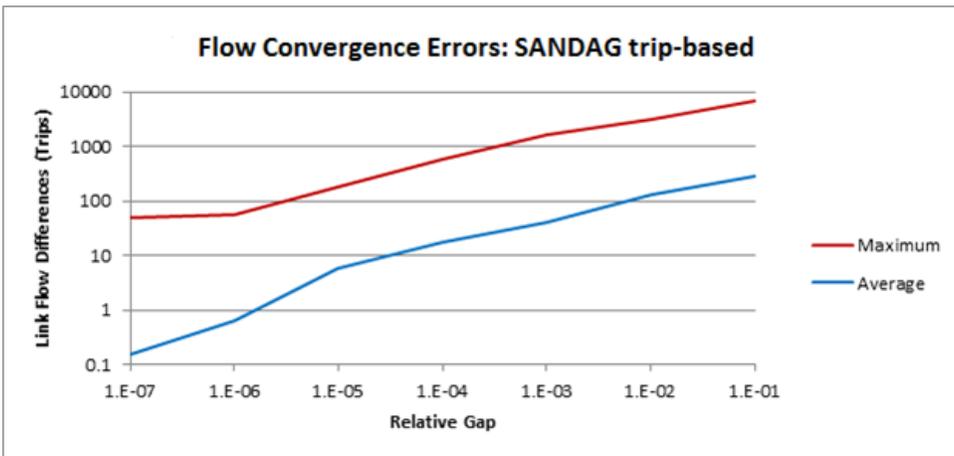
**Figure 5-10 Flow Convergence Errors in the PSRC AM Model**



**Figure 5-11 Flow Convergence Errors in the SANDAG AM ABM Model**



**Figure 5-12 Flow Convergence Errors in the SANDAG AM trip-based model**



Inspection of these error graphs reveals some interesting findings. At a .1 relative gap, convergence errors are enormous. For the AM period, they range from a maximum of 10,000 vehicles for the ARC, MAG, and SANDAG models to roughly 5000 for NCTCOG and PSRC. At

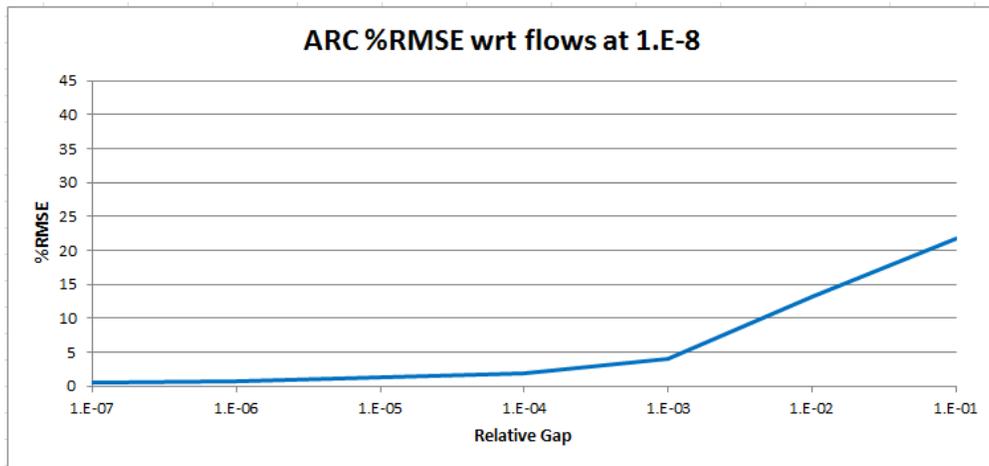
a .01 relative gap level which is one that is utilized by many MPOs across the country, the maximum link error is in the thousands of vehicles for most of the MPO traffic assignments.

At the convergence level of 1.E-4, we can see that the maximum link flow error is roughly 1000 vehicles or less for each MPO model except ARC. This error is rather larger than one might expect. The average error level is roughly 10 vehicles, but that may not be a very useful measure given the large number of links in each network.

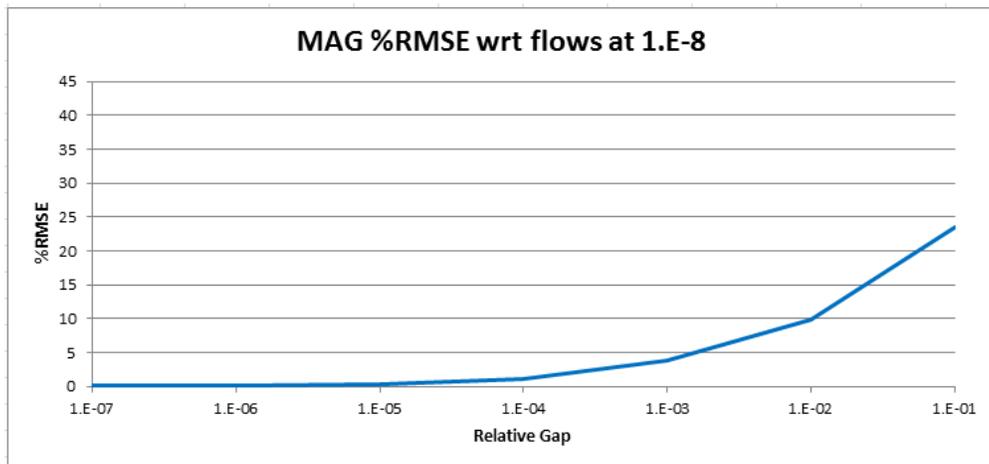
We were struck by the similarity in the error curves across the MPO models especially in view of the fact that the models themselves are rather different. Another point of note was that, unlike the other models, the maximum link error in the ARC model did not decline as rapidly with tighter convergence. This may be due to some other problem in the ARC network assignment.

Another way to look at convergence error is to plot it in terms of %RMSE differences between highly converged and lesser converged traffic assignments. This is done in the Figures that follow for each MPO model.

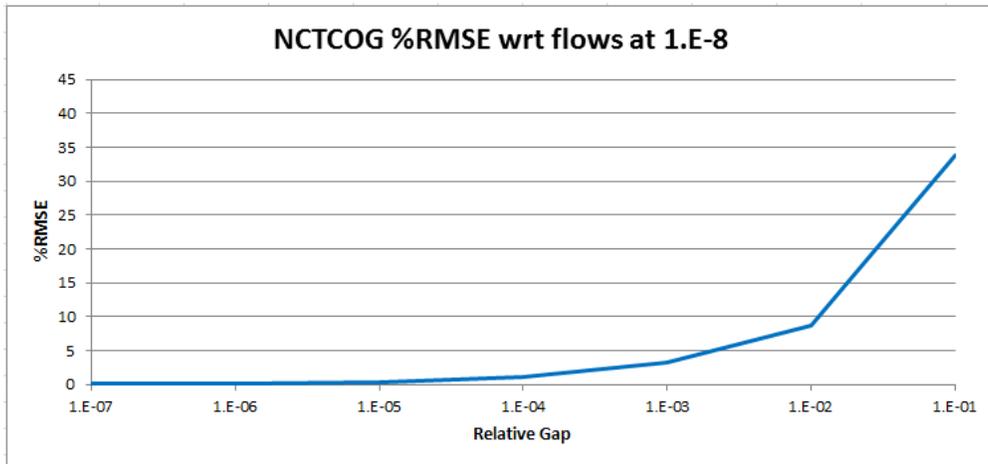
**Figure 5-13 ARC %RMSE Convergence Error**



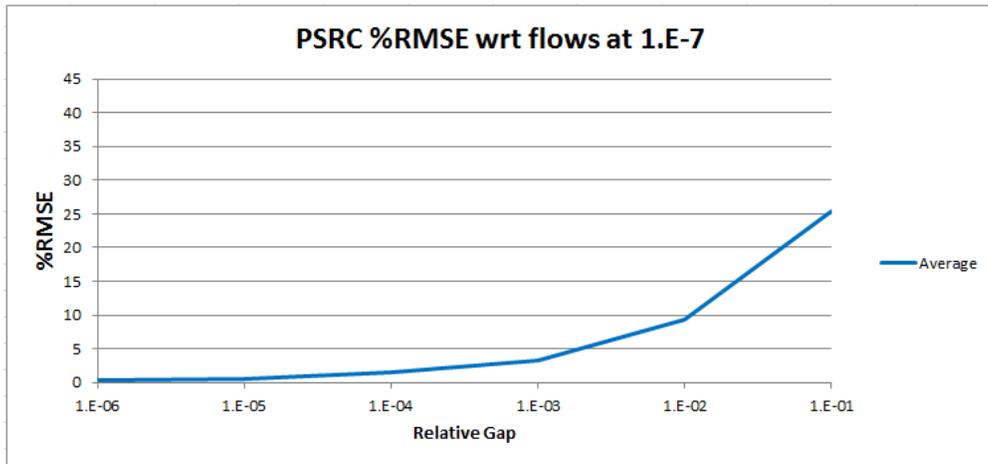
**Figure 5-14 MAG %RMSE Convergence Error**



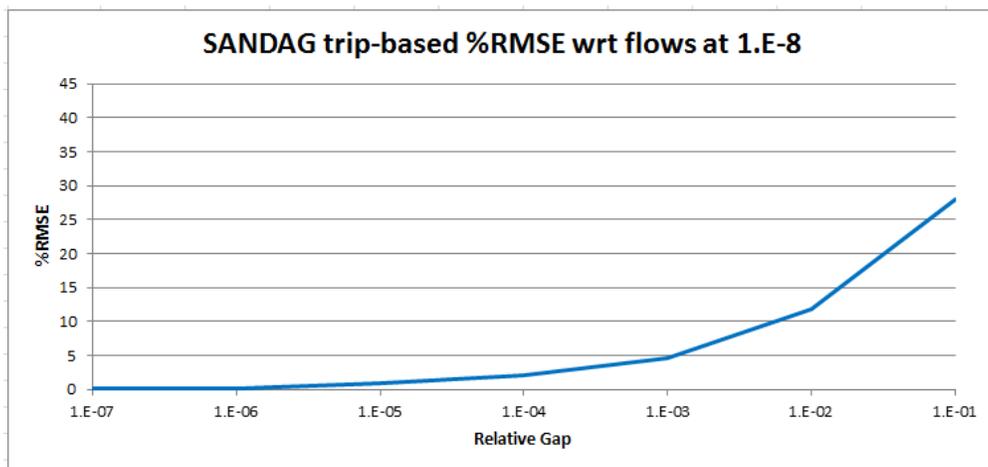
**Figure 5-15 NCTCOG %RMSE Convergence Error**



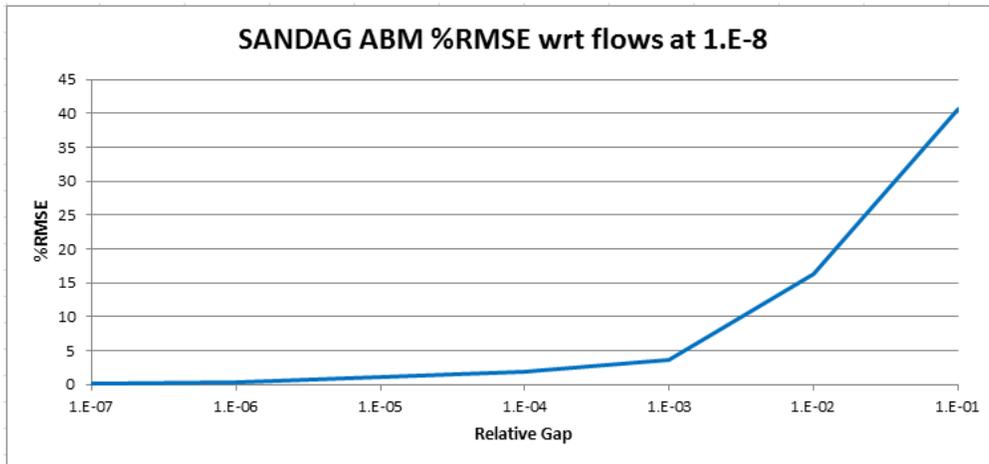
**Figure 5-16 PSRC %RMSE Convergence Error**



**Figure 5-17 SANDAG Trip-based Model %RMSE Convergence Error**



**Figure 5-18 SANDAG ABM %RMSE Convergence Error**



From the graphs above, we can see that convergence errors are on the order of 10-15% RMSE at a relative gap of 1%. We can also see that the errors can be reduced to very small %RMSE values. To get to a 1%RMSE in convergence error appears to require reaching a relative gap of 1.E-5.

## **Comparison of Assignment Volumes and Traffic Counts**

---

Traffic assignment outputs are traditionally compared with traffic counts to establish the degree to which a regional travel demand model captures a realistic portrait of regional travel for the base case scenario. A principal thrust of this project is to compare traffic assignment outputs with counts and travel times that are independently measured. This requires counts by direction and time period to be meaningful.

We asked each MPO to provide us with the counts that they had available for model validation. Their responses surprised us. What we learned is that the MPOs had very little data to support the validation that we had envisioned.

What we had been hoping to receive would have been hundreds of AM link counts by direction for each major functional class in the network. As you will see from the comparisons that we present, this amount of count information has not generally been available. That is not to imply that the MPOs did not have large amounts of count data. They typically did but much of it was either bi-directional or aggregate to daily counts by direction and therefore not of any use to us for this research.

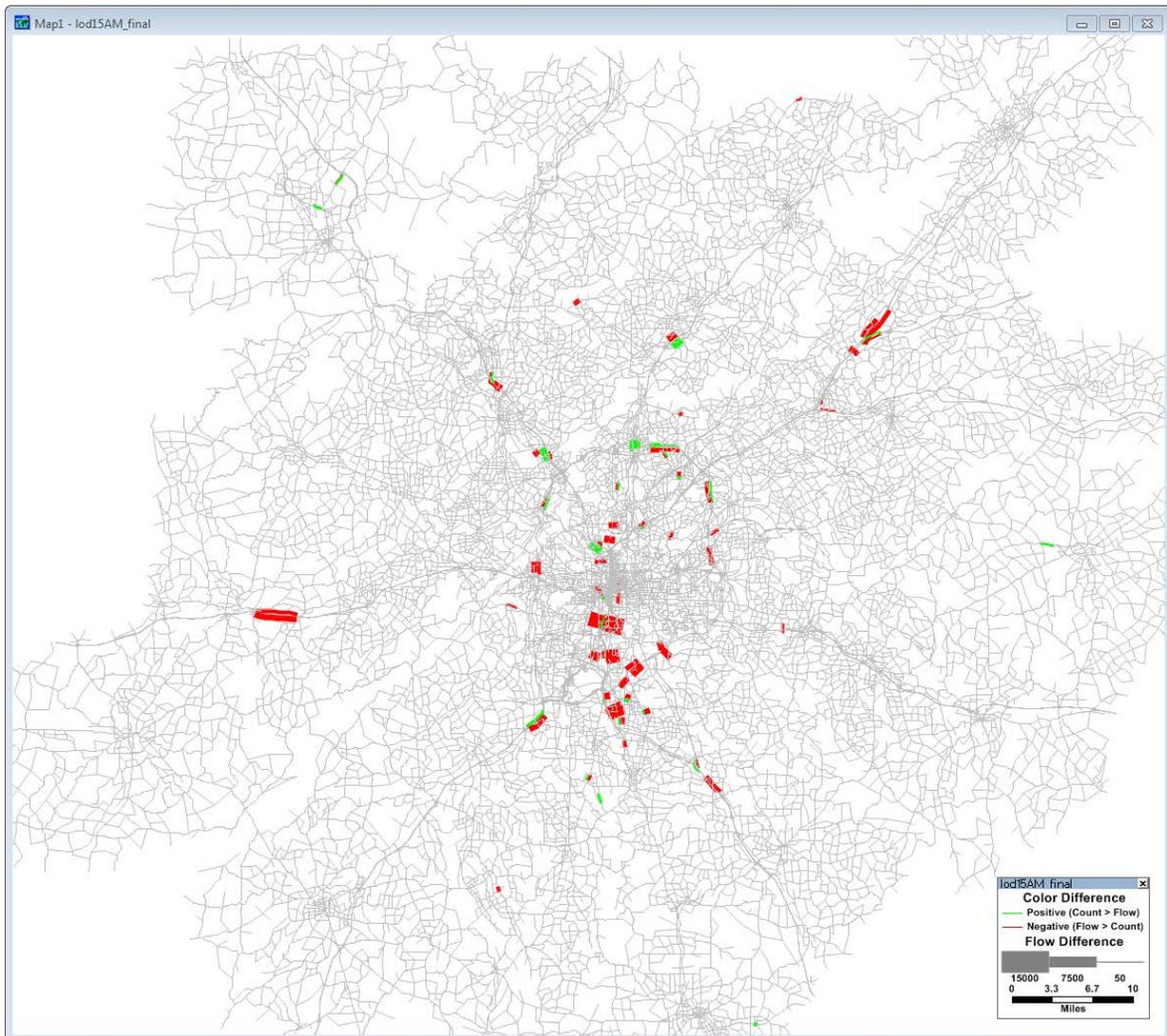
For two of the MPO models, we supplemented the data that we received from them with additional data that we had either collected for a project or were able to harvest from available sources.

In the maps and tables that follow, the counts were compared to the MPO base flows from assignments that were converged to a relative gap of 1.E-4. The maps show only the link flow differences that are greater than 50. Links that are shown in red signify that the flow is greater than the count, and links that are shown green indicate that the count was greater than the assigned flow. The thickness of each colored link indicates the magnitude of the difference between the link flows and the link counts.

### ***ARC flows and counts***

For ARC, we compared flows from the CUBE/Voyager model with the counts provided by the MPO at 130 locations.

**Figure 5-19 System-wide difference between traffic flows and counts for ARC**



In tabular form, the comparisons are given in Table 5-10. As one can see the %RMSEs are high except for freeways. Of course, the number of observations is so low that these comparisons are not likely to be statistically valid.

**Table 5-10 ARC Flows vs Counts by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Freeway	71	19.62	9.12
HOV	10	57.44	13.95
Arterial	44	64.95	29.66
Collector	4	108.53	100.95

**Table 5-11 ARC Flows vs Counts by Volume Group**

Volume group (Total flow on link)	Number of observations	% RMSE	% Diff Flows to Counts
0 – 4000	28	40.02	-6.75
4000-8000	23	49.11	23.81
8000-12000	10	22.85	13.72
12000-16000	19	26.32	15.16
16000-20000	10	17.34	10.02
>20000	39	18.69	9.73

**Table 5-12 ARC VMT Flows vs Counts by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Freeway	1,145,699	1,258,516
HOV	17,525	22,807
Arterial	52,416	61,090
Collector	913	1,961

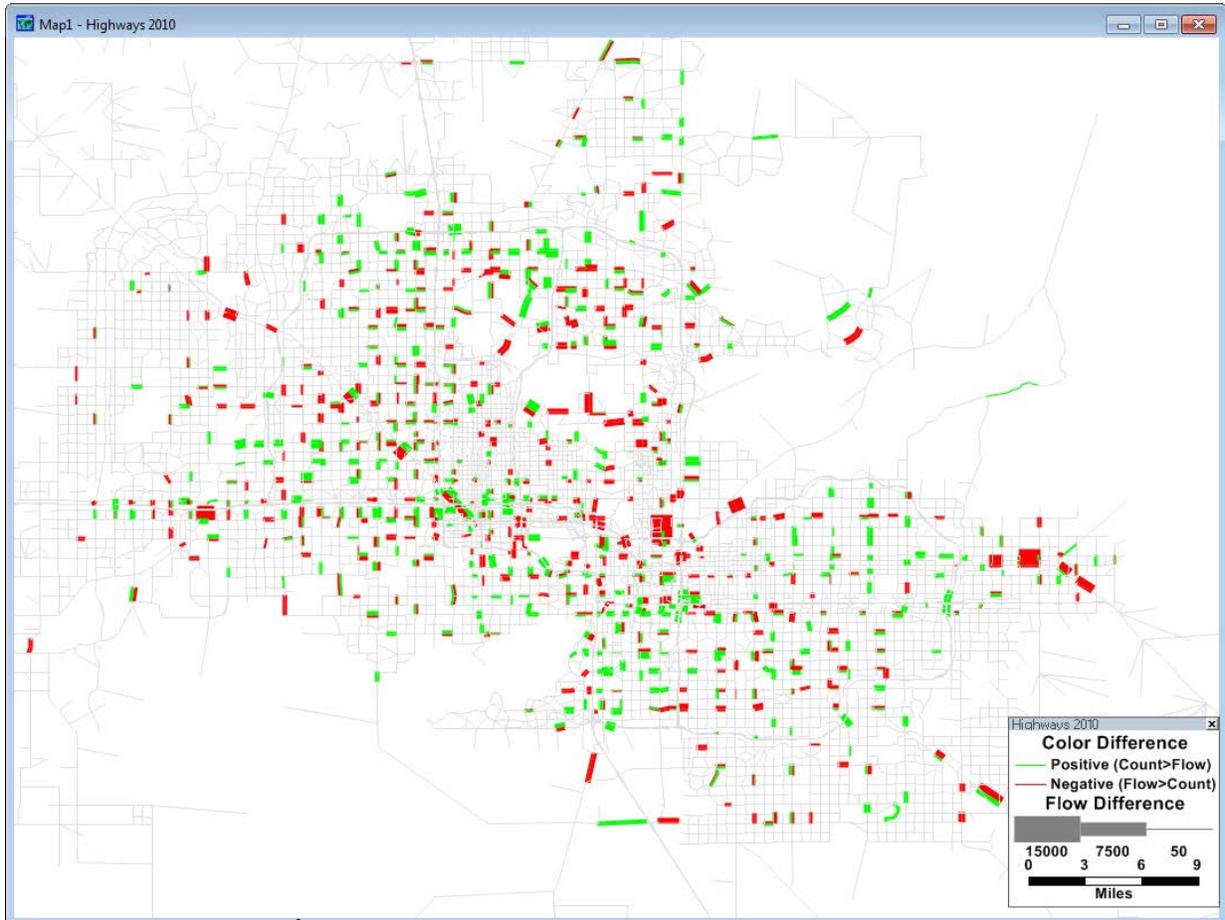
From the above tabulations, it appears that the ARC model overstates VMT consistently across all of the classes although the results may not be statistically significant or representative due to the small samples sizes for the counts.

ARC also has 5,400 links with directional counts but only with daily count data. These data suggest a fairly close match between assigned volumes and counts on a daily basis but do not provide information by time period.

## MAG flows and counts

Initially, MAG provided Caliper with directional counts for the PM period at 810 locations. The differences between the predicted flows are plotted in the map in Figure 5-20 that follows. We would like to make it clear that this analysis was done with the first version of the MAG model we examined while all of the other documentation and analysis for MAG pertains to a newer version.

**Figure 5-20 System-wide difference between traffic flows and MPO-provided counts for MAG**



While MAG had more than 1500 traffic counts and that would seem to be a sufficient number of observations, unfortunately only 48 observations were on highways. For that functional class, the sample size was insufficient to come to definitive conclusions about the model's fit to counts. With that caveat, the prior version of the MAG model had volumes that were a reasonable match with the observed PM data.

**Table 5-13 MAG Flows vs MPO-provided Counts by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	48	23.62	-1.46
Arterial	1507	44.25	0.94

**Table 5-14 MAG Flows vs MPO-provided Counts by Volume Group**

Volume group (Total flow on link)	Number of observations	% RMSE	% Flow/Count
0 – 1000	75	86.08	-54.28
1000-2000	134	62.60	-18.55
2000-4000	467	47.28	-9.09
4000-6000	582	39.40	1.91
6000-9000	231	40.66	8.63
9000-12000	40	37.91	12.37
>12000	30	21.03	4.92

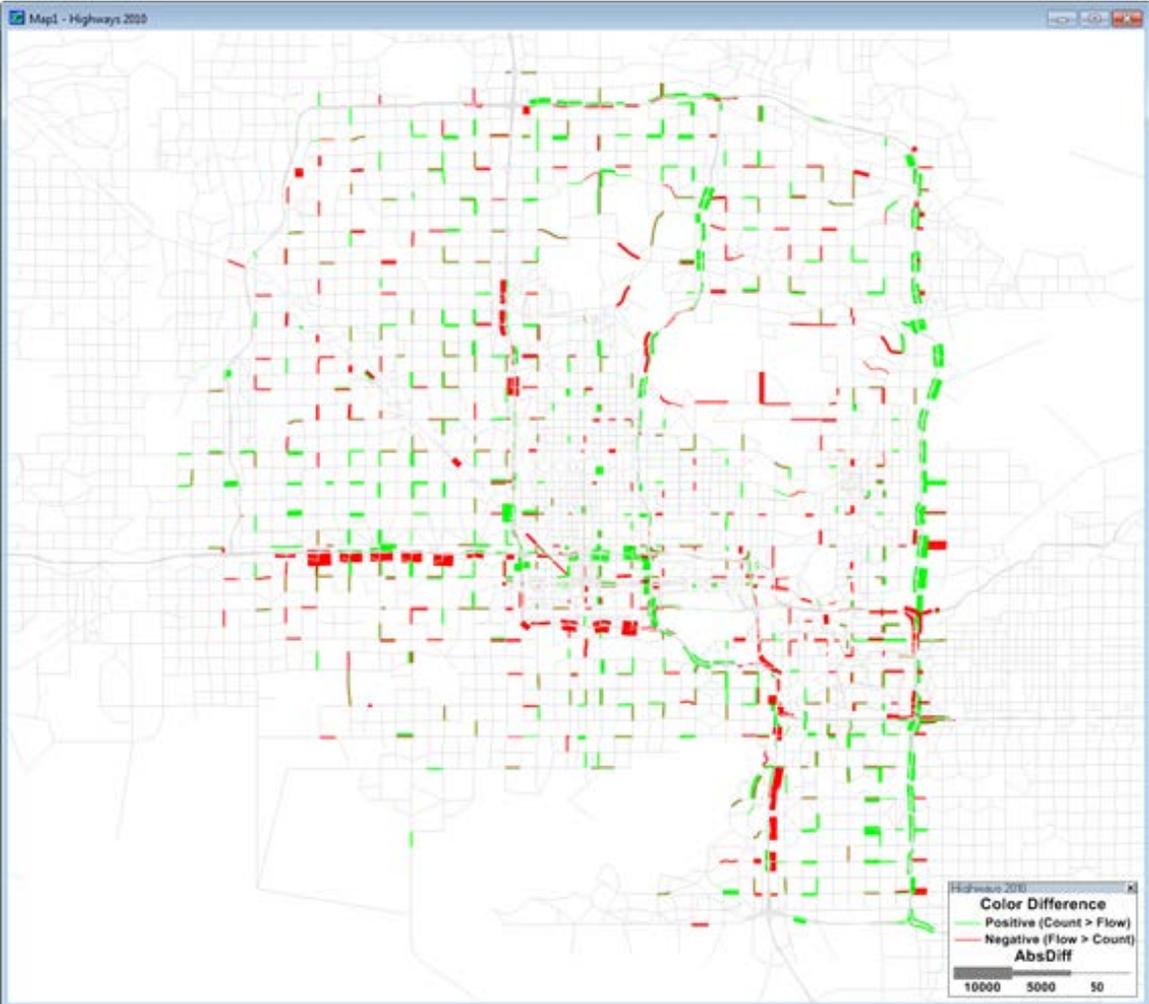
**Table 5-15 MAG VMT Flows vs MPO-provided Counts by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	293,406	293,426
Arterial	1,412,310	1,419,573

Overall, as indicated above, there was a good match between the modeled and measured VMT. We understand that MAG has collected additional traffic count data, but we were not able to use it in our analysis.

However, as a separate exercise, we also performed a comparison of modeled versus observed counts using directional counts for roughly 500 square miles of Central Phoenix that were assembled as part of a microscopic traffic simulation project that Caliper performed for MAG. These counts were at 900 locations and included freeways, arterials and collectors. The counts provided by the MPO as well as the counts extracted by Caliper span the years 2007-2011.

**Figure 5-21 MAG System-wide Difference between Traffic Flows and Counts (Compiled by Caliper)**



This comparison is very similar to the one above although the geographic pattern of the differences between flows and counts reveals some over-predicted and some under-predicted facilities. These counts reflect a reasonable fit of the MAG model with a closer match on freeways than on arterials.

**Table 5-16 MAG Flows vs Counts (assembled by Caliper) by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	253	22.71	-3.48
Arterial	1142	43.29	-0.34
Collector	58	69.63	-27.14

**Table 5-17 MAG Flows vs Counts (assembled by Caliper) by Volume Group**

Volume group (Total flow on link)	Number of observations	% RMSE	% Flow/Count
0 – 1000	66	74.69	-37.19
1000-2000	106	61.03	-15.81
2000-4000	400	49.08	-12.77
4000-6000	452	39.06	1.52
6000-9000	215	38.40	8.18
9000-12000	87	28.81	-3.99
>12000	136	19.86	0.59

**Table 5-18 MAG VMT Flows vs Counts (assembled by Caliper) by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	1,890,037	1,823,174
Arterial	1,149,770	1,131,062
Collector	23,165	18,411

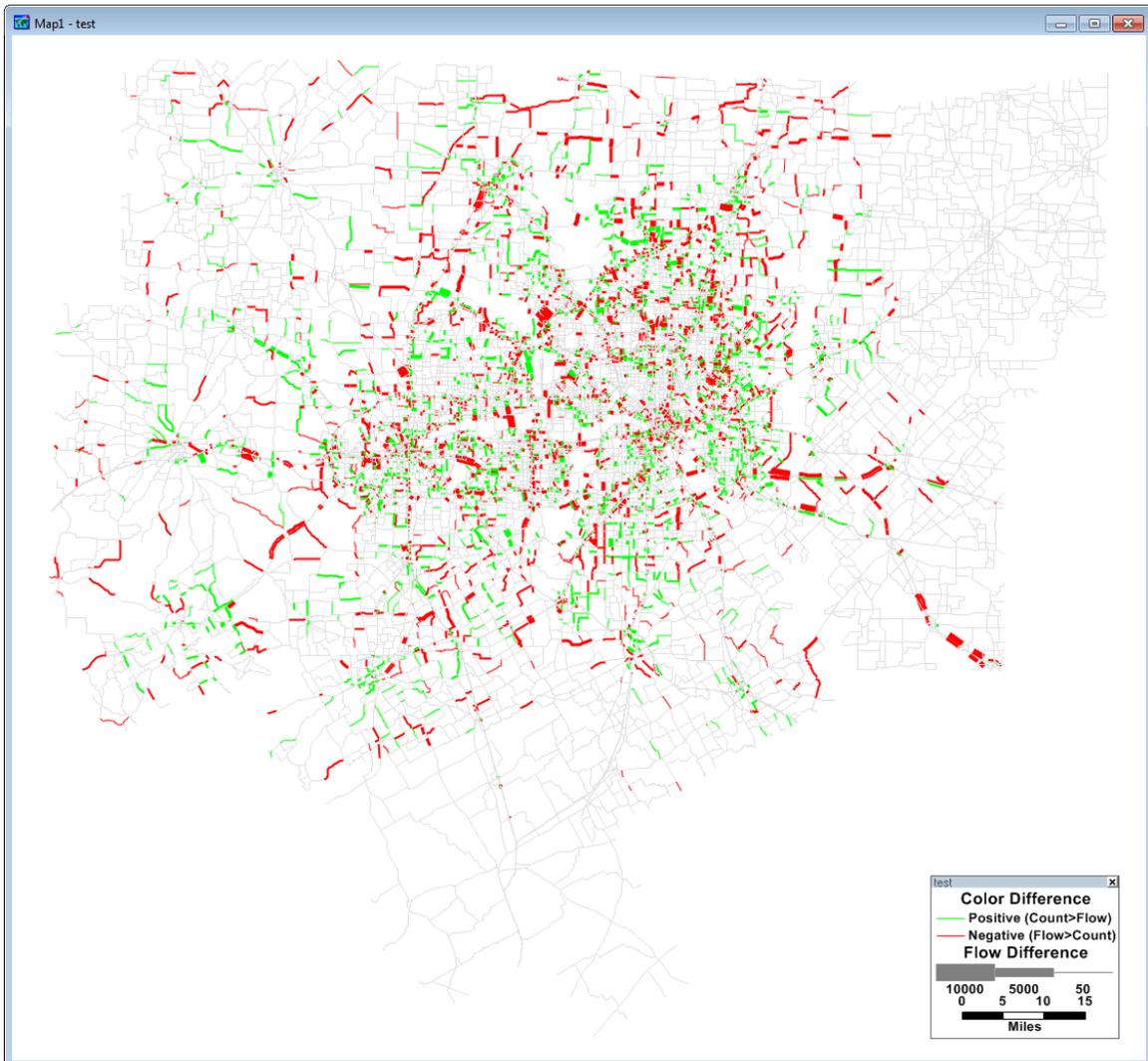
With these other counts there was still a good match between total VMT from the MAG model and that from the counts. It is less exact, which probably reflects the fact that the calibration focus in model development was the first set of counts.

***NCTCOG flow versus count comparison***

NCTCOG provided Caliper with 15 minute directional traffic count data for the MPO area. The counts were in a geographic point format where the points were slightly offset from the network link by directionality. Counts for all facility types were provided, but there were not many locations on interstate highways. We understand from NCTCOG that some of their freeways are so wide that safely collecting traffic counts is infeasible. Also, Texas DOT has not traditionally provided them with directional freeway counts by time period.

We processed the count information and transferred it to the planning network with GISDK macros that tie each point count to the proper network link and direction, transfer the 15 minute point count fields to network attributes, and then aggregate the counts for the AM period. Once again the color-coded links in the map in Figure 5-22 indicate flow differences of greater than 50 vehicles.

**Figure 5-22 System-wide difference between traffic flows and counts for NCTCOG**



In Table 5-19, we tabulate the flow differences. As indicated below and in the other tables the %RMSEs are quite high. To be fair, NCTCOG had never done this type of comparison before and had previously relied upon comparisons with annual average daily traffic (AADT) and bi-directional counts.

**Table 5-19 NCTCOG Flows vs Counts by Functional Class**

Functional class	Number of count locations	% RMSE	% Difference Flows to Counts
Highway	119	66.83	26.74
Arterial	1860	64.07	16.09
Collector	2442	93.78	-9.56
Frontage	361	79.20	4.87
Ramp	1399	77.51	12.27
HOV	2	51.37	-21.83
Centroid connector	20	131.19	-63.44

**Table 5-20 NCTCOG Flows vs Counts by Volume Group**

Volume group (Total flow on link)	Number of count locations	% RMSE	% Difference
0 - 1000	3017	94.79	-26.76
1000-2000	1190	61.4	14.21
2000-4000	900	57.23	23.57
4000-6000	381	56.52	21.64
6000-9000	204	59.36	31.86
>9000	33	56.93	39.41

**Table 5-21 NCTCOG VMT Flows vs Counts by Functional Class**

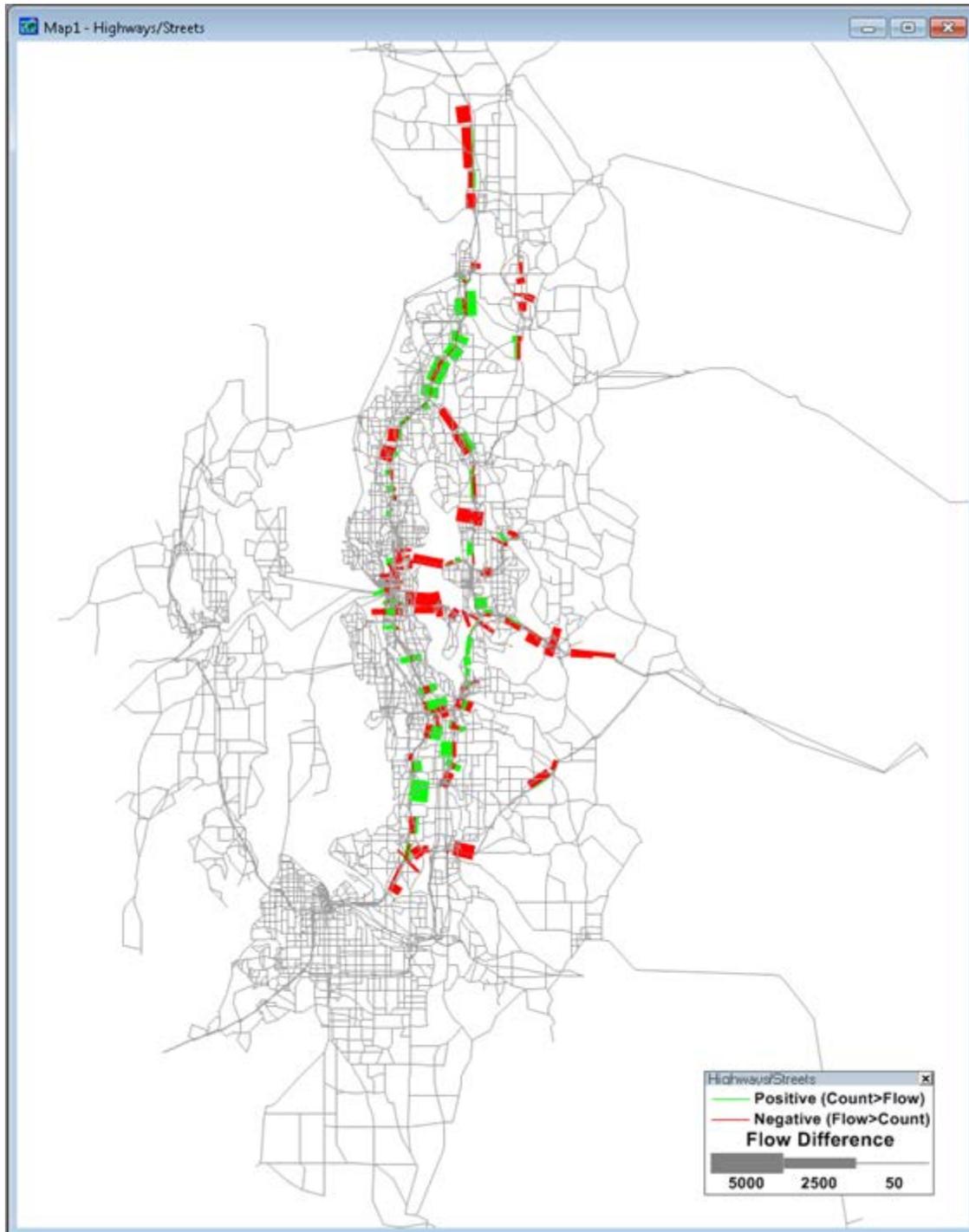
Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	341,996	448,628
Arterial	1,750,930	2,087,480
Collector	691,938	625,619
Frontage	178,367	177,538
Ramp	401,566	435,725
HOV	2,282	2,411

Perhaps what is instructive about this analysis is that reliance on matching bi-directional counts by time period or on matching AADT is not the best approach for model validation. Certainly, it can be misleading with respect to how well each time period and facility is modeled. Subsequent to this analysis, NCTCOG indicated that it would be a priority for them to obtain better and more voluminous count information.

### ***PSRC flow versus count comparison***

PSRC provided Caliper with directional counts for the AM period at 284 locations on freeways and expressways. These are compared with their corresponding traffic assignment results in the map and tables below.

**Figure 5-23 System-wide Difference between AM Traffic Flows and Counts for PSRC**



The differences suggest some geographical bias with more flows east-west and less flow north-south than counts. However, the overall %RMSE for freeways is relatively good. Since no arterial counts were provided, it is not possible to judge the match of arterial flows with counts or the overall freeway/arterial balance.

**Table 5-22 PSRC Flows vs Counts by Functional Class**

Functional class	Number of count locations	% RMSE	% Difference Flows to Counts
Freeway	270	20.89	4.29
Expressway	14	43.00	29.19

**Table 5-23 PSRC Flows vs Counts by Volume Group**

Volume group (Total flow on link)	Number of count locations	% RMSE	% Difference
0 – 4,000	110	47.00	8.68
4,000-8,000	28	31.60	11.43
8,000-12,000	60	18.04	6.00
12,000-16,000	58	14.94	2.14
>16,000	26	14.99	3.49

**Table 5-24 PSRC VMT Flows vs Counts by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	1,824,148	1,887,500
Expressway	24,239	29,920

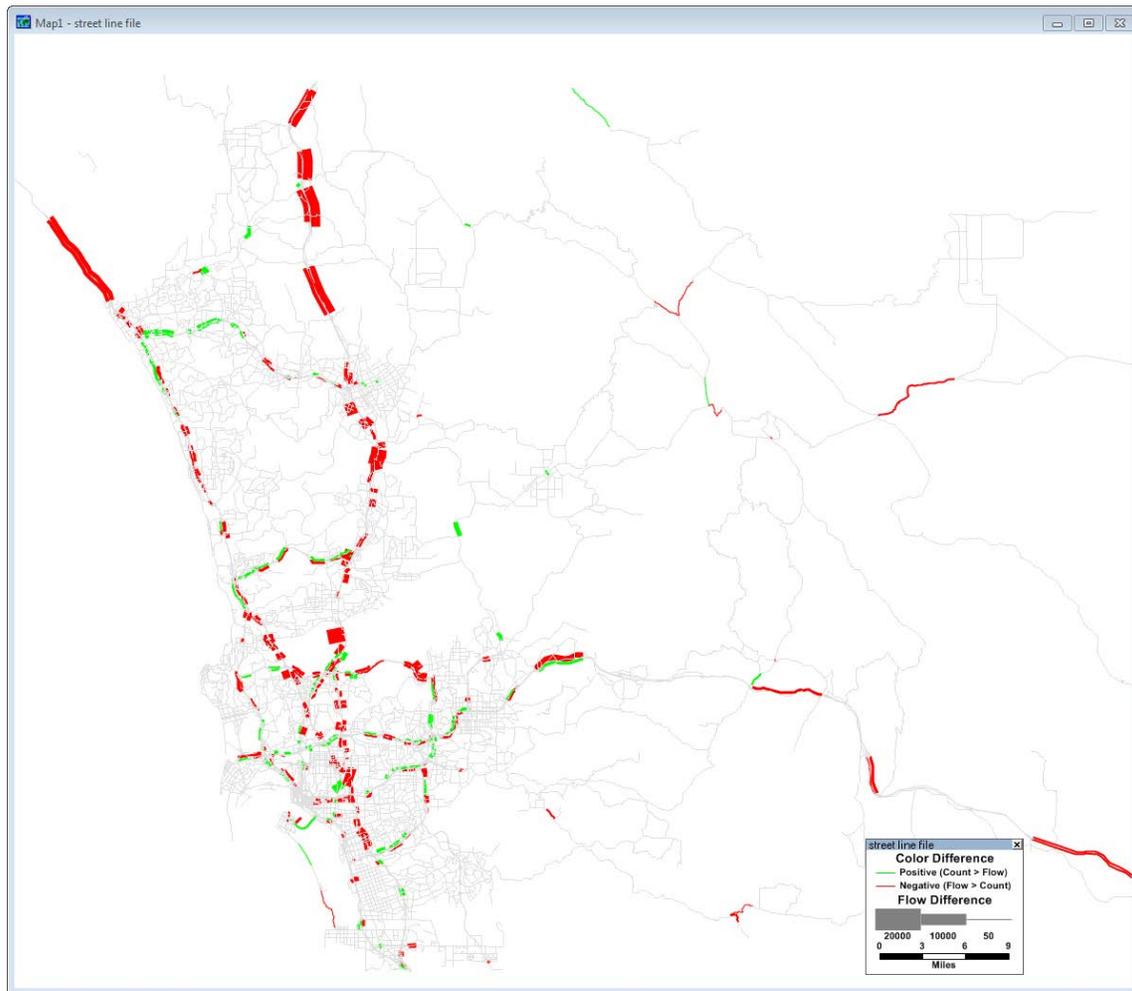
Based upon this sample of counts, the PSRC model overstates VMT somewhat.

### ***SANDAG flow versus count comparisons***

SANDAG provided Caliper with directional counts for the AM period at 401 locations. Most of these counts were directional but some locations had only two-way counts. Most of the counts were on the freeways.

In the map below we compare the counts to the flows from the SANDAG ABM model. The map indicates that the model flows exceed the counts in many locations and particularly in north-to-south flows in the morning.

**Figure 5-24 SANDAG System-wide Difference between the ABM Traffic Flows and MPO-provided Counts**



Generally, there is a reasonably good fit between the model and the counts at least as far as freeways are concerned. The number of arterial counts is very small and is probably not large enough to provide a statistically valid assessment. Clearly, a greater number of arterial counts would be desirable.

**Table 5-25 SANDAG ABM Flows vs MPO-provided Counts by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	363	21.58	8.09
Arterial	30	67.89	-21.18
Collector	6	89.60	-38.11
Ramp	2	25.71	-23.68

**Table 5-26 SANDAG ABM Flows vs MPO-provided Counts by Volume Group**

Volume group	Number of observations	% RMSE	% Flow/Count
0-2,500	24	101.63	12.35
2,500-5,000	29	39.62	-9.66
5,000-8,000	46	24.91	1.05
8,000-12,000	76	20.15	-1.16
12,000-16,000	74	23.20	10.75
16,000-20,000	83	16.18	5.53
>20,000	69	22.21	13.41

**Table 5-27 SANDAG ABM VMT Flows vs MPO-provided Counts by Functional Class**

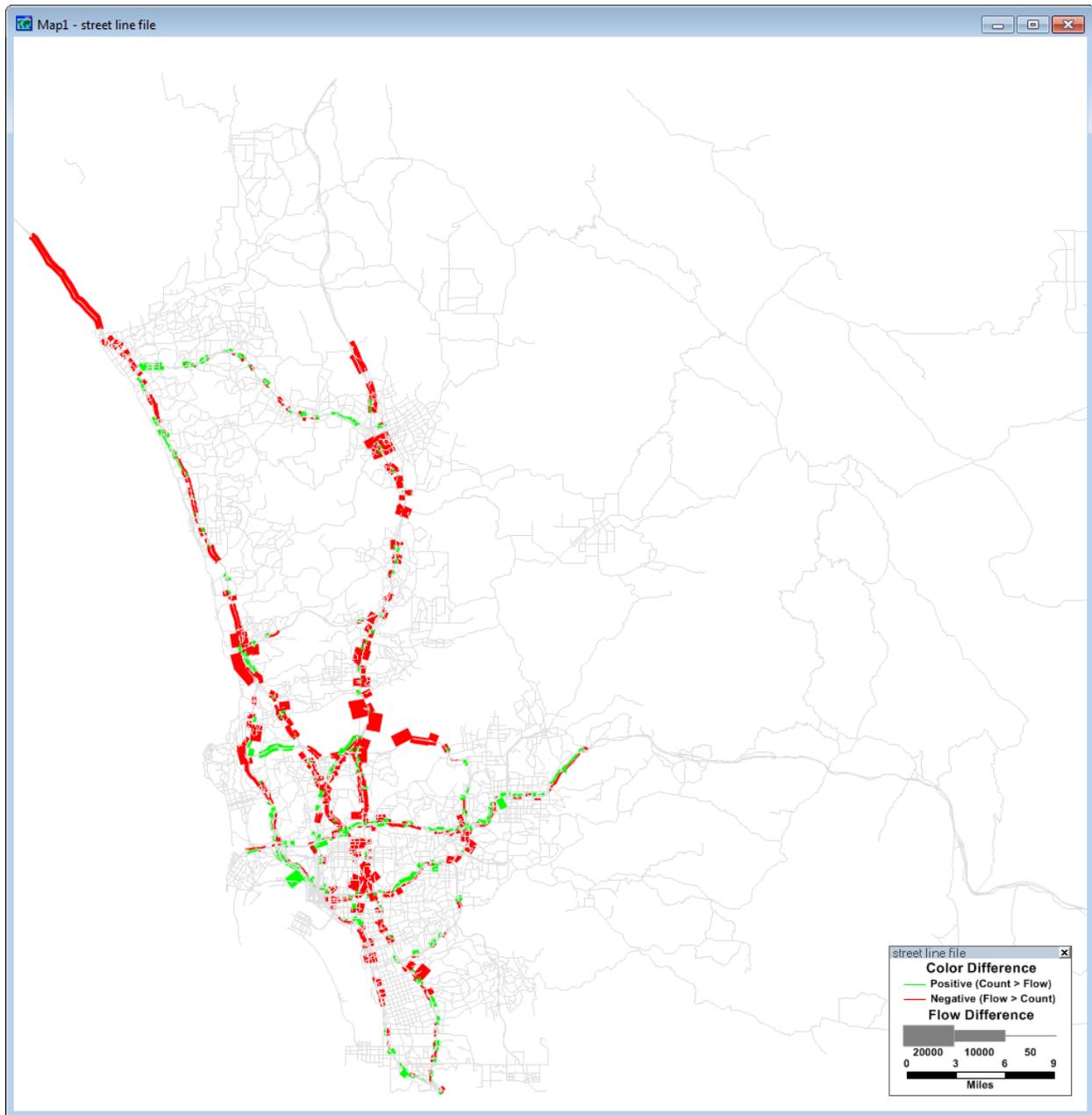
Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	2,657,046	2,978,272
Arterial	52,021	44,904
Collector	3,283	2,797
Ramp	2,377	1,889

Overall, when added across functional classes, the model VMT is higher than the observed traffic counts although it is lower in the case of non-freeway links.

Further, as part of a separate exercise, Caliper also extracted the Caltrans Performance Measurement System (PeMS) counts for all detectors active in 2010 in the San Diego highway network. These were at 825 locations and all of them were directional. These are primarily freeway counts as well. We next analyze how the model flows at an assignment convergence of 1.E-4 compare to these counts.

As indicated in the map, the comparison is similar but perhaps not quite as favorable. The differences in north-south flows and east-west flows are a bit more pronounced.

**Figure 5-25 System-wide Difference between Traffic Flows and PeMS counts (extracted by Caliper) for SANDAG ABM**



**Table 5-28 SANDAG ABM Flows vs Counts (extracted by Caliper from PEMS) by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	494	25.68	8.72
Ramp	352	96.60	5.46

**Table 5-29 SANDAG ABM Flows vs Counts (extracted by Caliper) by Volume Group**

Volume group	Number of observations	% RMSE	% Flow/Count
0-2,500	302	83.68	-13.18
2,500-5,000	65	62.02	15.36
5,000-8,000	58	35.94	4.14
8,000-12,000	92	30.24	-0.97
12,000-16,000	89	21.26	9.07
16,000-20,000	120	25.71	10.42
>20,000	115	22.17	14.40

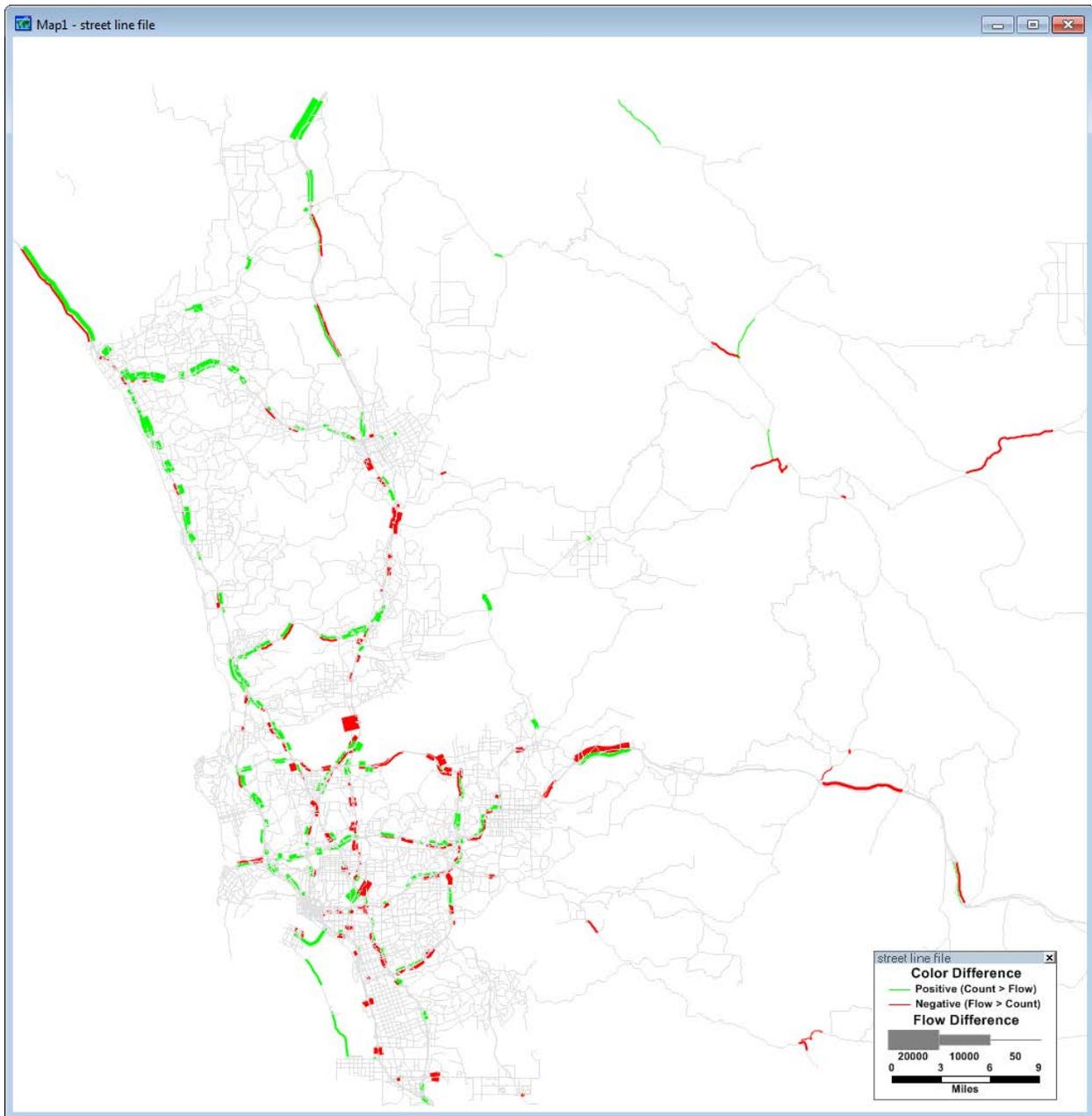
**Table 5-30 SANDAG ABM VMT Flows vs Counts (extracted by Caliper) by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	3,281,893	3,632,410
Ramp	94,538	109,348

In this comparison the model has a much higher predicted VMT than is apparent from the PeMS data. In this case the overestimate is more than 10%.

We performed the same analysis of comparing flows to counts (both MPO-provided and those from PeMS) for the SANDAG **trip-based** model. This comparison showed different results from those from the ABM. While the match to highway counts is good, the trip-based model underpredicts the overall flows that are overpredicted in the ABM.

**Figure 5-26 System-wide Difference between Traffic Flows and MPO-provided Counts for SANDAG Trip-based Model**



**Table 5-31 SANDAG Trip-based Model Flows vs MPO-provided Counts by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	363	19.09	-1.69
Arterial	30	85.92	33.95
Collector	6	182.31	130.54
Ramp	2	31.94	-31.93

**Table 5-32 SANDAG Trip-based Model Flows vs MPO-provided Counts by Volume Group**

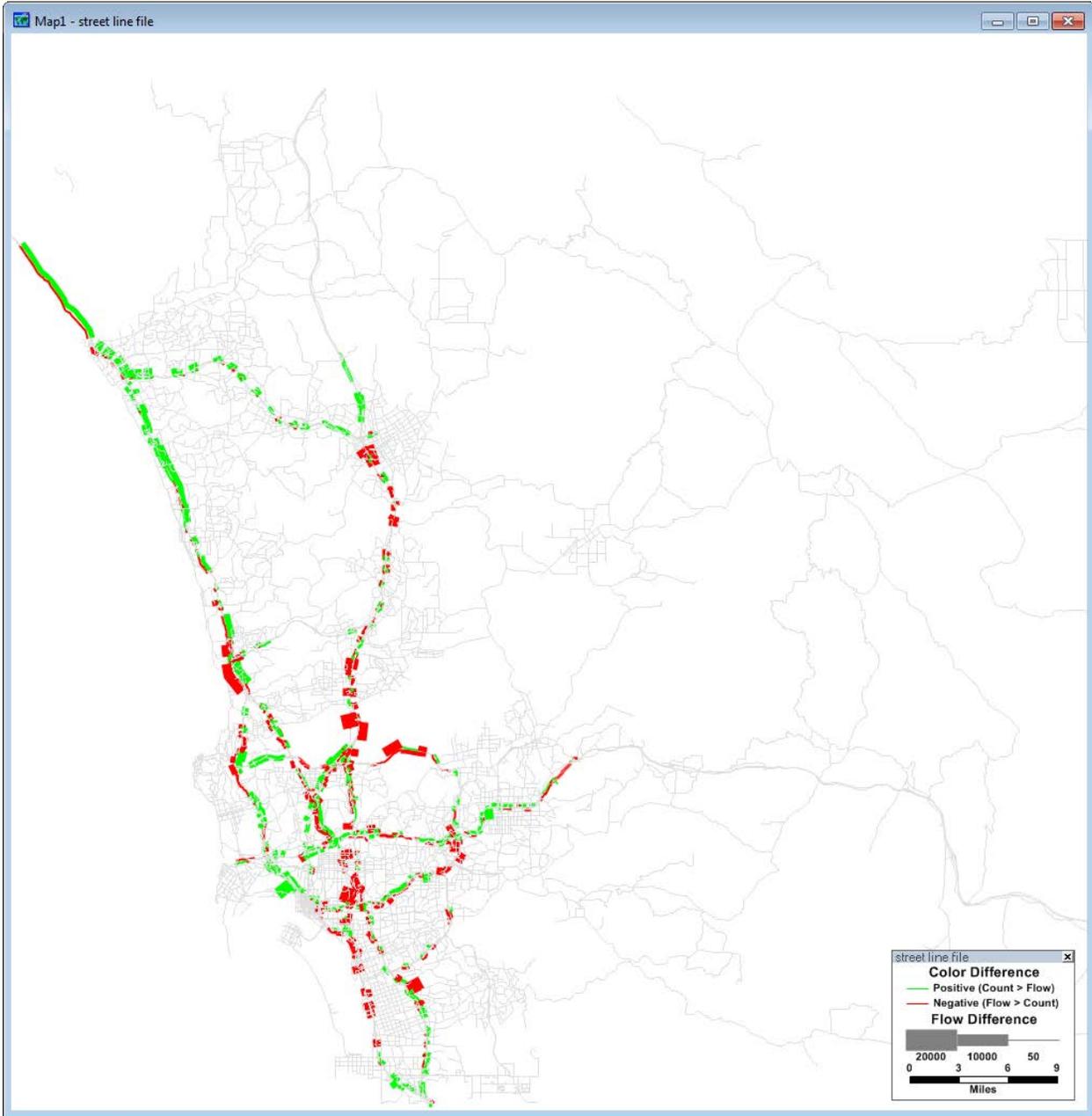
Volume group	Number of observations	% RMSE	% Flow/Count
0-2,500	23	116.15	47.74
2,500-5,000	35	41.24	0.32
5,000-8,000	50	35.31	-12.31
8,000-12,000	89	25.44	-2.71
12,000-16,000	95	17.20	-1.29
16,000-20,000	62	9.53	-4.32
>20,000	46	18.41	5.87

**Table 5-33 SANDAG Trip-based Model VMT Flows vs MPO-provided Counts by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	2,657,046	2,570,459
Arterial	52,021	74,573
Collector	3,283	10,882
Ramp	2,377	1,576

The trip based modeled VMT is a little lower overall than the VMT from observed counts. The results are a little bit different from the ABM model and may reflect the locations of the count stations. Repeating the trip-based analysis with the PeMS data, we find similar results.

**Figure 5-27 System-wide Difference between Traffic Flows and Counts (extracted by Caliper) for SANDAG Trip-based Model**



**Table 5-34 SANDAG Trip-based Model Flows vs Counts (extracted by Caliper) by Functional Class**

Functional class	Number of observations	% RMSE	% Difference Flows to Counts
Highway	494	23.66	-1.43
Ramp	352	95.06	0.50

**Table 5-35 SANDAG Trip-based Model Flows vs Counts (extracted by Caliper) by Volume Group**

Volume group (Total flow on link)	Number of observations	% RMSE	% Flow/Count
0-2,500	286	81.48	-16.92
2,500-5,000	97	63.04	4.10
5,000-8,000	63	38.36	-11.20
8,000-12,000	111	25.70	-6.85
12,000-16,000	105	28.78	3.65
16,000-20,000	85	14.22	-3.28
>20,000	86	18.32	6.50

**Table 5-36 SANDAG Trip-based Model VMT Flows vs Counts (extracted by Caliper) by Functional Class**

Functional class	Total VMT (Counts)	Total VMT (Flows)
Highway	3,281,893	3,229,041
Ramp	94,538	103,484

We do not ascribe any particular significance to the differences between the ABM and the trip-based model. Since the ABM was not yet deployed, we presume that SANDAG will perform further work on its calibration.

### ***Validation of multi-class assignments***

As noted previously, each of the traffic assignment models is a multi-class formulation. This is minimally required to impose restrictions on link use such that HOV lanes can only be used by carpools and that trucks are prohibited from some facilities. However, all of the MPOs use additional classes for one reason or another.

One reason for using multiple user classes is to distinguish variations in values of time (VOTs), which are needed when toll facilities are present or planned for the future. The ARC has separate toll and non-toll classes in the SOV and HOV categories but these have identical VOTs. NCTCOG and SANDAG have fixed VOTs by class; MAG does not specify VOT in the absence of toll links in the network.

The PSRC model in EMME/3 is the only one in the study that separates out SOV trips by income level for HBW trips and contains another SOV class for NHBW trips. In addition, PSRC has high occupancy and truck classes. Each separate class is modeled with a different VOT.

The VOT assumptions in the models are relatively simplistic in that each model class has a single, mean value of time and not a distribution of VOTs, which would undoubtedly be more plausible. We did not study how VOT assumptions impact traffic patterns, but it is expected that they do.

We had hoped to find evidence of multi-class validation on the part of MPOs and to use multi-class counts as part of evaluation of how well the traffic assignment models matched flows. However, due to the paucity of traffic counts generally, this work will have to be deferred until much better count databases become available.

## Other Traffic Assignment Investigations

---

The general absence of extensive count data by direction and time period deterred us from attempting to relate specific assignment practices to the goodness of fit of the predicted volumes with counts. This would be a fruitful future endeavor, perhaps in combination with attempting to predict both observed volumes and speeds.

We did, however, investigate several other topics that arose in the course of our review of the MPO models. In this section, we describe two of these investigations.

### ***Analysis of operating costs in traffic assignment impedance***

Our view is that vehicle operating costs should not be used in UE assignment models. Our argument is both theoretical and practical. First, we don't believe that operating costs are considered by travelers when making route choices. Second, even if they were, operating costs would not be represented as a fixed cost per mile. Most of the operating costs of motor vehicles are due to fuel costs, and these are not constant per link. Rather they are speed dependent and therefore more closely associated with travel times. Nor are fuel costs the same for all motor vehicles or all automobiles. For gasoline-powered automobiles, fuel consumption is minimized around 45 miles per hour.

Use of a distance-based operating cost term in the link impedance calculation is simply adding a constant to the volume-dependent travel time. The amount of the constant is also based upon an assumed value of time. In path-finding, a distance-based operating cost tends to favor paths shorter in distance rather than paths that are shorter in travel time and is, in that sense, antagonistic to the concept of travel time equilibrium. Adding a constant to the link impedance would be expected to facilitate assignment convergence, but we do not feel that is any justification for the practice.

Tolls, of course, should be incorporated in traffic assignment models and, to the extent possible, should be modeled as they are present in real world networks. This is fairly straightforward for link-based tolls and entrance-ramp to exit-ramp tolls which cannot be reduced to link-level tolls, but it is not really practical to model dynamic tolls in static traffic assignment models.

Irrespective of one's views on inclusion of operating costs in assignment models, we felt that empirical tests might be of interest, and so we conducted tests on the NCTCOG, SANDAG (trip-based) and MAG models by varying the operating cost or link impedance already in use by the MPO and performing traffic assignments to a relative gap of 1.E-4. The following tables summarize the results from these tests.

**Table 5-37 Traffic Assignments with Different Operating Costs for NCTCOG**

	Zero op. cost	15c/mile op. cost	40c/mile op. cost
Number of iterations	207	163	153
Computational time	1:00:14	00:50:18	00:47:21
Total VMT	28,595,866	28,255,707	28,054,966
Total VHT	879,433	881,495	935,593

**Table 5-38 Traffic Assignments with Different Operating Costs for SANDAG Trip-Based Model**

	Zero op. cost	15c/mile op. cost	40c/mile op. cost
<b>Number of iterations</b>	32	39	40
<b>Computational time</b>	00:38:32	00:46:14	00:47:26
<b>Total VMT</b>	15,734,165	15,732,776	15,731,290
<b>Total VHT</b>	442,553	442,594	442,651

**Table 5-39 Traffic Assignments with Different Distance-based Impedances for MAG**

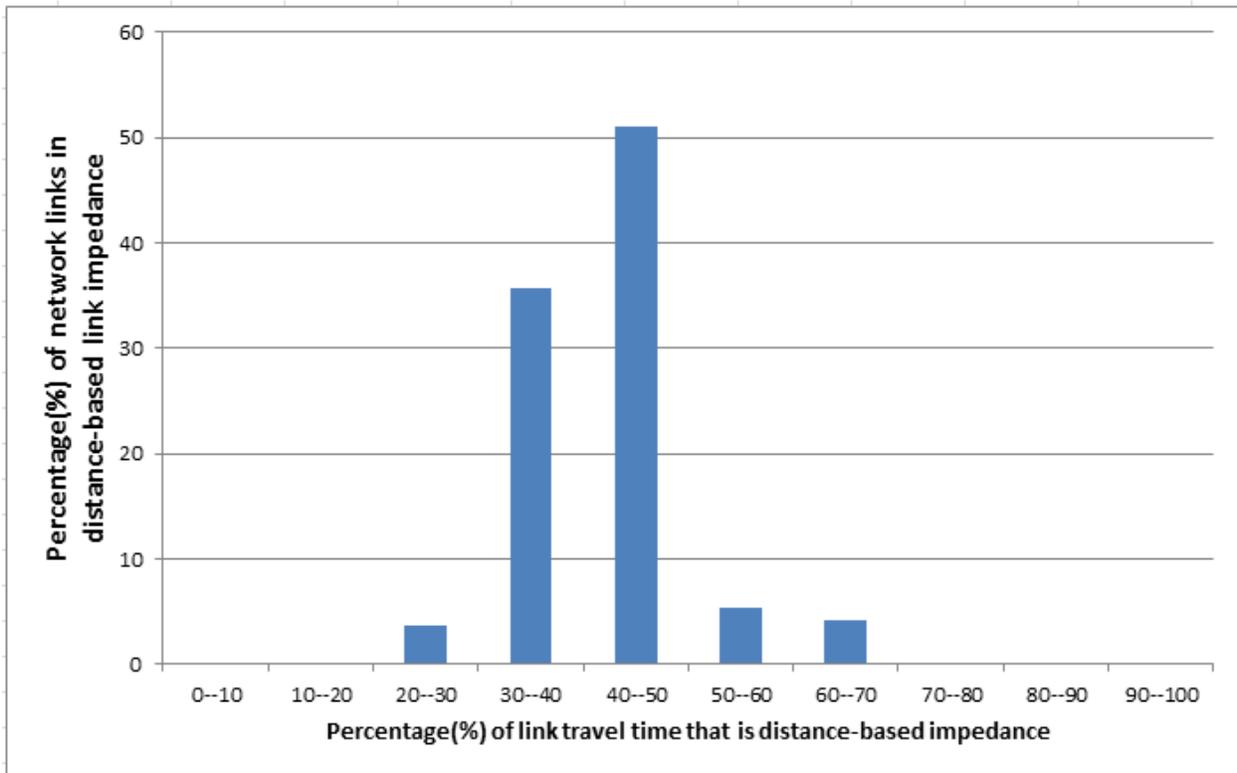
	Zero distance-based impedance	28c/mile distance-based impedance	40c/mile distance-based impedance
<b>Number of iterations</b>	66	45	44
<b>Computational time</b>	00:02:50	00:01:55	00:01:51
<b>Total VMT</b>	20,062,916	19,715,232	19,646,406
<b>Total VHT</b>	556,347	561,677	565,090

One can see this from these tables VMT decreases and VHT increases as operating costs are increased. As we suggested, the higher the operating costs, the faster convergence is except for the SANDAG model. This may be because the SANDAG VDF contains node delays which are prominent on arterials. Use of operating costs promotes travel on the arterials perhaps leading to some additional computational burden.

When distance-based impedance or operating costs are used, they may, unwittingly, dominate some link costs. To see this we use the MAG model as an example. MAG uses an additional impedance of 1.4 minutes/mile, which is incorporated within their VDF and added to the link travel time.

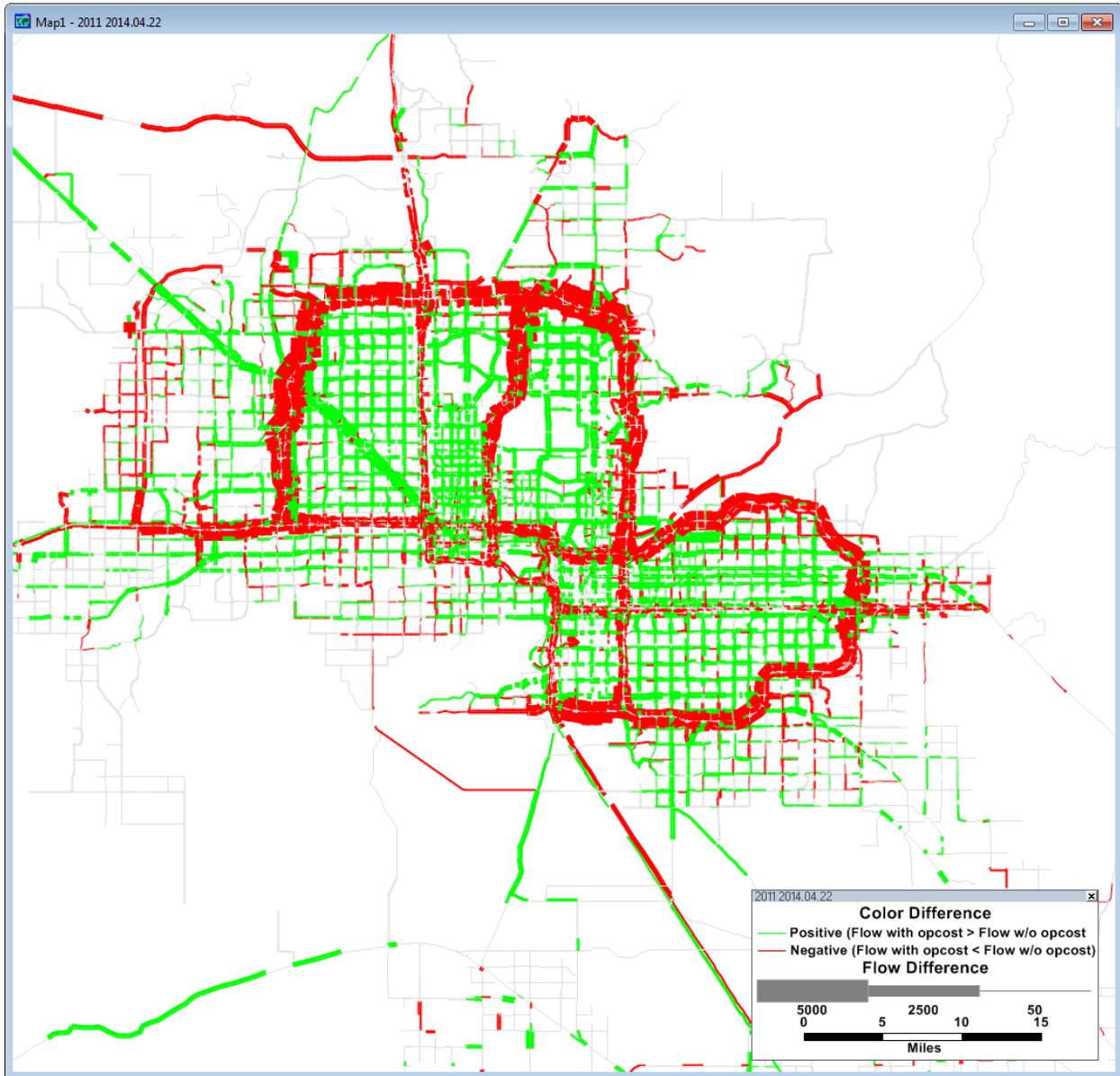
The following plot shows the percentage of network links that have impedances (expressed as time) within specified ranges of link travel time. More than half of the network links have operating costs that account for 40 to 50% of total link travel time.

**Figure 5-28 Percentage of Link Impedance from the Distance-based Component in the MAG Model VDF**



Does the use of operating costs or distance-based impedance components change the predicted traffic flow pattern? The next Figure shows the difference in link flows for MAG when the assignment is run with and without the link impedance term to a relative gap of 1.E-4 using the Bi-conjugate Frank Wolfe algorithm. Quite obviously the differences are large. Seemingly when the distance-based impedances are added, flows on all the arterials go up at the expense of the highways since they tend to provide shorter distance paths.

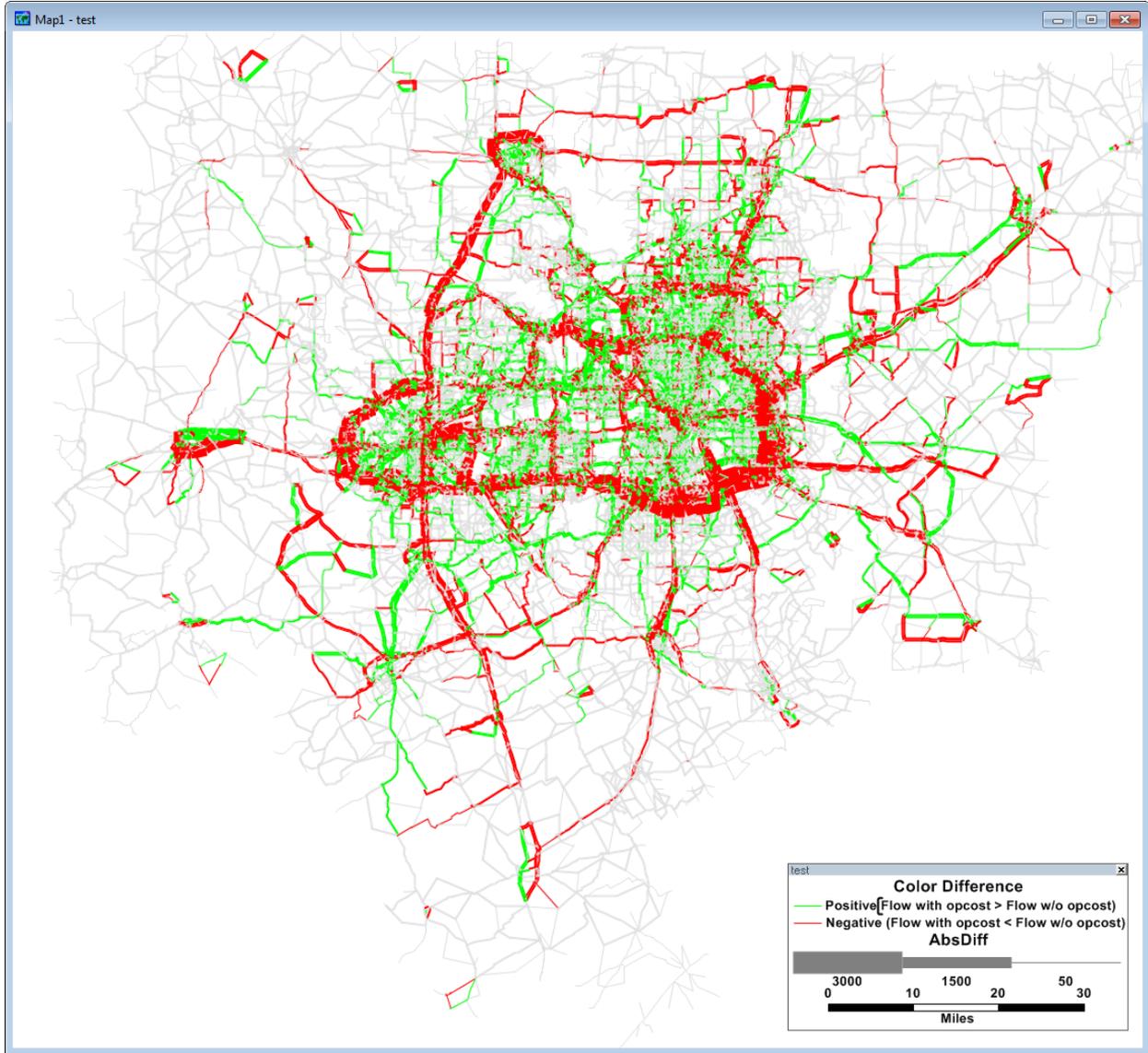
**Figure 5-29 Comparison of MAG Link Flows With and Without a Distance-based Impedance Component**



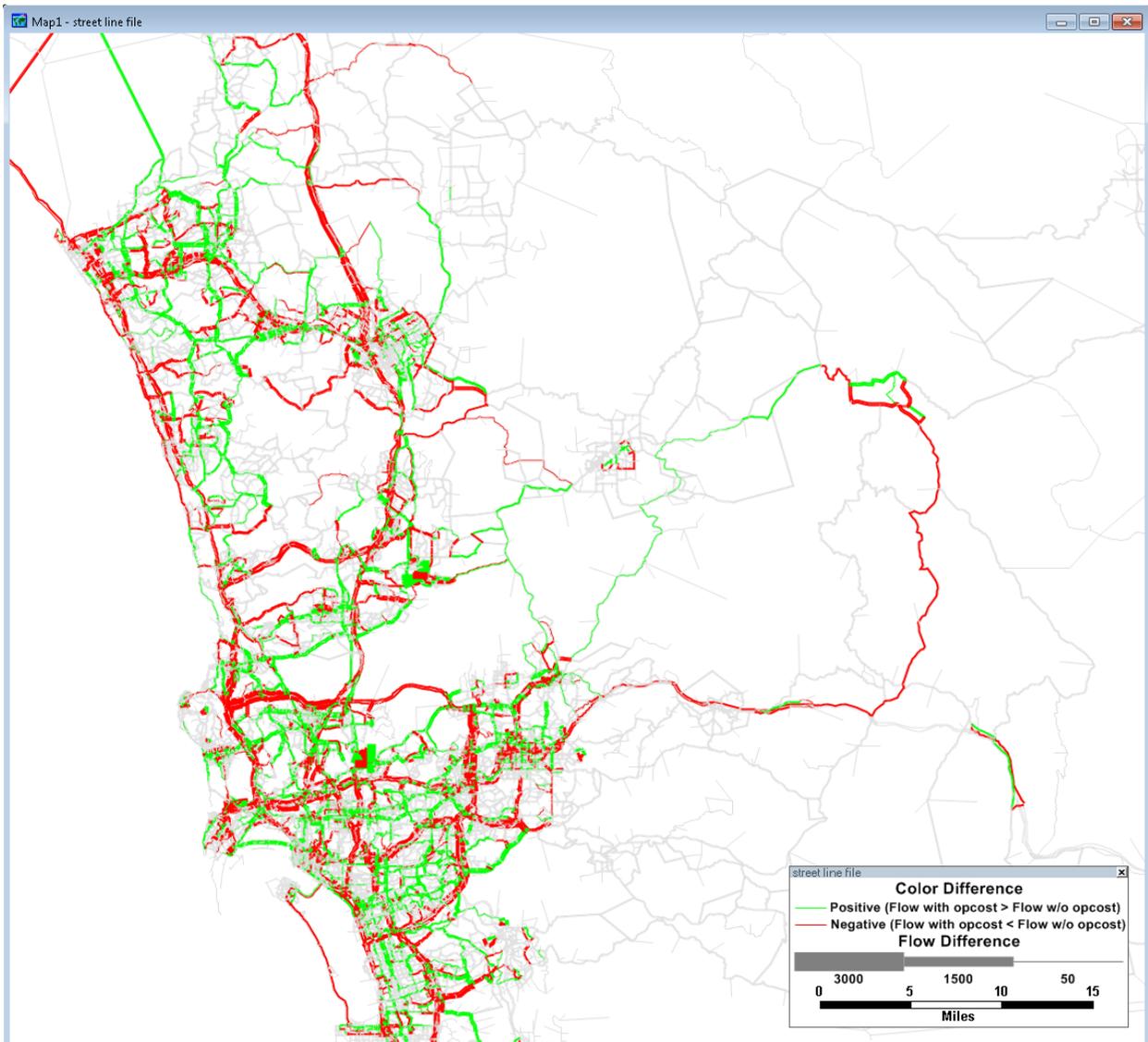
MAG considers the link impedance factor to be “useful for path selection”; it was empirically determined in past studies and used in the MAG model to reflect the right balance of vehicles between freeways and arterials.

In the next two maps, we see a similar pattern of reduced flow on highways and more arterial flow when we compare results with and without operating costs for the NCTCOG and SANDAG assignments run to 1.E-4 relative gaps using the BFW algorithm.

**Figure 5-30 Comparison of NCTCOG Link Flows With and Without Operating Costs**



**Figure 5-31 Comparison of SANDAG Link Flows With and Without Operating Costs**



Clearly the use of operating costs can have a significant effect on the goodness of fit and the predictions of traffic models. Some modelers justify the use of operating costs because they want their models to be sensitive to fuel consumption. But fuel consumption can be calculated as a post-process subsequent to an assignment for reporting purposes.

### ***PSRC trip rounding analysis***

The PSRC trip-based model is unusual in that there are no fractional trips input to the traffic assignment. A form of bucket rounding is used that zeroes out any matrix cell with less than one trip and adds the subtracted fractional trips to adjacent cells in the matrix.

This practice is not generally well thought of as it would seem to introduce errors into the model of an unknown sort. Also, these effects could be compounded with feedback, but we were not able to test that since we were unable to run the full PSRC model ourselves.

We performed a simple test of the effect of rounding on the traffic assignment results by comparing link flows with and without rounding using the bi-conjugate Frank Wolfe algorithm and the path-based method mentioned previously. With both algorithms, convergence was achieved more rapidly with the rounded trip tables with the time savings being quite large for the path-based method which is perhaps why the rounding is used.

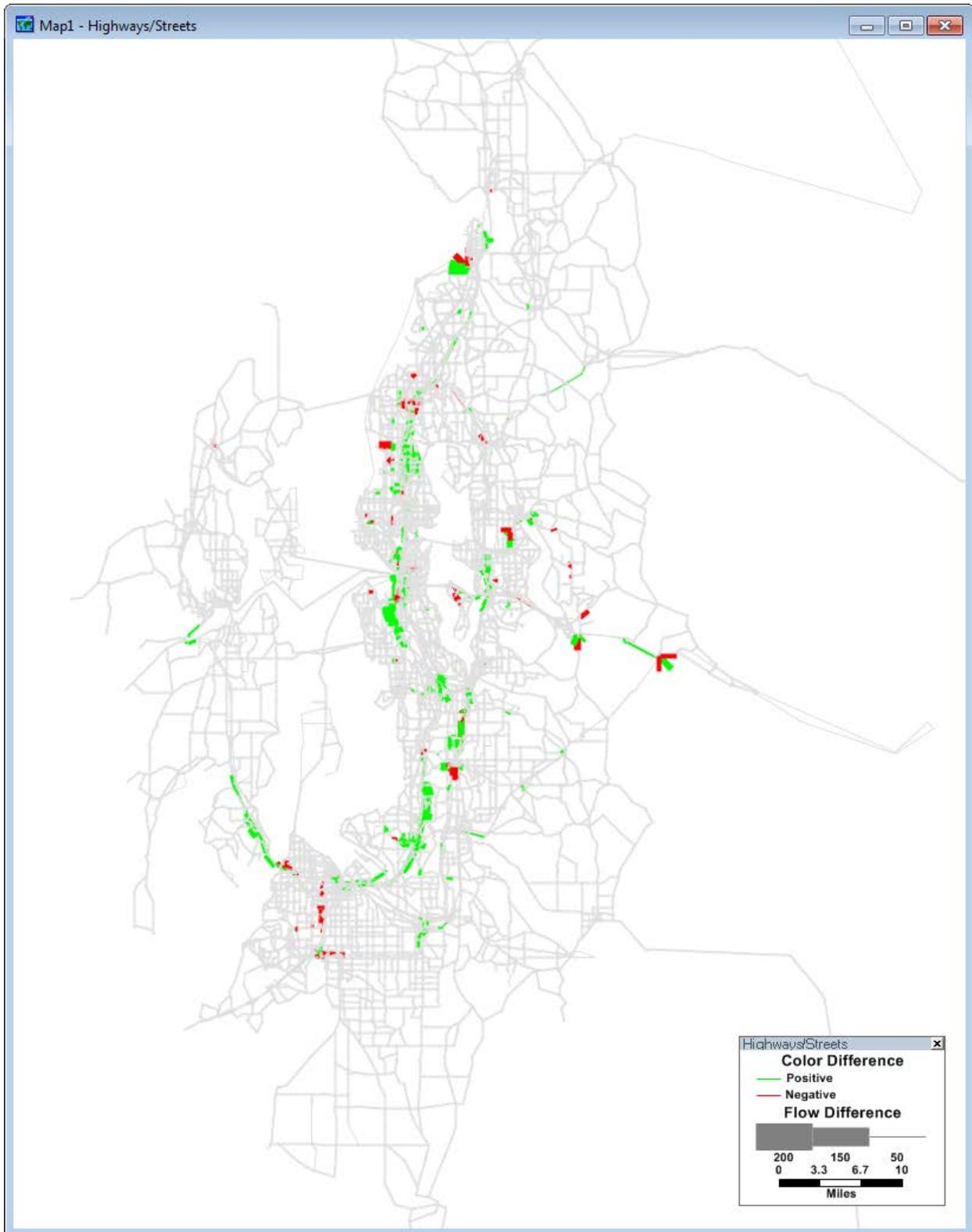
**Table 5-40 Comparison of Rounded and Unrounded PSRC Trip Assignments**

Method	Rounding	Iterations	Time	RMSE Diff (Rounded vs. Unrounded)
BFW 1.E-4	Unrounded	74	1 hr 50 min	
	Rounded	83	1 hr 35 min	2.13%
Path-based 1.E-4	Unrounded	10	2 hr 42 min	
	Rounded	10	40 min	1.88%

The reduction in computing time stems from the fact that the rounded matrix has about 1.16 million total cells summed from all classes while the unrounded matrix has about 138 million total cells. As noted in the table, there were relatively small %RMSE differences in the link flows. Both VMT and VHT increased as a result of the rounding, but the increases were rather small.

In Figure 5- 32 which follows, we mapped the link flow differences between the rounded and unrounded trip assignments. As in the other figures, we show only differences that are greater than 50 vehicles. The green links indicate the locations where the rounded flow is greater than the unrounded flow, and the red links indicate the links where the unrounded flow is greater than the rounded flow. In general, the rounding increases the flow on some links.

Figure 5-32 Comparison of Rounded and Unrounded PSRC Trip Assignments



Based on the map, it would also seem that the rounding can lead to some geographic bias.

## Conclusions

---

In this chapter we examined a variety of aspects of the traffic assignment components of each MPO model. These findings in addition to those presented in the prior chapter yield a portrait of current practices many of which are acceptable and some that can certainly be improved upon.

For all of the MPO models tested, the bi-conjugate FW algorithm can easily achieve relative gaps of  $1.E-4$  with reasonable volume-delay functions. This method is in all major software packages and always dominates FW in terms of both speed to a particular relative gap and the convergence level reachable. It is easily multi-threaded and, as a result, it will be computed more rapidly with more powerful computer hardware. It should be the default method utilized unless a faster alternative is available or a different algorithm is needed to reach a lower relative gap.

Our analysis of convergence error revealed that the maximum link flow error at a relative gap of  $1.E-4$  was approximately 1,000 vehicles for virtually all of the models. This may be a useful finding, and while tight convergence is desirable, it is not by itself a guarantee of a valid traffic assignment model.

We encountered a wide variety of approaches to selection of volume-delay functions, but little evidence that additional complexity in their formulation actually leads to significant model improvement. Indeed problems with VDF formulations can cause difficulties that will distort traffic assignment models in terms of both their convergence and their predicted link flows.

Model-based estimates of VMT and VHT will vary with traffic assignment convergence and certainly with volume-delay functions and other impedance components. In general, VHT will be lower and VMT will be higher as the relative gap is made smaller. Use of operating costs in traffic assignment models was shown to introduce particular distortions in traffic patterns.

A major and somewhat unanticipated finding is that MPOs do not have sufficient count data to validate their models properly and with suitable statistical significance. Even the MPOs with fairly large numbers of directional counts by time period often had very few for a particular functional class of roadway. This thwarts attempts to see if freeway and arterial utilization is well-modeled. Similarly, it would be desirable to compare link utilization by user class for trucks, HOV users, and toll payers with counts thereof. It seems to us that more extensive counting programs are warranted if model validation is to be improved in the future.

Modelers frequently report predicted versus observed measures in terms of gross aggregates. This practice appears to mask errors in assignment models that might be revealed by other means. As we believe we have shown, mapping model output is a useful tool for understanding how well a traffic assignment model performs.

Clearly, there are no uniform practices and there are obviously some substandard approaches in MPO traffic assignment models. We feel that there is something for everyone to learn about good practices and a need for further research to identify them.

Lastly, the type of scrutiny that we placed on these traffic assignment models is suggested as appropriate due diligence for other MPO models that will identify and remove problems before they impact model calibration and forecasts.



# Chapter 6

## Feedback Methods and Convergence Tests

As discussed previously, the use of feedback is a commonly accepted practice in urban travel demand modeling. For many modelers, feedback loops are motivated by the belief that long-term adjustments in land use and travel will be a consequence of major changes in transportation supply. For this reason, the congested travel times from a single loop of a model run are fed back to trip distribution and mode choice followed by a subsequent assignment and some number of additional loops of the model. In a model with elastic demand, feedback would include the trip generation or tour generation step as well. For other modelers, feedback is simply a means of generating an internally consistent model in the sense that the travel times that are used in trip distribution, mode choice, and assignment (or the logsums in activity-based models) are consistent with the travel times associated with the link volumes produced by the traffic assignment.

Despite the consensus among modelers of the appropriateness of feedback calculations in multi-stage models, our review of the 30 largest MPO models indicated that feedback methods and closure criteria in use were non-existent or flawed, ad hoc, or only partially implemented. In this chapter, we examine the feedback approaches taken in the 5 MPO models and perform a variety of empirical experiments with several of the models.

For this project, we had some modest goals for the feedback research. First, we wanted to see if rigorous measures of feedback convergence and tighter convergence criteria could be used with the MPO models. At issue would be questions of the complexity of the overall formulations and the computational burden associated with computing feedback. We also did not know, a priori, what levels of feedback closure could be achieved with deployed models. Second, we wanted to see if there were obvious systematic differences in the efficiency of the specific type of feedback method employed. However, we were not looking to address the issue of the fastest methods as we suspect these may be found to be problem dependent. Lastly, we wanted to shed light on how consequential feedback calculations might actually be in terms of the estimates of link flows, travel times, VMT, and VHT. As part of our analysis, we ran many more loops than are used in currently deployed models. Feedback in both trip-based and activity-based models was explored. The effects of using feedback in models to obtain congested travel times and to estimate project impacts will be explored more fully in subsequent chapters of this report.

### Overview of the 5 MPO Model Feedback Approaches

---

Our examination of the 5 MPO models revealed significant differences in the approaches taken to model feedback. These include differences in the feedback methods, the convergence tests, and the convergence levels employed. There were also differences in the time periods for which feedback is performed. The feedback practices of the MPOs are listed in the Table that follows and discussed thereafter.

**Table 6-1 MPO Model Feedback Methodology**

MPO Model	Description
<b>ARC ABM</b>	Method of Successive Averaging (MSA) on the link flows. Convergence is achieved when %RMSE difference between feedback link flows < 5%, starts with congested AM speed estimates for the peak periods. Feedback is performed for all 5 time periods used in assignment.
<b>MAG</b>	MSA on link flows. Convergence criterion of 3.8% applied to the maximum of the link flow RMSE and trip table RMSE for the PM peak period only. The MD and PM assignments are performed in each feedback loop. The AM and NT assignments are only performed in the final loop.
<b>NCTCOG</b>	Skims are averaged after assignment. A weight of 0.25 is used for previous average skims and 0.75 is used for the current loop skim. Number of loops is user-determined from 3 to 12 but in most cases is set at 5, which was determined by the MPO based on prior testing using skim RMSE <= 1%, Max change in skim cells < 10%, Link Volume RMSE <= 2% & other tests. In AM and OP assignments are performed in each feedback loop and used for skimming. PM assignment is performed in final loop only.
<b>PSRC</b>	Skims for all time periods averaged between loops except after the first loop which begins with free-flow times. Number of loops fixed at 5.
<b>SANDAG trip-based</b>	Number of feedback loops fixed at 4. Simple averaging of skims after each loop. No averaging on flows. All 3 time periods assigned in each feedback loop and all are used for skimming.
<b>SANDAG ABM</b>	MSA on the link flows. Number of loops fixed at 3. Sampling percentages for population synthesis model are set at 20%, 50% and 100% for first, second and third loops respectively. (A sampling percentage of 20 means each person's trips are multiplied by 5). All 5 time periods are assigned in each feedback loop and all are used for skimming.

As discussed previously, solving for feedback convergence involves achieving a close match between the origin-to-destination congested travel times used in applying travel model components and those that correspond to the ultimate assigned link flows. From an observational point of view, it would appear this goal can be approached in a variety of ways and with varying degrees of success.

Three of the 5 MPOs performed feedback for all time periods, which we believe is a necessary practice. If validation and forecasting are performed for all model time periods, it would seem essential that each period's model should be converged and to the same minimum degree for each. Also developing reliable results for a base case or a forecast year would normally require 24-hour outputs that are most appropriately summed from time period components. Performing an AM or PM time period assignment only in the last feedback loop will not result in a satisfactory outcome in terms of consistency for that time period.

Three of the 5 MPOs use link flow averaging with the method of successive averages that was described previously in Chapter 3. This method is generally considered to be a good or best-practice method. This method is in theory probably convergent but not necessarily with any particular efficiency, or in any practical time frame, or with any guarantee of external validity. The other two MPO models use travel time skim averaging, neither of which are necessarily effective or efficient according to the research literature.

## ***Closure metrics and tolerances***

Three of the five MPOs use closure criteria that are based on comparison of successive link flows. The other two do not use an explicit closure metric, which begs the question of the uncertain comparisons that would be made between base case and scenario cases.

Another observation is that those MPOs who do use a formal closure have very loose conditions. The particular closure metric of either 5% or 3.8% in successive link flows is very weak given that a consistent change over future iterations of 3.8 or 5% would lead to drastic flow differences over another ten or more iterations. Offhand, one cannot say how consequential that might be. However, we can make a guess at how close the various models are to estimates of converged flows. This will be discussed later in this chapter.

## ***Initial speeds***

Generally, it is efficient to begin each model run with a good estimate of congested travel speeds that are pertinent for each time period in the model. When prior estimates are not available for a particular scenario, they can be generated from a prior model run or derived by an alternative means. One novel option for a base case model might be to use estimated travel times from commercial sources.

The 5 MPOs had somewhat differing approaches to travel times used to launch the first loop of their models. ARC begins with estimated congested AM speeds that are based upon area type and facility type. Off-peak speeds are taken from a lookup table of free flow speeds. The AM speeds are used for the AM and PM peak periods while the off-peak speeds are used for the other three time periods. Using the AM peak speeds for the PM peak is problematic as volumes and travel times are asymmetric by time period. MAG, NCTCOG and PSRC all begin with free flow times.

SANDAG uses congested speeds generated from an initial highway assignment using a trip matrix from a prior run of the model. Since the model is run frequently during development and application, this provides increasingly better estimates of initial congested speeds.

## ***Bus speeds***

All of the models use bus speeds that are dependent upon road network speeds. These may be free flow speeds leading to the use of free flow bus speeds in the first loop or they may be congested bus speeds that are based upon congested auto speeds.

Congested bus speeds are typically modeled as being slower than auto speeds by some proportional factor that may be related to area type or the functional class of the link. There may be also a minimum speed for buses as well as a maximum. This has a certain logic to it but may pose challenges to feedback convergence as it further impacts shifts between transit and auto modes.

Use of variable bus speeds complicates the problem of achieving feedback convergence as it introduces additional variation in mode split. Theoretically, it is possible that these practices could break the convexity of the overall model. In practice, we found that all of the models could be made to be convergent even with bus speeds varying by feedback loop.

Below we provide a short description of the bus speed determination method for each MPO.

**ARC:** In the ARC model, the congested bus speeds and times are the same as the congested auto speeds and times. The bus speeds however are constrained by a user input minimum and maximum bus speed.

**MAG:** In the MAG model, transit times are based on the highway times plus a transit factor. The full equation is:

$\text{Transit\_time} = \text{highway\_congested\_time} + \text{link\_distance} * \text{transit\_delay\_factor}.$

The  $\text{transit\_delay\_factor}$  is dependent upon the area type, functional class and mode of the route.

**NCTCOG:** In the NCTCOG model, the congested bus speeds and times are the same as the congested auto speeds and times. Mode level dwell times are also added based upon transit stops along the routes.

**PSRC:** In the PSRC model, the transit time is a factor of the congested auto time. The factor varies from about 1.0 to about 1.3 depending upon the transit link type. The minimum allowable transit speed is 5 mph.

**SANDAG ABM and Trip-based Model:** In the SANDAG models, the congested bus speeds and times are the same as the congested auto speeds and times. Mode level dwell times are also added based upon transit stops along the routes.

### ***Appropriateness of feedback closure metrics***

In our view, the consistency of travel times skims is one of, if not the most preferable of metrics for assessing feedback convergence. Models begin with travel times and end by producing assigned flows, which can be used to produce the corresponding output travel times. Congested travel times have the great virtue that they can be observed and measured permitting direct external validation of results. Given that it is more important to match the real world than an arbitrary figure of merit, this should be considered pivotal. Moreover, a model can be evaluated on its ability to match both link flows and congested travel times and future predictions thereof.

Estimated link flows, trip tables, and congested travel times are all interdependent and modifying any one of these will have an impact on the others as processed through the model components and loops. This means that averaging one or more of these quantities in feedback loops will have effects on the others. Perhaps as a result, diverse averaging practices are utilized by MPOs without necessarily any deep consideration of consequences.

A further problem is that there is a lack of information and insight into appropriate numerical levels for specific convergence metrics such as congested skims or link flows. It has been discussed previously that the mere fact that there is a small change from one iteration to another does not guarantee a good solution.

If the model uses a traffic assignment method that is itself limited in convergence, then feedback convergence may be accelerated but to a solution that is inferior to one using an improved traffic assignment algorithm. A more subtle effect is that if the averaging scheme itself reduces the distance between successive iterations the stopping point will be determined by the averaging scheme itself. We have a preference for averaging a quantity that is not the figure of merit used to determine closure. However, even this may not remove the effects of the averaging method from the results. As a result, there is reason to believe that the ultimate model output will be conditional upon the feedback method chosen as well as myriad other factors such as the traffic assignment convergence and many other aspects of a multi-stage model.

Given the number of issues surrounding feedback methods, we resort to performing a fairly broad, but certainly not exhaustive, series of empirical calculations. These are designed to examine the basic behavior of some MPO models and help modelers understand various aspects of feedback methods and outcomes.

## **Feedback Runs**

---

In addition to the feedback tests performed on the models based in TransCAD, we also requested that the ARC and PSRC MPOs, which have models based in CUBE/Voyager and EMME/3 respectively, perform model runs to a high number of feedback loops and provide us a summary of results. While ARC was unable to comply with the request within the project timeframe, PSRC was able to provide some partial results.

As part of the study, we performed multiple feedback tests on the MAG and NCTCOG trip-based models and the SANDAG activity-based model. These models were selected for the most intensive scrutiny since we were able to run them end-to-end without the need of any MPO assistance. For each MPO, the model performance on the original feedback method employed by the MPO was compared to other feedback approaches that are in use in practice. For these tests, we used the traffic assignment convergence that the MPO uses in their model.

Our approach was to begin by running the models in a manner similar to their current form but with different feedback strategies. We illustrate the results with 6 plots for each MPO. The first 3 plots show the percent RMSE differences between the travel time skims, the trip tables, and the link flows from successive feedback loops. The second 3 plots show the percent change between the travel time skims, the trip tables, and the link flows from successive feedback loops.

We then attempt to assess feedback convergence errors in the only way practical. Feedback convergence error can be approximately assessed by comparing highly converged solutions with lesser ones, much in the same way that we did for the traffic assignment models. We did this on an exploratory basis for the MAG model. This exploration is necessary because the mere fact that there are small percentage changes from loop to loop doesn't mean that there are small changes over many loops. Basically, we are trying to understand how different the link flows are at different levels of feedback convergence. This should provide some perspective on how many feedback loops should be computed.

## Feedback runs with the MAG model

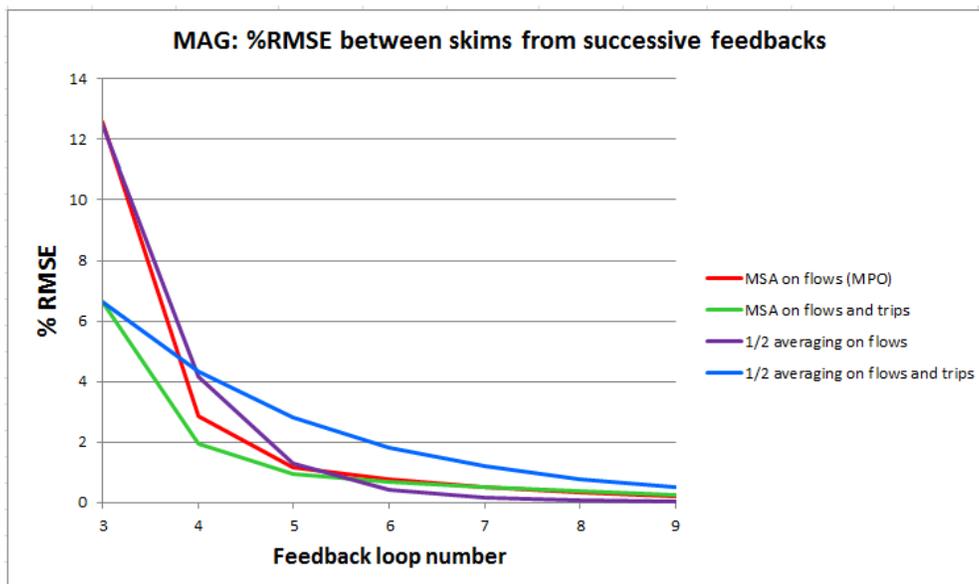
The MAG base model uses MSA averaging on flows from the PM time period as its feedback approach. The model begins with free flow speeds, which accounts for the high initial link flow %RMSEs. The MAG model performs a maximum of 10 feedback loops but stops sooner if the %RMSE difference of the PM flows and the %RMSE difference of O-D trips are both less than 3.8%.

As a test, we ran 10 feedback loops of the MAG model using alternative feedback methods. The results are shown in the figures that follow. We exclude the final loop from the analysis since the assigned classes from the final assignment are organized differently compared to the other loop assignments. We also exclude the first loop from the graph to avoid distorting the graph since MAG begins with free-flow times resulting in large %RMSE differences between the 2nd and 1st loop. The feedback loop number on the x-axis shows the %RMSE or % change relative to the previous loop.

In the first set of graphs, we plot the %RMSE differences between travel time skims, trip tables, and link flows, respectively, from successive feedback loops. The %RMSE differences between skims are for the single occupancy (SOV) class while the %RMSE differences between trips and flows are for the combination of the SOV and Shared-Ride classes. The methods compared include MSA averaging of link flows, MSA averaging of both link flows and trip tables, a constant  $\frac{1}{2}$  weight used to average flows, and a constant  $\frac{1}{2}$  weight used to average both flows and O-D tables.

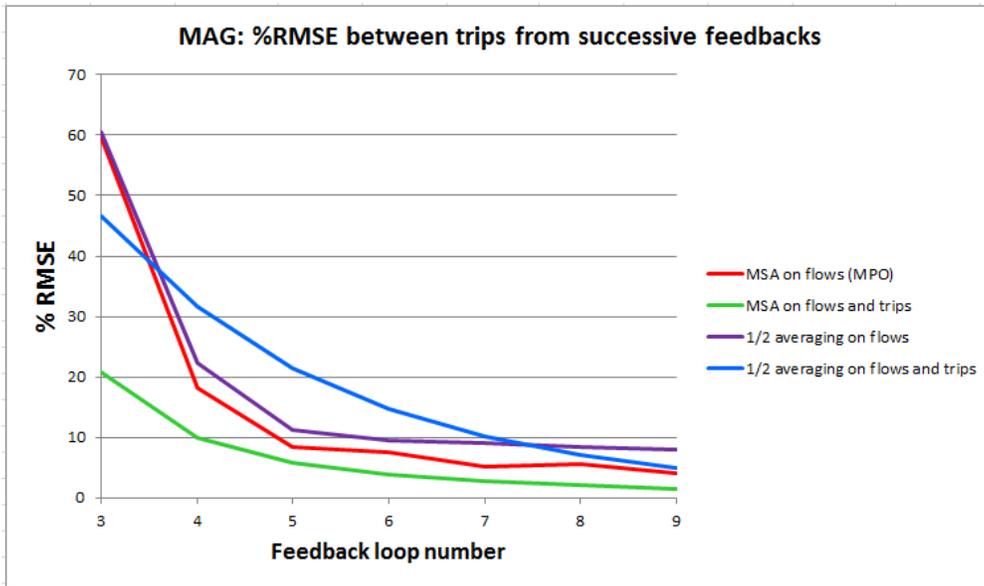
While the rate of change of all the methods declined over the 8 loops, MSA on link flows and  $\frac{1}{2}$  weight averaging on flows performed the “best” in the sense that they reduced successive skims to smaller and smaller differences more rapidly.

Figure 6-1 %RMSE between MAG PM Travel Time Skims from Successive Feedback Loops



If we consider the %RMSE between successive trip tables, then MSA averaging of both link flows and trip tables is associated with the most rapid %RMSE decline between loops. This is not surprising because applying MSA to trip tables is guaranteed to reduce those differences with increasing iterations.

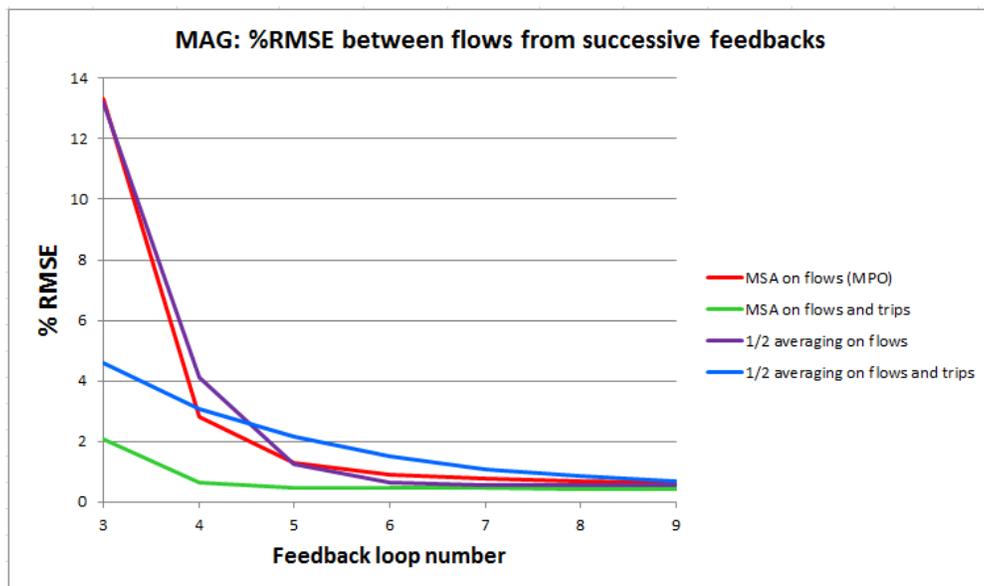
**Figure 6-2 %RMSE between MAG PM Trips from Successive Feedback Loops**



Decreasing the differences rapidly does not itself equate to maximal efficiency in computing feedback convergence to the true equilibrium point. It may equate to stalling the solution more rapidly as we have seen with the Frank-Wolfe traffic assignment.

If we examine the %RMSE of successive link flows, we see a similar effect in that the variable being averaged with MSA shows rapidly declining differences. In this case for the MAG model, when MSA is applied to both link flows and trip tables, the differences are smaller earlier on although they become more or less the same after 8 loops.

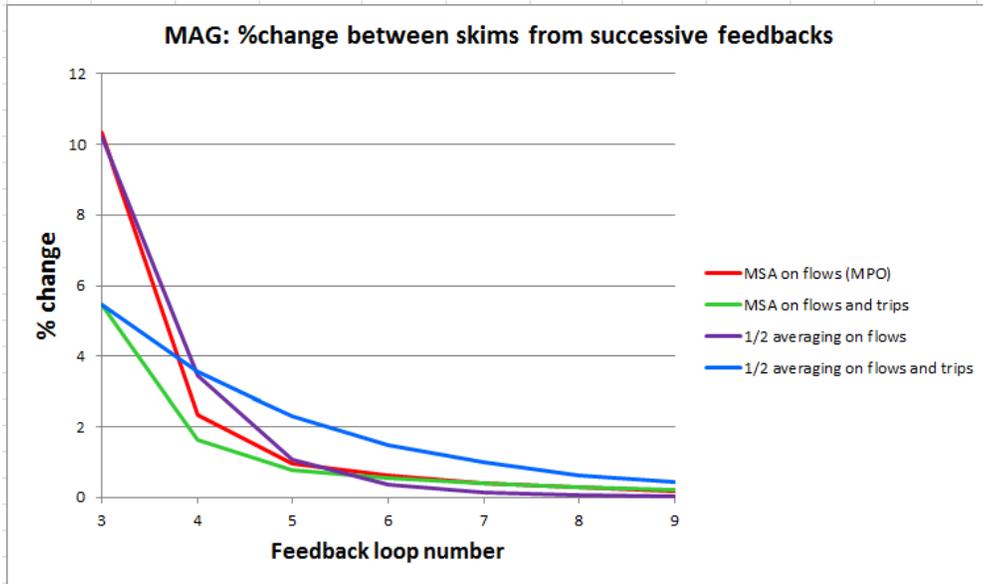
**Figure 6-3 %RMSE between MAG PM Link Flows from Successive Loops**



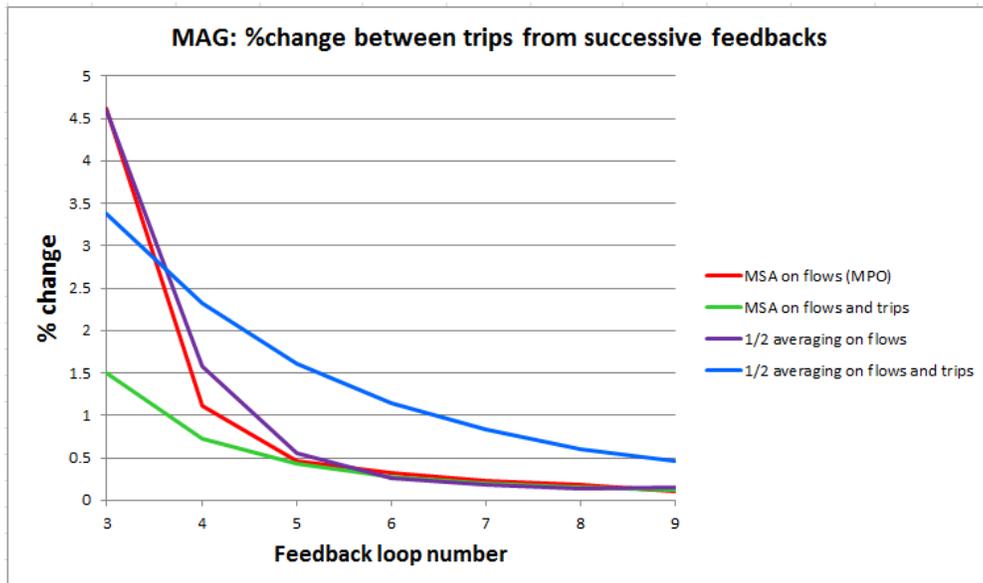
Interestingly, after nine iterations all of the methods wind up in a similar place with respect to successive differences in link flows but not in the congested skims or trip tables as seen below.

We can observe similar, but not identical patterns when we examine the percentage change between loops as opposed to the %RMSEs. Below we plot the percentage changes in the congested travel time skims, trip tables, and link flows as a function of the number of feedback loops. MSA on link flows consistently produces the smallest percentage changes across all three metrics. MSA on both flows and trips produces the smallest differences between successive link flows but not between successive skims.

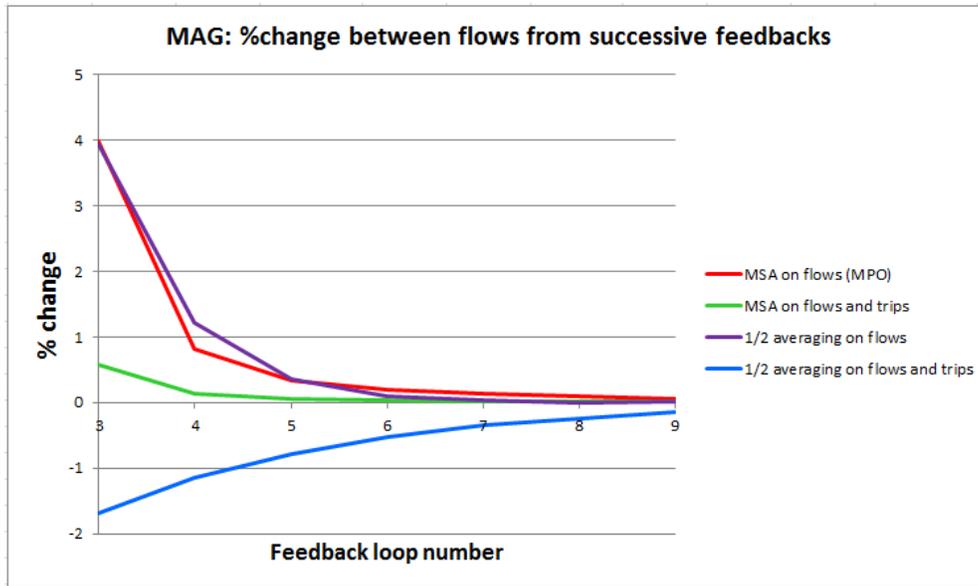
**Figure 6-4 % Change in MAG PM Skims from Successive Loops**



**Figure 6-5 % Change in MAG PM Trips from Successive Feedback Loops**



**Figure 6-6 % Change in MAG PM Link Flows from Successive Feedback Loops**



As indicated above, 1/2 averaging of both flows and trip tables does not compare favorably to the other methods in terms of % absolute change over 9 feedback loops.

In the Table below, we can see the estimated PM period output VMT and VHT by feedback loop using MSA on the link flows feedback method.

**Table 6-2 MAG Model Estimated VMT and VHT Using MSA on PM Link Flows**

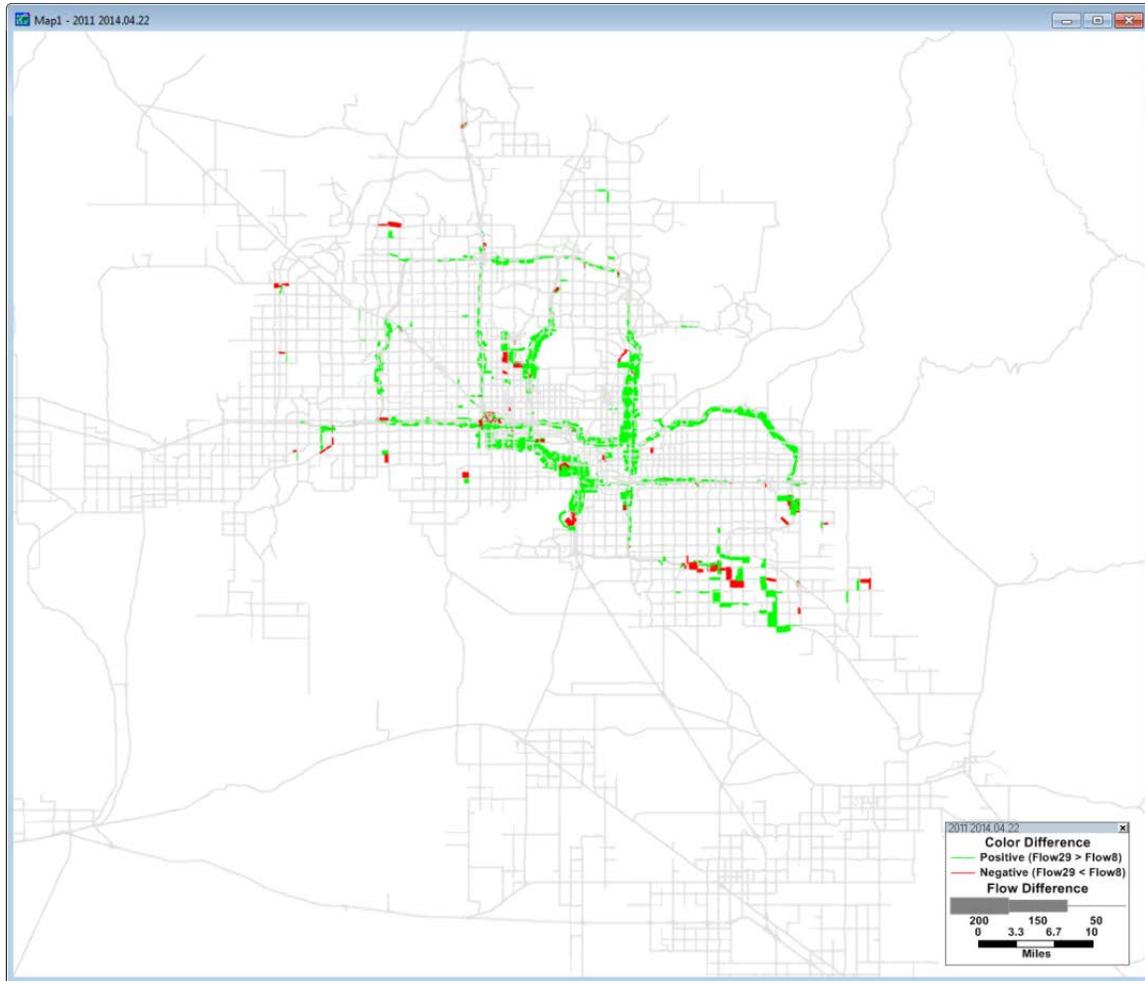
Feedback loop (i)	VMT	$\Delta(\text{VMT}(i)-\text{VMT}(i-1))$	VHT	$\Delta(\text{VHT}(i)-\text{VHT}(i-1))$
1	34,439,464		1,205,384	
2	28,186,067	-6,253,397	825,781	-379,603
3	29,222,733	1,036,666	880,107	54,326
4	29,444,422	221,689	892,475	12,368
5	29,538,199	93,777	897,617	5,142
6	29,592,119	53,920	900,650	3,033
7	29,632,825	40,706	902,827	2,177
8	29,658,799	25,974	904,217	1,390

The estimates of VMT and VHT are clearly very different in early feedback loops and could be quite unreliable. This is one reason why feedback convergence is important.

Ignoring the first loop results, which greatly overstate VMT and VHT due to the use of free flow starting travel times and the resulting massive congestion, after the 8 loops the VMT and VHT estimates are still increasing albeit by a rather small amount.

To get a sense of the errors associated with running only a small number of feedback loops, we increased the number of loops considerably. If we run another 20 loops or so, we find that VMT increases by another 51,069 and VHT by 2,703. If we plot the link flow differences between these two feedback scenarios (loop 28 and loop 8), one can see that estimated traffic levels will be different as shown below, where the green links are the ones with higher flow at the end of loop 28 when compared with flows at the end of loop 8. However, the link flow differences are rather small and are probably not be of consequence.

**Figure 6-7 Flow Differences with an Additional 20 loops of the MAG Model with MSA Link Flow Averaging**



This following table shows the degree of change in link flows, travel time skims, and trip table RMSEs for the same run of the MAG model. As one can see rather small changes in the percentage of link flows do not imply small changes in the trip table RMSE. Similarly, rather small changes in the travel time skims also do not mean that trip tables are not changing.

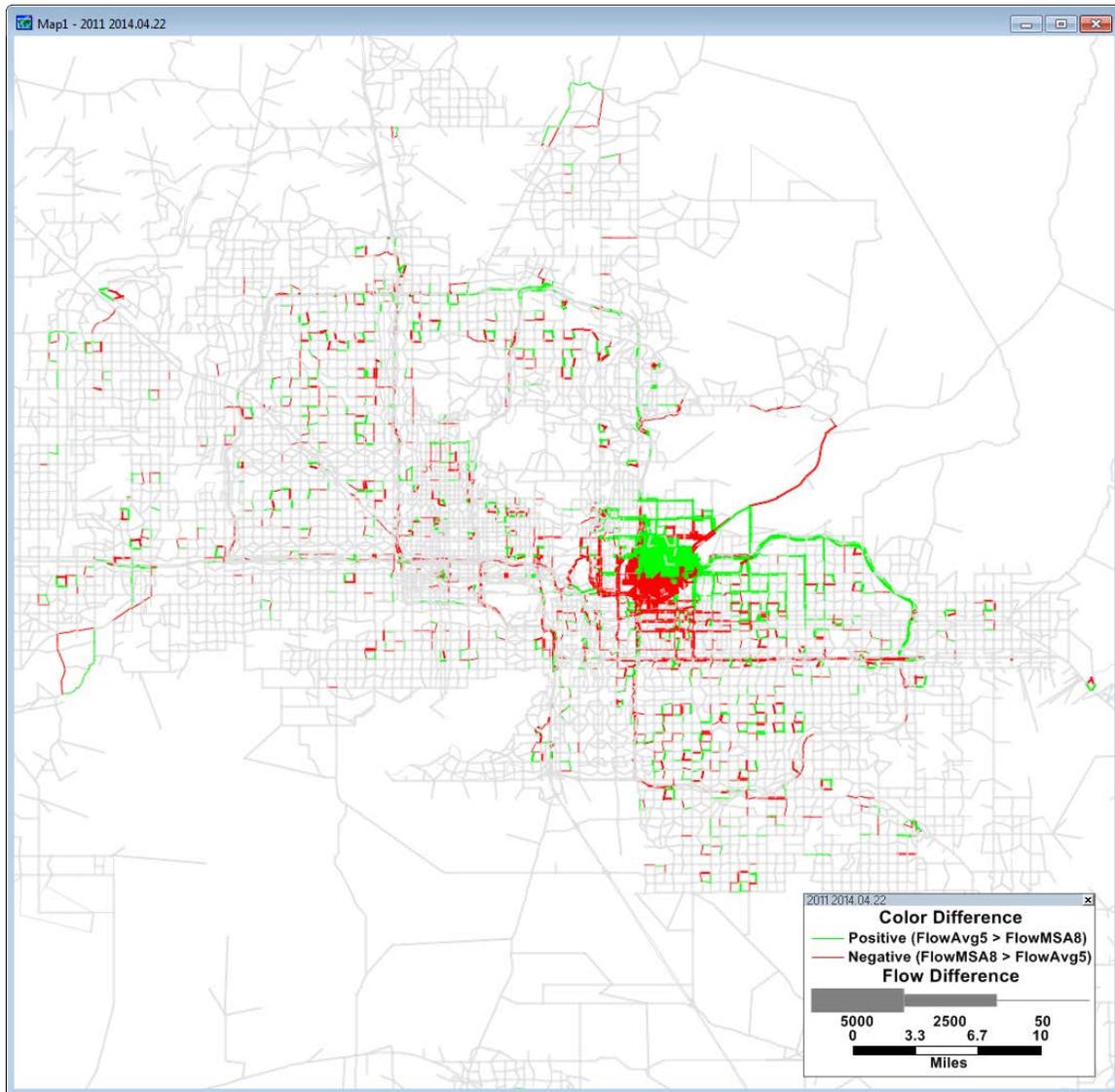
**Table 6-3 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics for the MAG Model**

Feedback_iteration	LOV_SKIM_RMSE	LOV_SKIM_CHANGE	OD_RMSE	OD_CHANGE	FLOW_RMSE	FLOW_CHANGE
2	103.37	88.46	275.77	20.08	51.75	-18.75
3	12.58	10.33	59.61	4.62	13.31	3.98
4	2.84	2.35	18.09	1.11	2.82	0.81
5	1.16	0.96	8.38	0.47	1.28	0.34
6	0.76	0.63	7.66	0.32	0.90	0.19
7	0.50	0.42	5.22	0.23	0.78	0.14
8	0.34	0.28	5.61	0.19	0.70	0.09
9	0.22	0.19	4.05	0.11	0.64	0.05
10	0.15	0.13	2.79	0.09	0.61	0.04
11	0.10	0.08	5.81	0.11	0.59	0.02
12	0.07	0.06	5.78	0.12	0.70	0.03
13	0.05	0.04	3.58	0.07	0.71	0.01
14	0.03	0.03	4.07	0.06	0.68	0.00
15	0.03	0.02	6.07	0.09	0.67	0.01
16	0.02	0.01	6.59	0.09	0.66	-0.01
17	0.02	0.01	4.31	0.08	0.63	0.00
18	0.02	0.01	5.24	0.07	0.66	0.00
19	0.02	0.01	5.81	0.09	0.68	-0.00
20	0.02	0.01	5.33	0.08	0.70	-0.00
21	0.01	0.01	4.04	0.07	0.64	0.00
22	0.01	0.01	4.06	0.06	0.67	0.01
23	0.01	0.01	5.42	0.08	0.64	-0.00
24	0.02	0.01	5.69	0.09	0.67	-0.01
25	0.02	0.01	4.46	0.09	0.60	0.01
26	0.01	0.01	3.90	0.07	0.62	-0.01
27	0.01	0.01	5.63	0.09	0.67	0.00
28	0.02	0.01	5.47	0.08	0.73	-0.00
29	0.02	0.01	4.14	0.06	0.64	0.00

The link flow %RMSE difference is less than the threshold 3.8% after the third loop while the O-D %RMSE is less than that threshold after the 9<sup>th</sup> iteration. One can observe that the O-D %RMSE for each loop is somewhat constant suggesting that the trip table keeps changing as more loops are run. This suggests the need for more stringent closing criteria and many more loops than are used in current practice.

We wondered if the choice of averaging method would be consequential in leading to differences in predicted link flows. To have a brief and preliminary look at this question, we compared the 8th loop of the MSA method and the 5th loop of the ½ flow averaging method after we determined that these loops had somewhat similar travel time skims. A comparison of the link flows appears in the map that follows. As one can see there are noticeable differences in the flow patterns. The %RMSE difference between the link flows for this comparison is 6.38%. Perhaps more importantly, there are geographic differences in the traffic patterns that appear to be associated with the use of different east-west travel corridors. While other and more definitive tests of the role of the method in influencing the outputs should be conducted, we can observe that unlike traffic assignment where computing to the same relative gap gives very similar link flows irrespective of the algorithm used, the same cannot necessarily be said for feedback computations.

**Figure 6-8 Comparison of Flows from MSA and ½ Flow Averaging with the MAG Model**



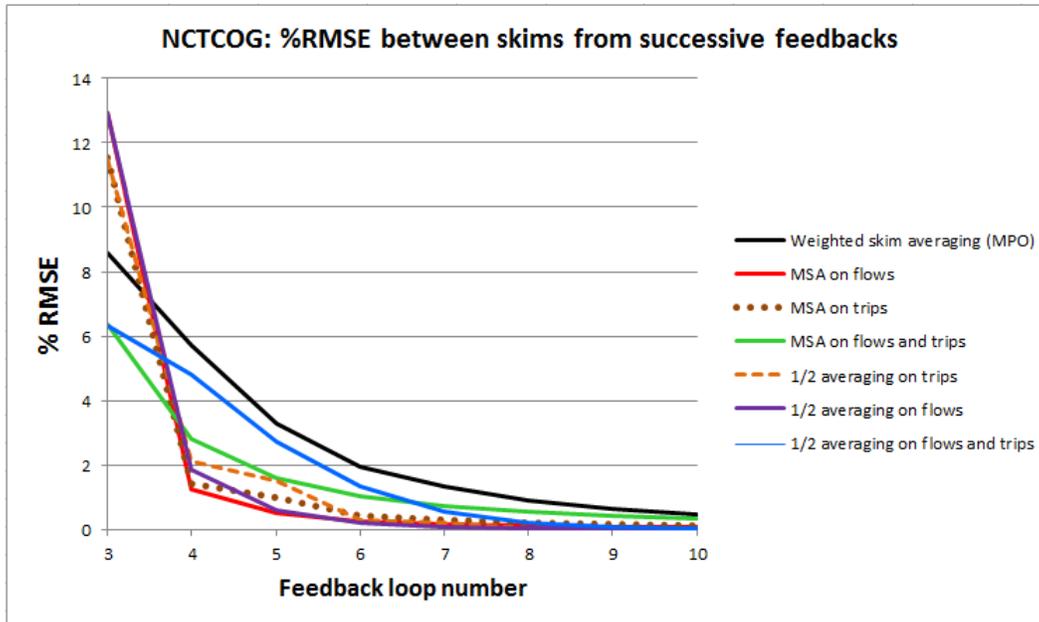
### ***NCTCOG model feedback runs***

We conducted a similar set of analyses with the NCTCOG model. Once again, we ran 10 feedback loops and excluded the first loop from the charts since NCTCOG begins with free flow times. The NCTCOG base model averages skims between feedback loops after assignment using weights of 0.25 for the prior loop and 0.75 for last loop computed. As can be seen, this helps with convergence when comparing %RMSEs between skim matrices, but the method is less effective in reducing link flow or trip table differences.

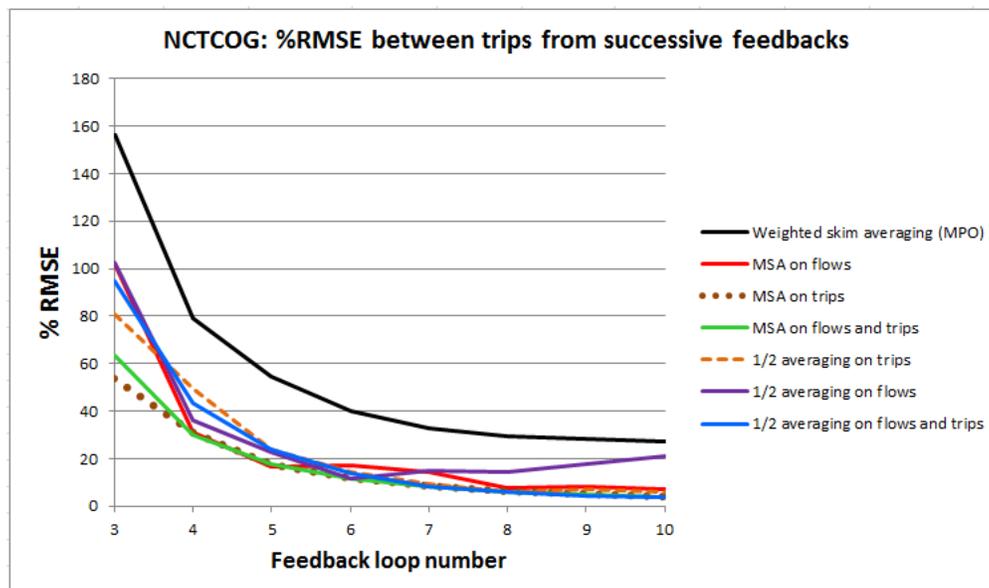
In the plots that follow, the %RMSE differences between skims are for the SOV class while the %RMSE differences between trips and flows are for the PCE weighted combination of the SOV, Shared-Ride, and Truck classes. The metrics compared below are for the AM time period.

The MPO's feedback method of weighted skim averaging is the least effective in terms of achieving very small %RMSE differences in travel time skims. The performance of this method compared to the others does not improve even when %RMSE differences in flows/trips are plotted. When run to a higher number of feedback loops, most of the alternative approaches when applied to the NCTCOG model show similar performance. However, if one were to run the model to a smaller number of feedback loops, the differences in performance would be very apparent. MSA on trip tables, one-half averaging of trip tables and link flows, and MSA on link flows consistently do well on all 6 metrics and in most cases, outperform the other methods.

**Figure 6-9 %RMSE in NCTCOG AM Skims from Successive Loops**

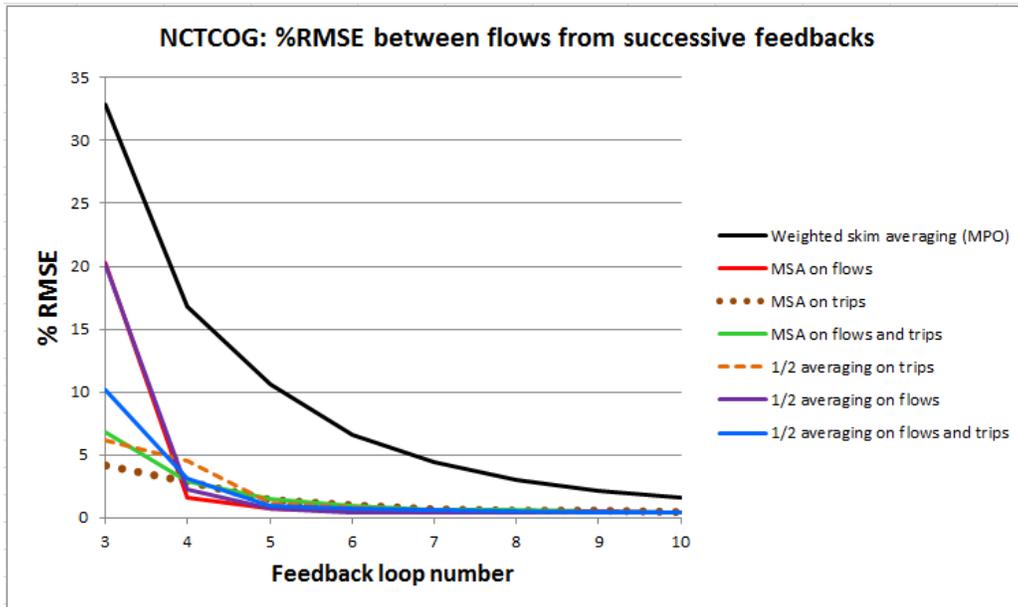


**Figure 6-10 %RMSE in NCTCOG AM Trip Tables from Successive Loops**



As shown in Figure 6-10 above, the %RMSEs between trips is consistently much higher for the weighted skim averaging method than the others. The graph above also indicates that with 1/2 averaging of flows the differences between trip tables actually starts to increase after about 6 feedback loops for this model.

**Figure 6-11 %RMSE in NCTCOG AM Link Flows from Successive Loops**



As shown in Figure 6-11 above, all of the other averaging methods lead to much smaller link flow changes from loop to loop than the weighted skim averaging feedback method.

When examining percentage differences, the weighted skim averaging method used by the MPO displays the largest differences. When flows are averaged and then the congested link times are computed from them, the flows and times are consistent with each other. This does not hold when the skims are averaged directly and that may also lead to larger differences in trip distribution and mode choice.

Figure 6-12 % Change in NCTCOG AM Skims from Successive Loops

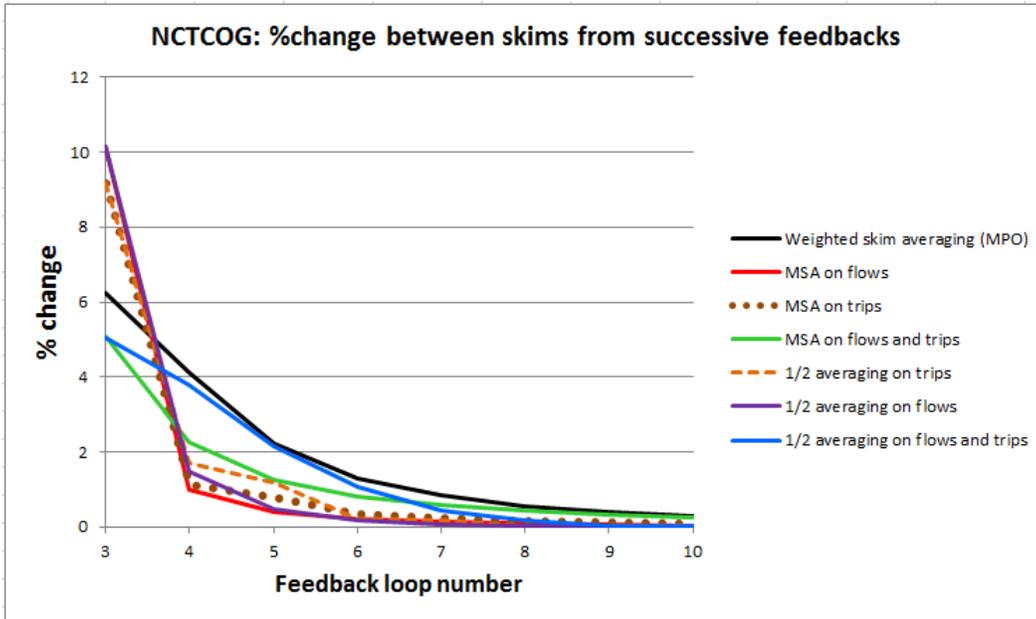


Figure 6-13 NCTCOG percentage changes in trip tables

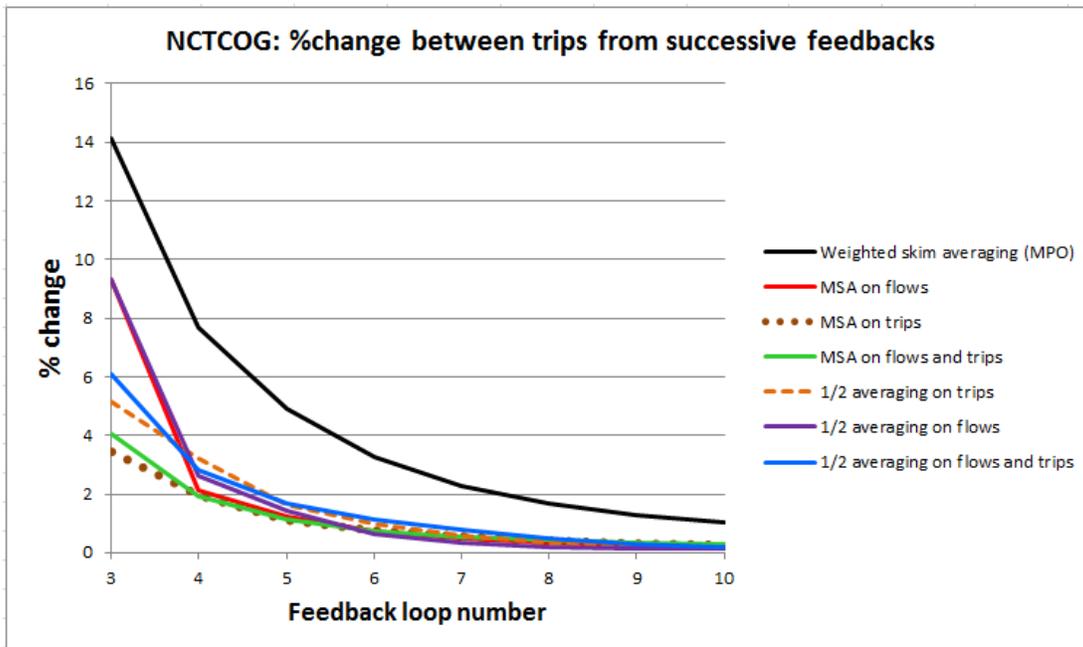
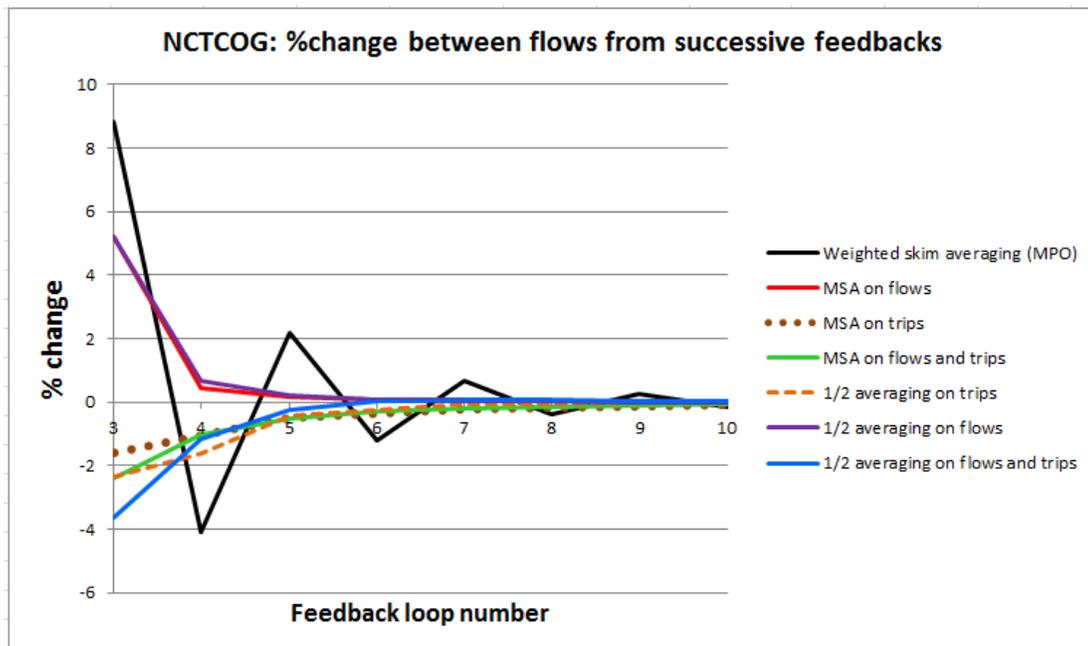


Figure 6-14 NCTCOG percentage changes in link flows



The oscillation in flows that results from using skim averaging to perform feedback is clearly shown in the last plot. This, of course, means that there could be a significant error from premature termination of the feedback process.

Next, we show geographically the differences between flows from the 5th and 10th feedback loops of the NCTCOG model when the weighted skim averaging method was used. The reason the 5th loop was chosen was because the MPO typically uses a fixed number of 5 feedback loops in the base model. The 10th loop flow was chosen to serve as a measure of “converged flow.”

**Figure 6-15 Link flow Differences between the 5th and 10th Feedback Loops for NCTCOG Model with the Weighted Skim Averaging Method**

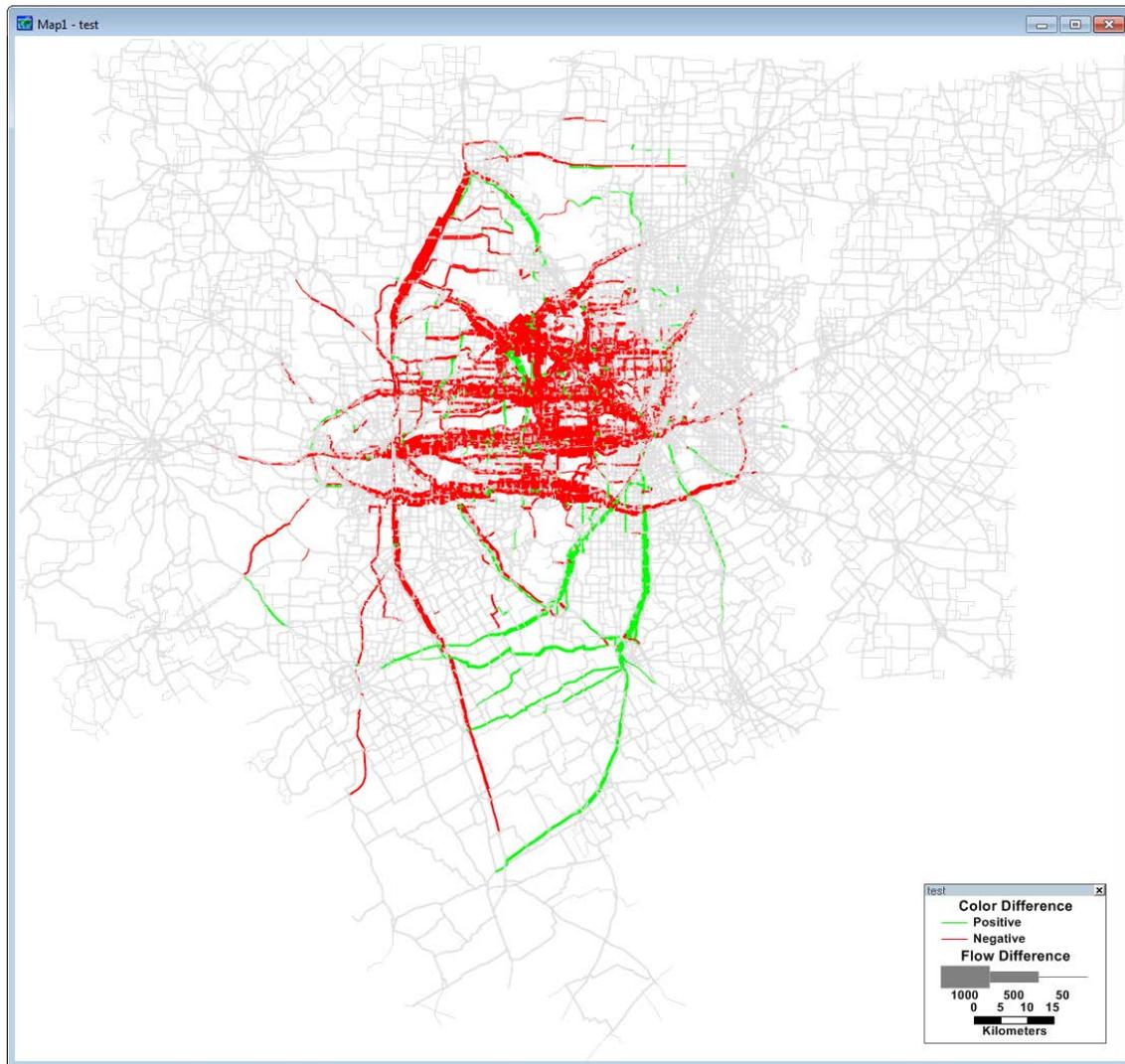
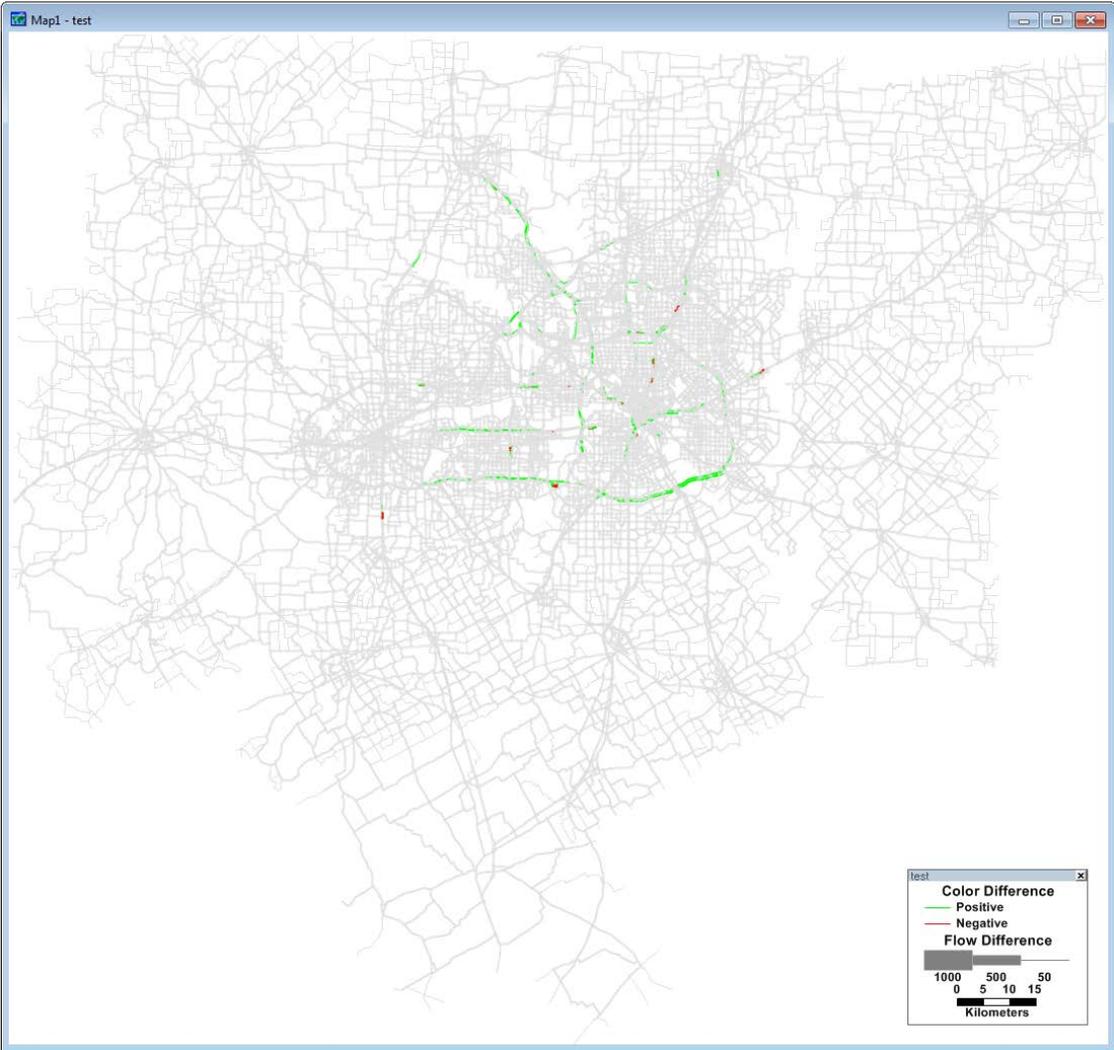


Figure 6-15 illustrates that the link flows after 5 loops of the weighted skim averaging method are significantly different from those obtained after 10 loops. This again highlights the errors that can result from premature termination of feedback.

As a point of comparison we also plotted geographically the differences between the flows from the 5th and 10th feedback loops of the NCTCOG model when the MSA on flows method was used. As seen in Figure 6-16 below, the flows after the 5th loop of the flow MSA method are quite similar to those after the 10th loop which is what one might aim to achieve in a model set to terminate after 5 loops.

**Figure 6-16 Link Flow Differences between the 5th and 10th Feedback Loops for NCTCOG with the MSA on Flows Method**



Changes in VMT and VHT for the NCTCOG model using the MPO's feedback method are shown in the Table below for the first 10 iterations. The oscillation in link flows is reflected in parallel oscillation in regional VMT and VHT.

**Table 6-4 VMT and VHT Changes by Loop for the NCTCOG Weighted Skim Averaging Method**

Feedback loop (i)	VMT	$\Delta(\text{VMT}(i)-\text{VMT}(i-1))$	VHT	$\Delta(\text{VHT}(i)-\text{VHT}(i-1))$
1	39,356,317		1,350,130	
2	32,496,096	-6,860,222	971,559	-378,571
3	35,091,272	2,595,176	1,101,454	129,895
4	33,787,596	-1,303,676	1,029,754	-71,701
5	34,455,154	667,558	1,065,913	36,160
6	34,082,872	-372,282	1,044,803	-21,110
7	34,290,801	207,929	1,056,776	11,973
8	34,167,500	-123,301	1,049,329	-7,447
9	34,240,562	73,063	1,053,901	4,572
10	34,193,905	-46,657	1,050,855	-3,046

The oscillation evident in VHT and VMT is likely to be a characteristic of the skim averaging method and clearly can have artifacts in plan evaluation. Here, too, the use of too few feedback loops will accentuate this problem.

A compilation of the loop to loop changes for 30 feedback loops using the MPO's weighted skim averaging method is given in the Table that follows.

**Table 6-5 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics from the Weighted Skim Averaging Feedback Method for the NCTCOG Model**

Feedback_iteration	LOV_SKIM_RMSE	LOV_SKIM_CHANGE	OD_RMSE	OD_CHANGE	FLOW_RMSE	FLOW_CHANGE
1	46.45	38.58	466.64	30.44	52.30	-18.80
2	8.57	6.23	156.97	14.14	32.82	8.83
3	5.72	4.13	79.24	7.71	16.85	-4.11
4	3.28	2.22	54.48	4.88	10.61	2.20
5	1.96	1.28	40.06	3.27	6.57	-1.20
6	1.33	0.85	33.03	2.28	4.40	0.68
7	0.89	0.55	29.63	1.67	3.05	-0.40
8	0.64	0.39	28.11	1.28	2.20	0.24
9	0.47	0.27	27.09	1.03	1.65	-0.15
10	0.36	0.20	25.92	0.85	1.31	0.10
11	0.28	0.15	25.65	0.71	1.07	-0.07
12	0.22	0.11	19.04	0.60	0.87	0.04
13	0.17	0.09	25.87	0.51	0.73	-0.02
14	0.14	0.07	24.85	0.46	0.67	0.01
15	0.12	0.06	24.25	0.40	0.60	-0.01
16	0.09	0.04	23.12	0.34	0.55	0.00
17	0.07	0.03	23.61	0.32	0.54	0.00
18	0.06	0.03	26.24	0.30	0.50	-0.00
19	0.05	0.03	25.56	0.28	0.48	0.01
20	0.05	0.03	21.78	0.27	0.53	-0.01
21	0.05	0.02	17.08	0.26	0.60	0.01
22	0.04	0.02	16.76	0.26	0.53	-0.00
23	0.04	0.02	17.29	0.26	0.60	-0.00
24	0.05	0.03	25.13	0.29	0.53	-0.00
25	0.05	0.03	22.44	0.28	0.51	0.00
26	0.05	0.02	24.38	0.27	0.50	-0.01
27	0.04	0.02	23.77	0.25	0.44	0.00
28	0.04	0.02	23.48	0.26	0.46	-0.00
29	0.04	0.02	23.56	0.26	0.45	0.00
30	0.04	0.02	21.70	0.26	0.48	-0.01

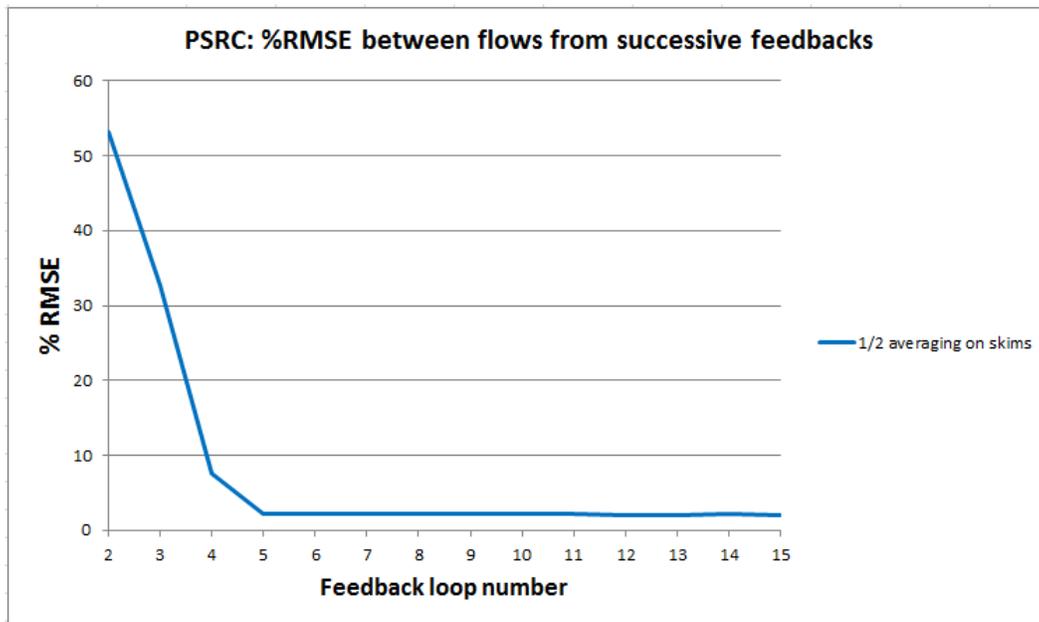
One can observe that even though the flow changes are very small there are still some changes in the trip table after 30 loops.

### **Feedback in the PSRC model**

PSRC was able to provide us with the %RMSE on flows between feedback loops with the number of loops set to 15. They do not save skims and trip matrices at each feedback loop. PSRC averages travel time skims between loops and runs 5 feedback loops in their regular model. There is no flow averaging performed.

The plot for the AM period in the Figure below indicates that the link flow %RMSE change stagnates after the 5th feedback loop and never goes below 2%.

**Figure 6-17 %RMSE in PSRC Link Flows from Successive Loops**



PSRC rounds their O-D trip matrices prior to assignment, so that is possibly why the link flow differences are constant after 5 iterations

### **Feedback runs with SANDAG activity-based model**

To maintain consistency with the prior analyses for MAG and NCTCOG, we similarly ran the SANDAG model to 10 feedback loops and excluded the first loop from the plots that follow. Once again, the %RMSE differences between skims are for the SOV class while the %RMSE differences between trips and flows are for the PCE weighted combination of the SOV, Shared-Ride and Truck classes.

The SANDAG activity-based model contains a significant stochastic element, which is apparent in the feedback tests below. While in the base model the first 3 loops are at 20%, 50%, and 100% sampling of the population synthesis model, for the purpose of feedback testing all the loops were run with a 100% sample. The metrics compared below are for the AM time period. The MPO employs MSA on link flows as its feedback approach and does so without using an explicit closure metric.

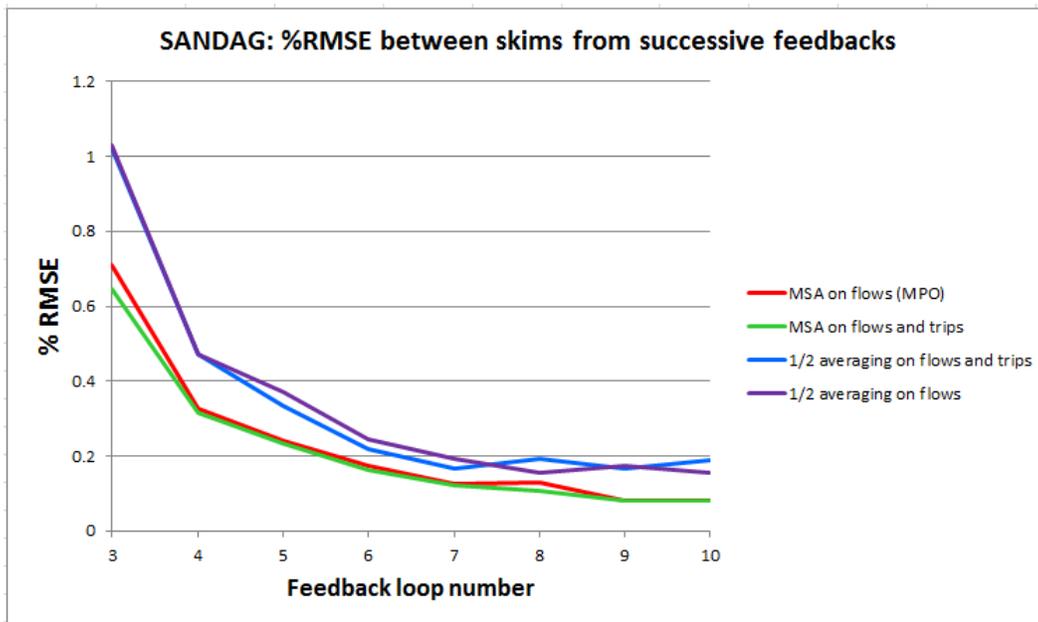
Examining Figure 6-18, one can note that the differences between successive skims are small in absolute terms for the SANDAG model. This is not surprising given that the SANDAG model uses congested travel times from previous model runs in its initial feedback loop.

The differences in the trip table %RMSE and in the link flow %RMSE are very large, both in absolute terms and in comparison to other models. We believe that this is due to the stochastic nature of the SANDAG ABM and if that is the cause, it would suggest that it may be very difficult or impossible to achieve feedback convergence with these models.

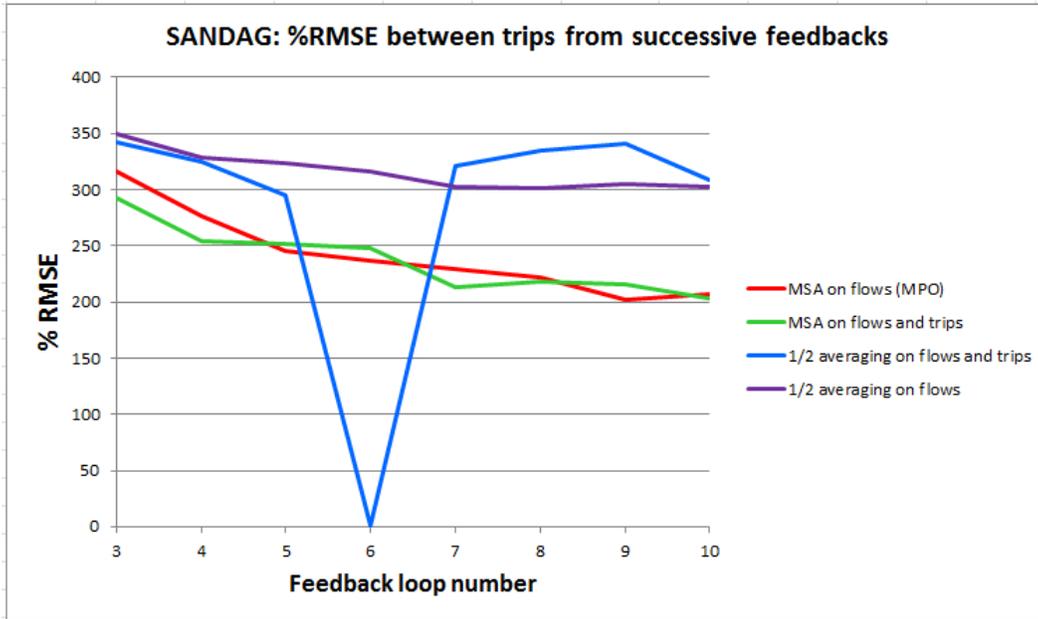
Scanning across the charts, MSA on flows and MSA on flows and trips seem to achieve the smallest loop to loop changes when compared to the other methods. One-half averaging of flows for both flows and trips seems ineffective by comparison.

Irrespective of method, it does not appear that the SANDAG ABM model achieves a reasonable degree of feedback stability or convergence.

**Figure 6-18 %RMSE between SANDAG AM Travel Time Skims from Successive Loops**



**Figure 6-19 %RMSE between SANDAG AM Trip Tables from Successive Loops**



In the figure above, the apparent drop to zero at the 5th loop for the method averaging flows and trips isn't actually zero. It's a very small change of a 1.24 %RMSE.

**Figure 6-20 %RMSE between SANDAG AM Link Flows from Successive Loops**

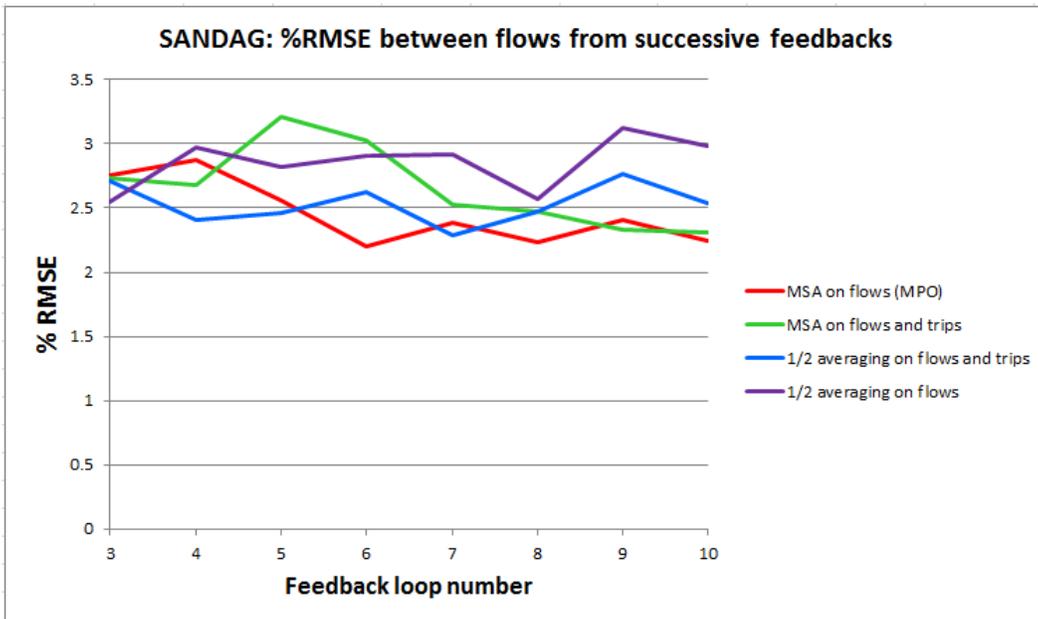


Figure 6-21 % Differences between SANDAG AM Travel Time Skims from Successive Loops

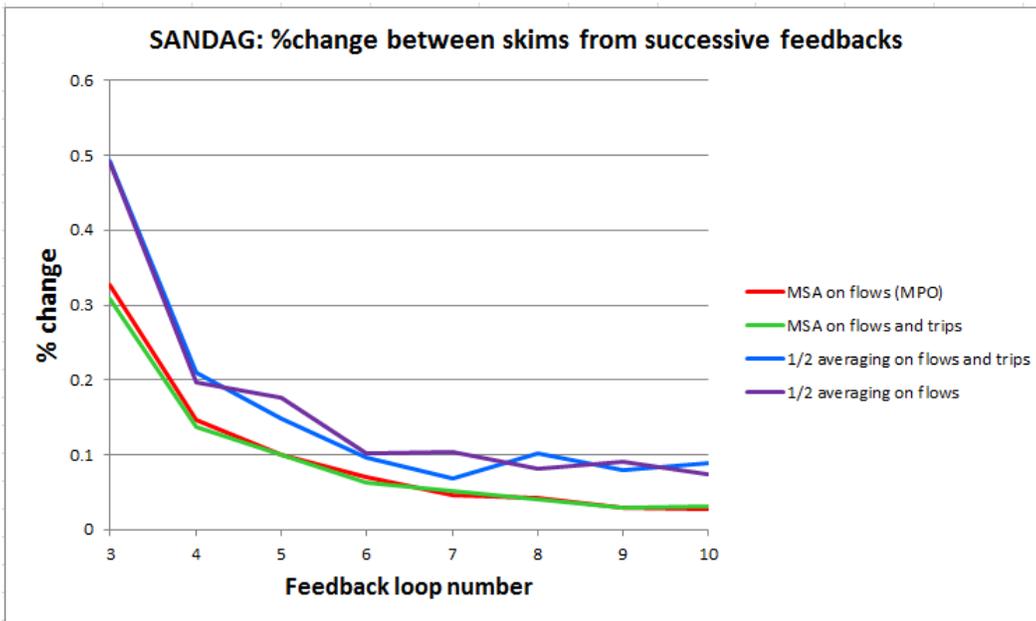
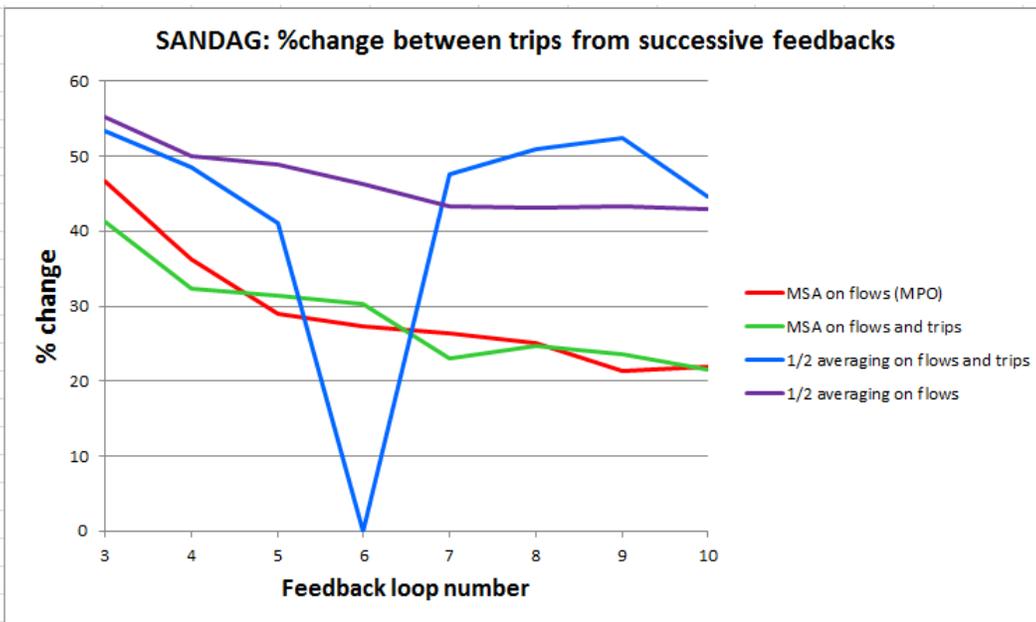
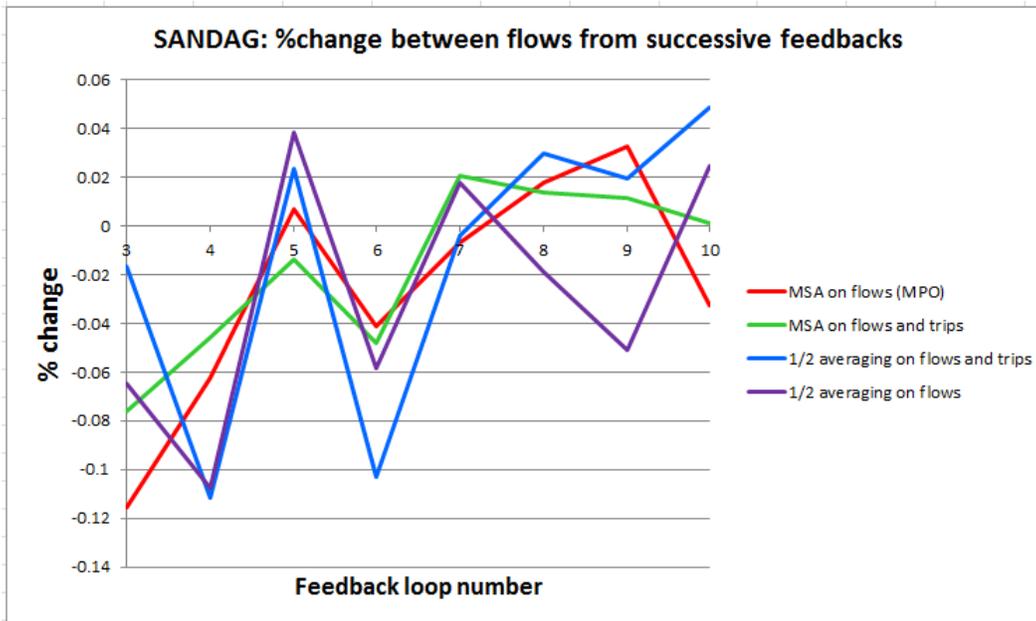


Figure 6-22 % Change between SANDAG AM Trip Tables from Successive Loops



**Figure 6-23 % Change between SANDAG AM Link Flows from Successive Loops**



The higher variation of trips for SANDAG compared with the other MPOs may be due to the nature of their ABM model. Even when random starting seeds are fixed, the different levels of congestion encountered for each feedback loop may lead to different and stochastic outcomes in the choice models. Also, the SANDAG ABM contains time-of-day models that are sensitive to congestion while the other trip-based models model time of day as a fixed component. The variation in time of day trips based on congestion levels may lead to variations in AM trip O-D matrices and link volumes.

Below, we tabulate the changes in skims, trip tables, and link flows by loop for a 30-loop run of the SANDAG ABM computed using MSA on the link flows. As one can see, even when the changes in skims are very small there are still significant changes in trip tables from loop to loop.

**Table 6-6 Loop by Loop Skim, Trip Table, and Link Flow Change Statistics for the SANDAG Model**

Feedback_iteration	LOV_SKIM_RMSE	LOV_SKIM_CHANGE	OD_RMSE	OD_CHANGE	FLOW_RMSE	FLOW_CHANGE
2	1.69	0.87	372.78	61.93	15.78	1.96
3	0.71	0.33	315.98	46.59	2.75	-0.12
4	0.33	0.15	275.81	36.16	2.87	-0.06
5	0.24	0.10	245.89	29.00	2.56	0.01
6	0.17	0.07	236.55	27.26	2.20	-0.04
7	0.12	0.05	228.94	26.33	2.39	-0.01
8	0.13	0.04	222.24	25.16	2.24	0.02
9	0.08	0.03	202.29	21.30	2.41	0.03
10	0.08	0.03	206.81	21.92	2.25	-0.03
11	0.08	0.02	211.11	22.71	2.48	-0.01
12	0.06	0.02	213.84	22.86	2.05	0.02
13	0.06	0.02	171.04	15.58	2.46	-0.06
14	0.05	0.02	181.35	16.75	2.17	0.01
15	0.06	0.02	186.18	18.15	2.15	0.04
16	0.05	0.01	179.22	16.19	2.14	0.00
17	0.05	0.01	183.48	17.67	2.25	-0.01
18	0.04	0.01	18.96	0.12	2.58	-0.01
19	0.06	0.01	203.67	21.56	2.48	-0.02
20	0.04	0.01	129.71	9.12	2.53	-0.01
21	0.04	0.01	148.60	11.80	2.46	-0.01
22	0.04	0.01	161.96	13.79	2.31	0.03
23	0.03	0.01	123.11	8.15	2.47	-0.05
24	0.03	0.01	14.43	0.10	2.25	0.03
25	0.03	0.01	205.46	21.95	2.16	0.01
26	0.03	0.01	137.21	10.03	2.58	-0.00
27	0.02	0.01	179.84	17.14	2.34	-0.02
28	0.03	0.01	139.21	10.61	2.25	0.02
29	0.03	0.01	161.30	13.52	2.29	-0.02
30	0.03	0.01	172.16	15.57	2.21	0.05

In this case of an ABM, it appears that small changes in some metrics may not be sufficient for achieving model consistency if other metrics are still changing considerably. Also, we observed that the changes in VMT and VHT did not continuously decline as they do in trip-based models. This can be seen from inspection of Table 6-7 below.

**Table 6-7 SANDAG ABM VMT and VHT Differences by Feedback Loop (with MSA on flows)**

Feedback loop (i)	VMT	$\Delta(VMT(i)-VMT(i-1))$	VHT	$\Delta(VHT(i)-VHT(i-1))$
1	16,524,632		473,987	
2	16,956,810	432,178	491,789	17,802
3	16,939,370	-17,440	491,091	-697
4	16,929,713	-9,657	490,501	-590
5	16,929,080	-633	490,235	-266
6	16,918,752	-10,328	489,858	-377
7	16,920,743	1,992	489,795	-63
8	16,925,224	4,481	489,967	173
9	16,927,425	2,200	490,123	155

We are not sure whether all of these findings are purely the result of the ABM formulation or might be attributable to other factors. Clearly, some further examination will be required to understand the consequences of feedback in this and other ABM implementation. To be fair, we remind readers the SANDAG ABM was under development when these tests were being performed, so these results may not pertain to its final form.

## Conclusions

---

The portrait that emerges from this analysis is not especially encouraging with respect to current model forecasts, as it appears that the models examined provide answers that will change with the computation of additional feedback loops. Nevertheless, it seems that there is no fundamental barrier to computing tighter solutions in terms of input and output congested skims or other measures, at least in trip-based models.

Our analysis suggests that explicit feedback closure criteria should be used and inspected as part of the modeling process. Clearly, it is not always obvious how variable the model outputs will be without some empirical analysis. Also, it appears that the model results will depend upon and will not be independent of the means of generating those results. This requires that we accept the fact that whatever solution we arrive at is conditional upon many factors including the measures averaged, the averaging method, the traffic assignment convergence, and other aspects of the multi-stage model such as the trip distribution and mode choice models.

Deployed models including the 5 MPO models we examined in detail use very loose closure criteria for feedback. Our analysis also suggests that tighter closure is warranted and is achievable. Stopping when the link flows are still changing 1% a loop can be quite insufficient. Also, we have seen that even when the congested skims are changing .01 % a loop might not guarantee that a stable solution has been reached.

Beginning the models with very good prior estimates of congested travel times will reduce the number of feedback loops required to meet closure criteria. Apart from that we doubt that there is a dominant feedback method appropriate for all models and suggest that the choice of feedback method be empirically determined. There is rather little if any research on the effectiveness of feedback methods beyond 10 or 20 feedback loops, but it is for more highly converged models that the choice of method will be most interesting. As before, we stress that external validation should be part of the process of judging feedback practices and outcomes.

There is considerable scope for further research and testing on appropriate feedback strategies for regional models. We did not pursue the topic of tradeoffs between assignment convergence and feedback stability, but this is certainly worth investigating. While there might be some computational efficiency in using lower levels of assignment convergence in early loops, it may be safer to use tight convergence all the time.

There was clear indication that activity-based models may pose new issues for feedback approaches. Apart from stochastic behavior that might preclude achieving comparable travel time skims between inputs and outputs, some methods like trip table averaging may not make any sense at all with an ABM.

In thinking about feedback, we would like to distinguish between closure metrics that are the stopping criteria used and convergence, which is the difference between a current solution and the estimated eventual solution if the computations were carried out sufficiently further.

Our examination of the FW traffic assignment showed that its convergence tailed at a certain point and that this leads inevitably to differences in link flows that are in some sense tied to the FW algorithm rather than any property of the user equilibrium solution. By analogy, it seems likely that feedback practices also leave their imprint on the solutions generated such that we would expect, and we find differences in the traffic flows, congested speeds, and VHT estimates that are clearly associated with the means of generating them.

If we accept the fact that different feedback methods will lead to different answers, we might consider that speed of convergence may be less important than the quality of the solution reached. In that regard, we return to the point that models need to be about external predictive validity, and therefore many modeling choices may ultimately have to be judged in terms of forecasting ability and not simply internal metrics.



# Chapter 7

## Project Impact Analysis

Ultimately, we are interested in the ability of travel demand models to produce useful forecasts of the impacts of various highway and transit improvement projects. In this chapter, we examine a variety of projects taken from MPO long-range plans with a view to understanding if the models produce plausible forecasts. While models are not always used to evaluate single projects, it is unreasonable to think that they will be adequate predicting the effects of numerous projects at once if they do not produce plausible results for individual components of an overall plan.

The general procedure we employed was to compare matched sets of model runs with and without a project, and then to run the models in stages ranging from a single traffic assignment, to a single model loop, and then to a model with feedback loops. This was done for both highway and transit projects. The traffic assignments were all run to a convergence level of 1.E-4 or a lower relative gap as a point of reference as this is achievable and has been suggested as a sufficient level of User Equilibrium (UE) convergence for modeling. While we did not use lesser convergence levels, we are confident that they would be characterized by a considerable additional amount of error and therefore would not be of great interest for this research.

It should perhaps be emphasized that this research is enabled by the availability of traffic assignment algorithms that are able to reach high levels of convergence. Now that these methods are available, we are able to study model behavior in ways not previously possible.

We did not pick projects in areas where the models had the largest convergence errors, nor did we avoid them. We simply picked without reference to the model characteristics or results. A worst case analysis could be performed, but we leave that to others.

This analysis leans most heavily on the three MPO models that we were able to run completely on our own. We asked ARC and PSRC to make similar runs for us, but they did not have the time and resources to run the same tests that we performed for the other MPOs. As we have noted previously, we used versions of the models that we prepared and updated, so our results are not necessarily indicative of those that the MPO models would produce. For each of the 3 MPOs, we analyzed at least one highway project and one transit project. For ARC, we analyzed a roadway project using a TransCAD version of their traffic assignment with some modification. PSRC made some model runs for us for a project that we specified.

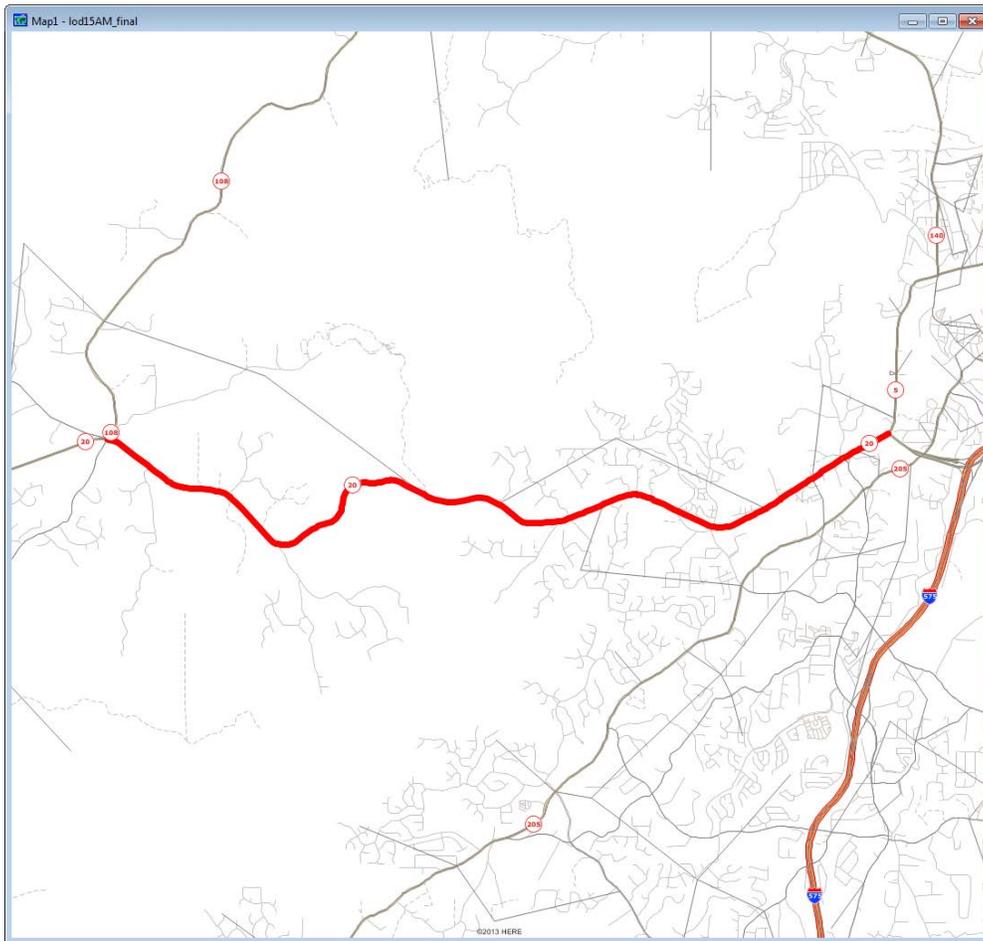
For the project evaluations that involved feedback, we used the feedback approach that was being used by the MPO and not the alternatives that we used in the work reported in the last Chapter.

In this chapter we faithfully present the results of each analysis. The purpose is to document not only the individual results, but to build the case for conclusions that apply more broadly to impact analysis and modeling procedures with MPO models.

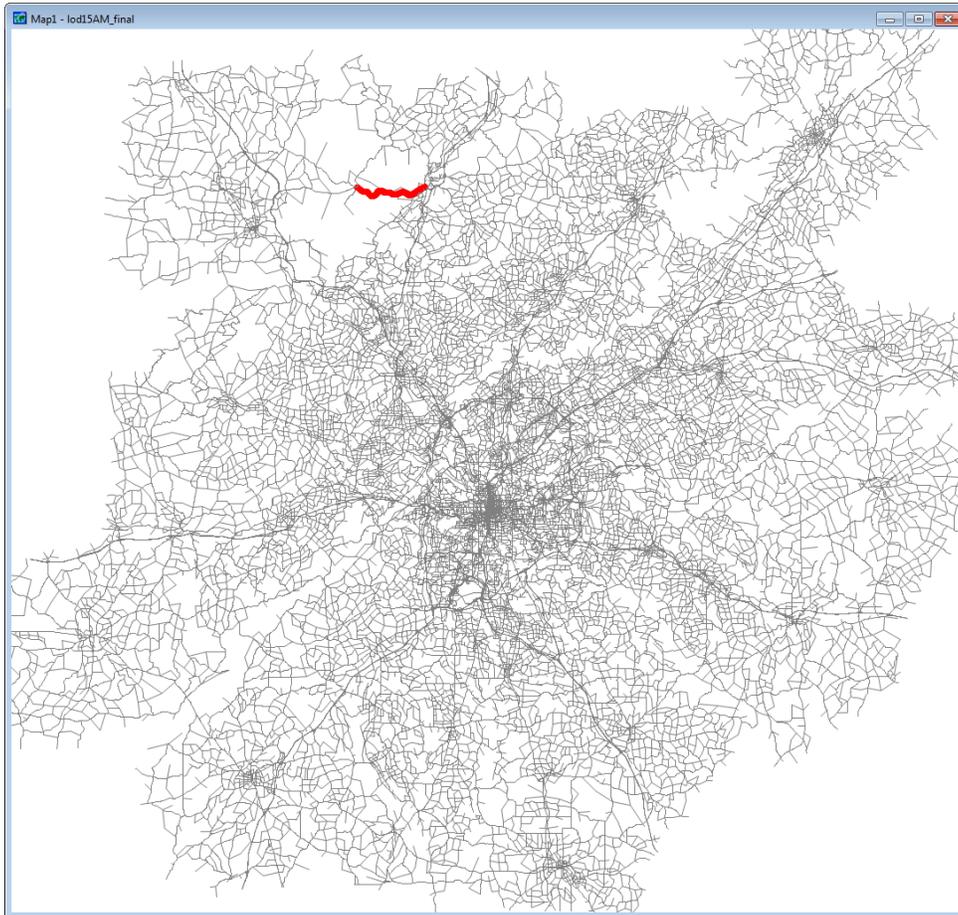
## Impact of a Roadway Project in Atlanta

For most of the duration of our project, the ARC model was being actively changed. Due to its state of flux, we did not attempt to run the Atlanta ABM model. Instead, we obtained the assignment scripts, networks, matrices, and output flows for the base year scenario from the MPO and implemented the assignment model in TransCAD. Once we had achieved a reasonably close match to the ARC results, we coded a future year highway project into the network. The project chosen was part of a 2040 scenario and involved the widening of an arterial SR20 from 1 to 2 lanes in each direction on the section connecting SR108 and I-575. We then compared the assigned AM flows with and without the project. The extent and location of the project are shown in the maps that follow.

**Figure 7-1 Roadway Project on SR20 Connecting SR108 and I-575 in the ARC Region**



**Figure 7-2 Roadway Project Location and Extent in the ARC Network**



The ARC's base year model uses an assignment convergence level of 1.E-4 relative gap, but does not converge below .0002 when ARC runs it. As described in Chapter 4 and 5, we changed the volume-delay curve to apply the same function that is used for volume-to-capacity (V/C) ratios below 1 to V/C ratios over 1. After this change was implemented, our version of the assignment converges to lower relative gaps. We then proceeded to perform the comparative analysis using the path-based assignment method in TransCAD.

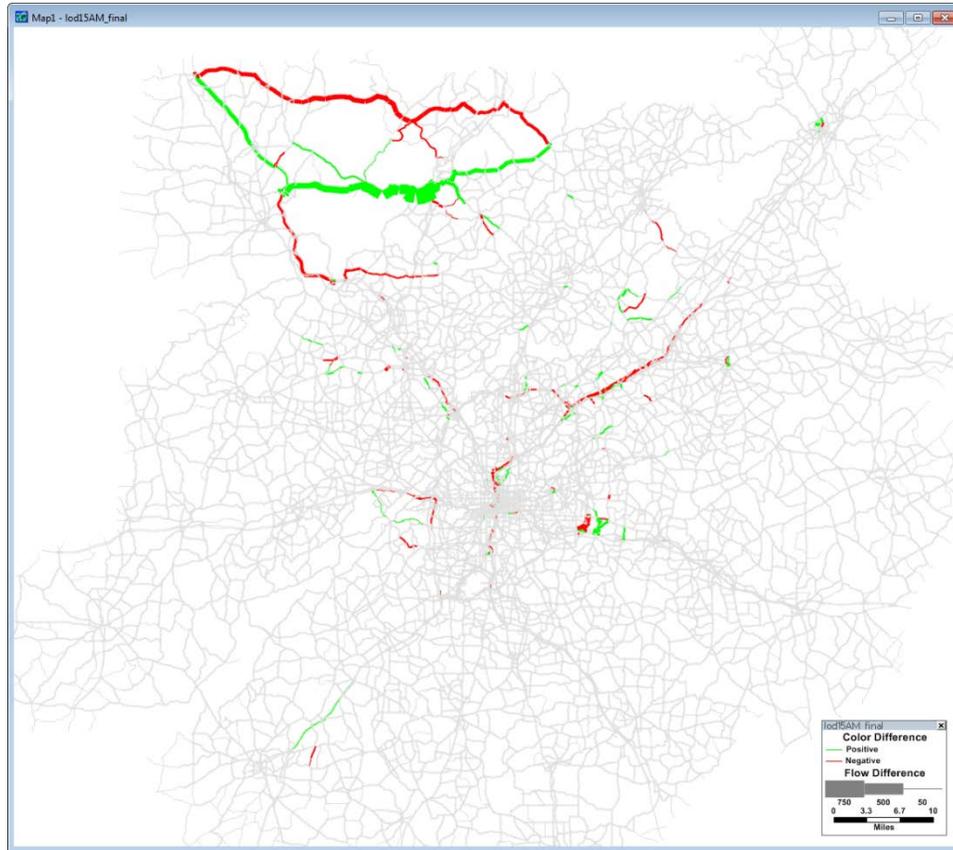
The impact of the project as computed with traffic assignments to 1.E-4 convergence is illustrated in the Figure that follows. The flow differences in the map are highlighted in green for links that gained 50 or more trips and in red for links that lost 50 or more trips. The width of the lines is scaled as a function of the magnitude of the flow change as indicated in the map legend.

The flow changes are indicative of diversion to the added highway links which gain flow that is taken from other generally parallel links. However, some of the changes are rather far away from the project and would appear to be spurious.

In the figure below we tabulate the maximum and average flow differences calculated both in the vicinity of the project and elsewhere in the network. We also calculate the changes in vehicle miles traveled (VMT) and vehicle hours traveled (VHT) that we associate with the project based upon the analysis.

The project is estimated to produce a savings of 226 vehicle hours of travel for the AM period, and also leads to a reduction in vehicle miles of travel. However, some of the highway flow changes occur far from the vicinity of the project and seem implausible as consequences of the project.

**Figure 7-3 Flow Differences in the ARC Network at 1.E-4 Convergence**

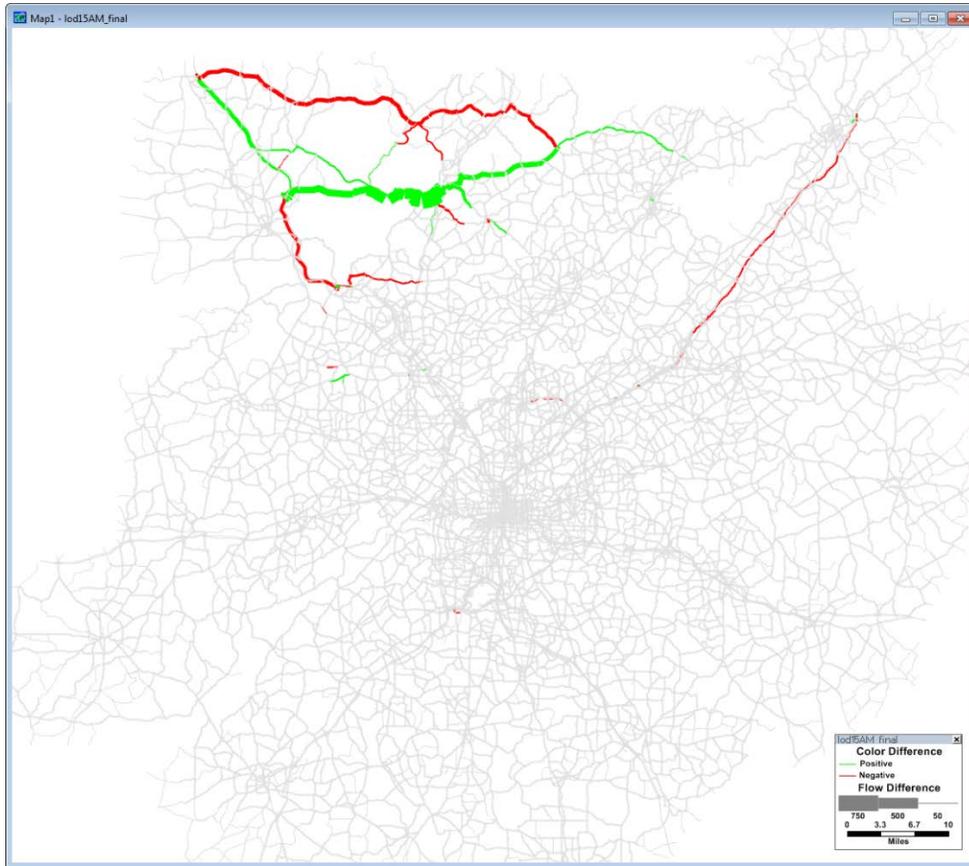


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	718.22	18.70
Outside the vicinity of project	254.34	6.87

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	39,948,574	1,241,955	3,452,881
After project added	39,948,318	1,241,729	3,452,881
$\Delta$ (Project-base)	-256	-226	0

In the next two figures, we map the results for the same analysis but performed for each of two higher orders of magnitude convergence in the relative gap.

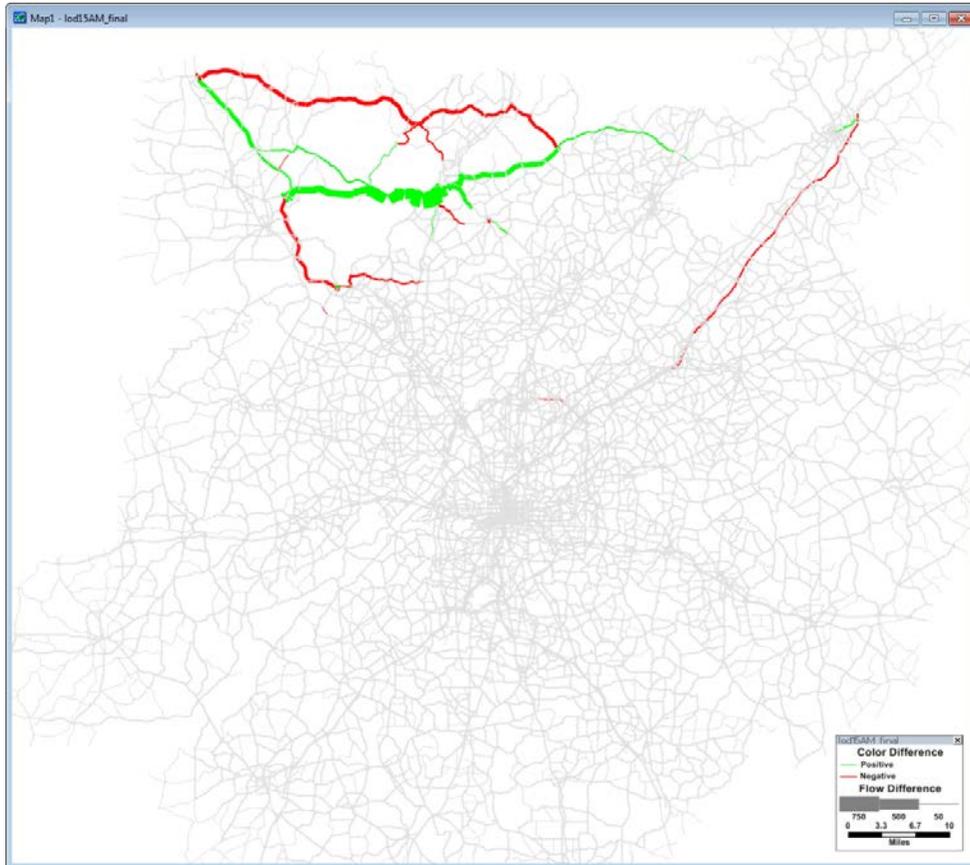
**Figure 7-4 Flow Differences in the ARC Network at 1.E-5 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	779.43	18.78
Outside the vicinity of project	179.40	2.76

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	39,946,450	1,241,580	3,452,881
After project added	39,945,636	1,241,290	3,452,881
$\Delta$ (Project-base)	-814	-290	0

**Figure 7-5 Flow Differences in the ARC Network at 1.E-6 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	777.26	18.55
Outside the vicinity of project	179.32	1.29

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	39,946,163	1,241,580	3,452,881
After project added	39,945,428	1,241,305	3,452,881
$\Delta$ (Project-base)	-735	-275	0

We observe that the results differ somewhat in the more converged traffic assignments and that the spatial impacts are more localized than in the first impact calculation.

The following table summarizes the analysis of the highway project impacts using our version of the ARC assignment model. Each row gives the changes in VMT and VHT for the three listed convergence levels, respectively.

**Table 7-1 ARC Network Highway Project Impact Summary**

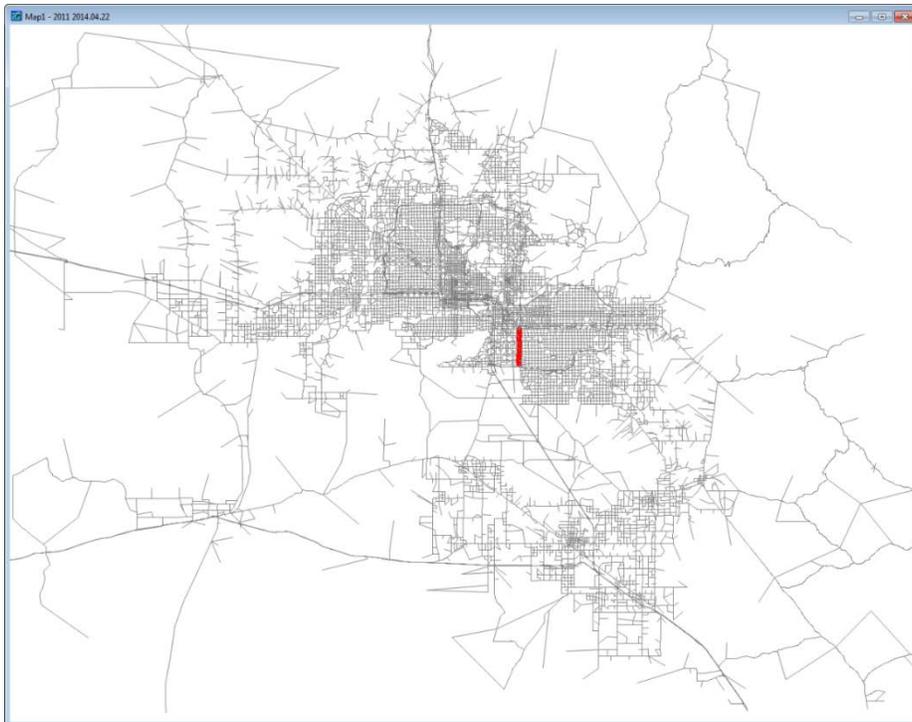
Highway assignment convergence	Type of model run	Δ AM VMT (Project-base)	Δ AM VHT (Project-base)	Δ AM Highway trips (Project-base)
1.E-4	ARC Highway AM assignment only	-256	-226	0
1.E-5	ARC Highway AM assignment only	-814	-290	0
1.E-6	ARC Highway AM assignment only	-735	-275	0

While the VHT savings from the project are similar at the three convergence levels, the VMT savings at a relative gap of 1.E-4 are about a third of those estimated from an assignment to 1.E-6. In this case, the level of convergence definitely influences the estimated impact of the project.

## Impact of a Roadway Project in Phoenix

We next analyze the effect on flows of adding a highway improvement project to the 2011 MAG base year model network. The future-year highway project is from the MAG's 2025 plan network, and it involves the addition of a lane in each direction on sections of the AZ 101 freeway. The location and extent of the project in the MAG's network is highlighted in red below.

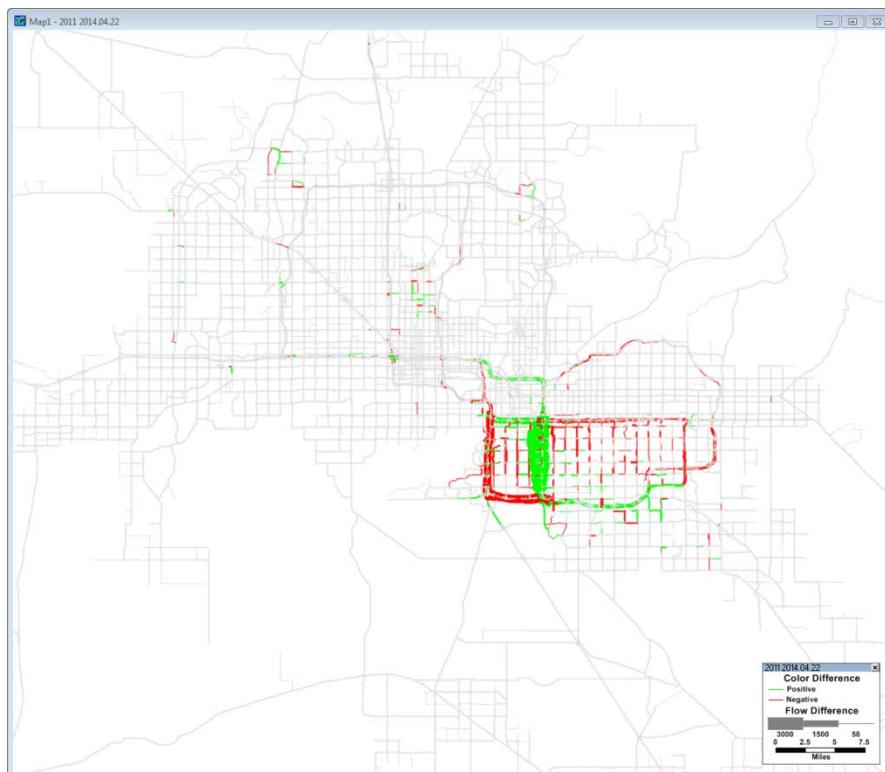
**Figure 7-6 Roadway Project Scope in MAG Network**



We ran the MAG PM highway assignment with and without the project added using the input origin-destination (O-D) matrix corresponding to the base year demographics in both cases. The PM highway assignment was chosen to enable better comparison with the results from the full model run, which uses the PM flows to determine feedback convergence. The highway assignment was performed to three convergence levels.

Below we show the highway flow differences on the map using the same graphic convention as before by highlighting in green the links that had flow increase by 50 or more vehicles and in red links that lost flow of 50 or more vehicles. As one can see, the highway project attracted considerable flow that was diverted from other links. The width of the colored links indicates the level of flow as specified in the map legend. Based upon this analysis, there is a 1000+ VHT improvement due to the project and also an increase in VMT. The before-and-after summary statistics and comparisons are shown in the table below the map.

**Figure 7-7 Highway Flow Differences in the MAG Network at 1.E-4 Convergence**

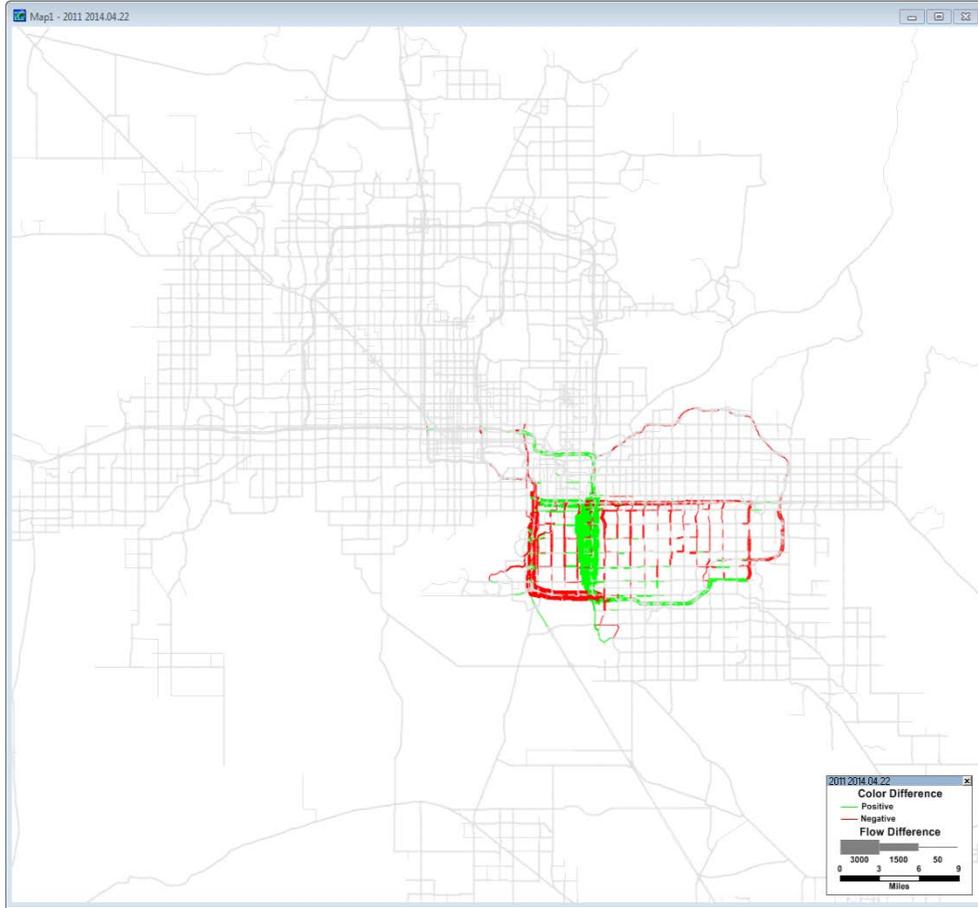


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3523.11	70.04
Outside the vicinity of project	321.35	8.57

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	29,428,727	890,252	3,547,115
$\Delta$ (Project-base)	+2,827	-1,117	0

There is some noise or spurious error evident in the traffic assignment in that there are changes in flows on links rather far removed from the likely impact areas. These remote changes largely disappear when the assignment is run to an order of magnitude greater convergence with a relative gap of 1.E-5, as shown in the Figure below. Overall, the VHT and VMT impacts are roughly the same as in the assignment run to the 1.E-4 lower relative gap.

**Figure 7-8 Highway Flow Differences in the MAG Network at 1.E-5 Convergence**

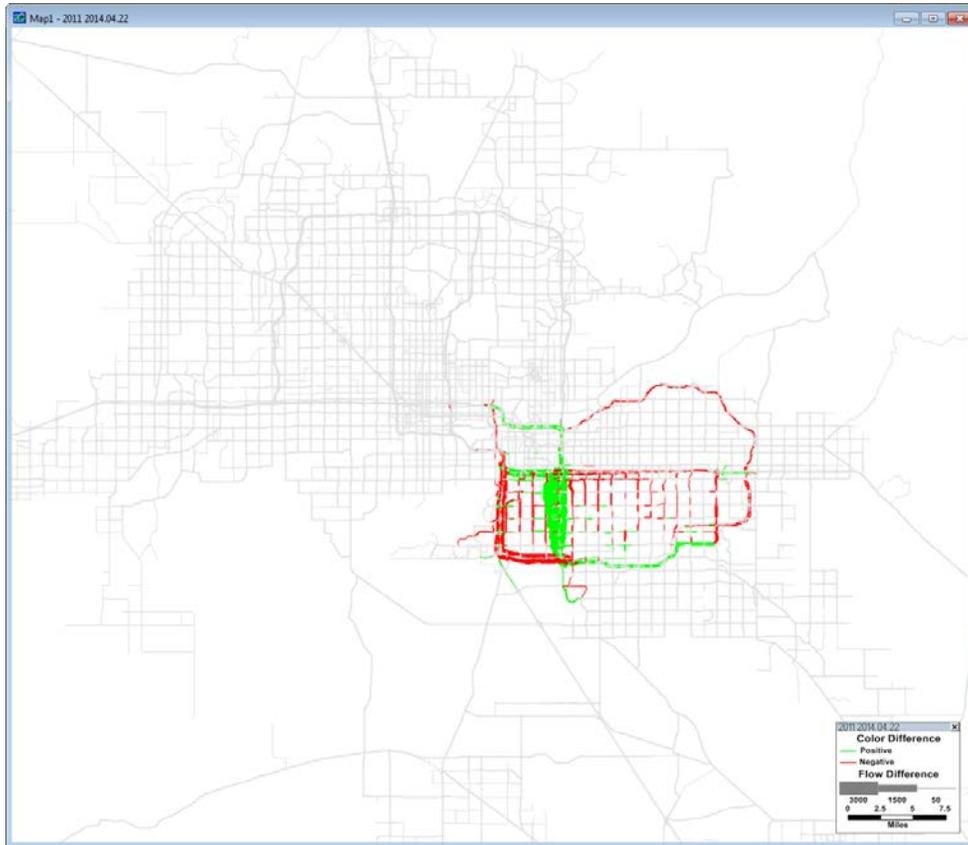


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3526.20	67.46
Outside the vicinity of project	285.68	3.71

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,741	891,402	3,547,115
After project added	29,428,406	890,289	3,547,115
Δ (Project-base)	+2,665	-1,113	0

As a further experiment, the assignment was run to a relative gap of 1.E-6, but the results were quite similar. This can be seen from inspecting the figure and table that follow.

**Figure 7-9 Highway Flow Differences in the MAG Network at 1.E-6 Convergence**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3530.42	66.29
Outside the vicinity of project	234.50	2.91

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,405,402	890,430	3,547,115
After project added	29,407,641	889,373	3,547,115
$\Delta$ (Project-base)	+2,239	-1,057	0

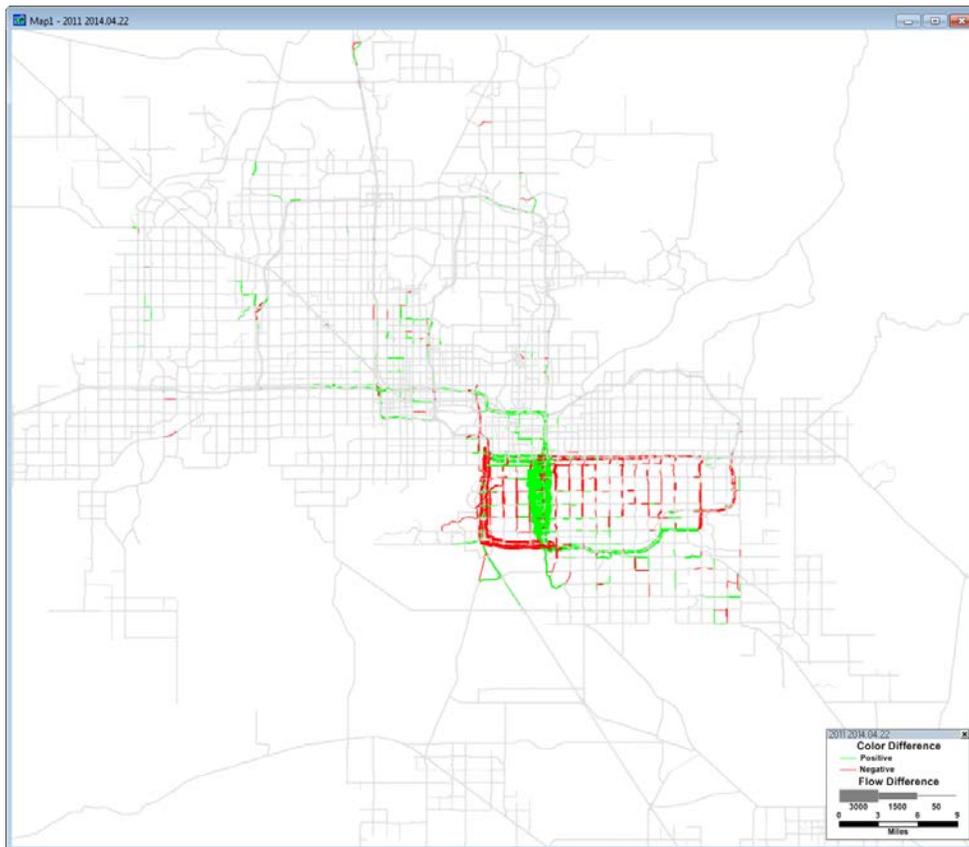
At 1.E-6, there is a small change to the overall estimated VMT and VHT of roughly 5% when compared to the results at 1.E-5. The extra computing involved may be warranted if differences of less than 5% in the final answer are judged to be consequential.

### ***MAG mode choice and assignment with highway project added***

Of course, there is the possibility that the project might have some small impact on mode choice. To examine this, we repeat the analysis with the model skims from the project scenario along with the same fixed total trip table from the base model as inputs to the mode choice step. After mode choice, highway assignments were run to convergence levels of 1.E-4 and 1.E-6, respectively.

With the mode choice component, highway demand rises by more than 2000 PM trips with the result that there is an overall increase in VHT. Once again in the 1.E-4 assignment, there are affected link flows all over the region and not just within the corridor and sector in which the project is located.

**Figure 7-10 MAG Highway Network Flow Differences at 1.E-4 Convergence**

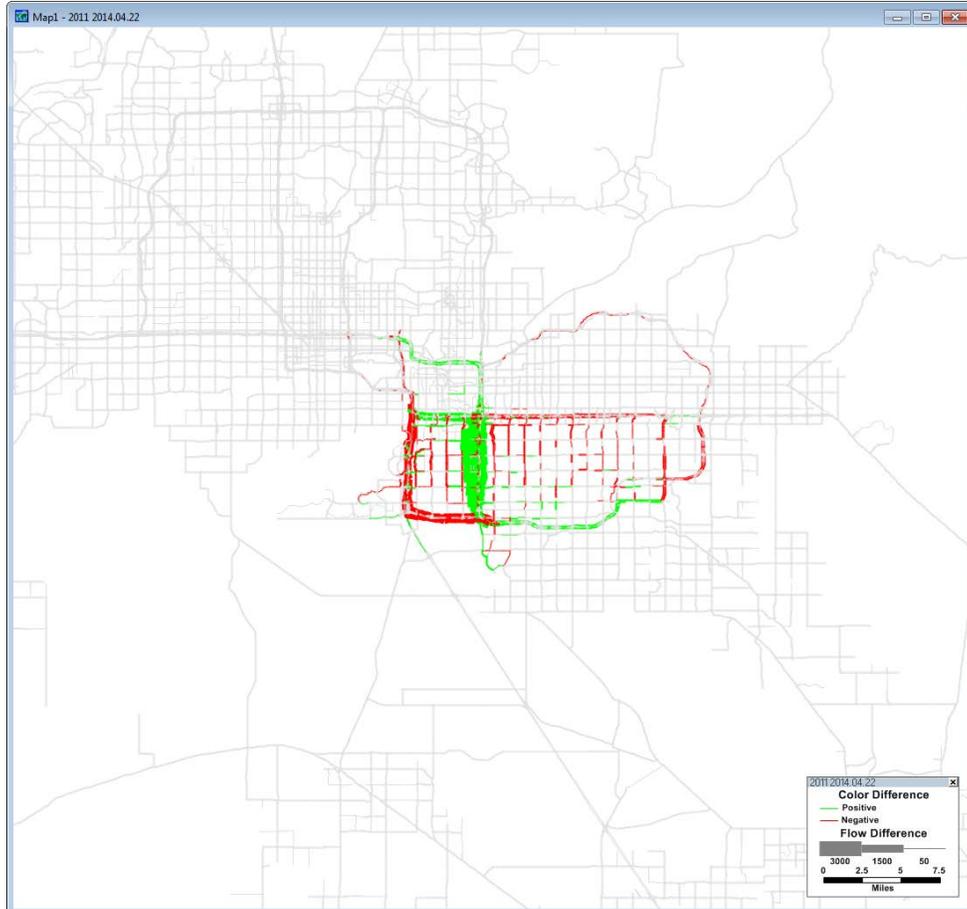


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3712.67	72.02
Outside the vicinity of project	313.79	9.09

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	29,459,312	891,988	3,549,465
$\Delta$ (Project-base)	+33,412	+619	+2,350

When computed to a 1.E-6 relative gap, the impacts are more focused and a different conclusion is reached about the project impacts. This is evident from inspecting the map and table that follows.

**Figure 7-11 Highway Flow Differences in the MAG Network at 1.E-6 Convergence**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3629.82	60.17
Outside the vicinity of project	271.28	2.34

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,428,457	891,605	3,547,163
After project added	29,434,269	890,692	3,547,379
$\Delta$ (Project-base)	+5,812	-913	+216

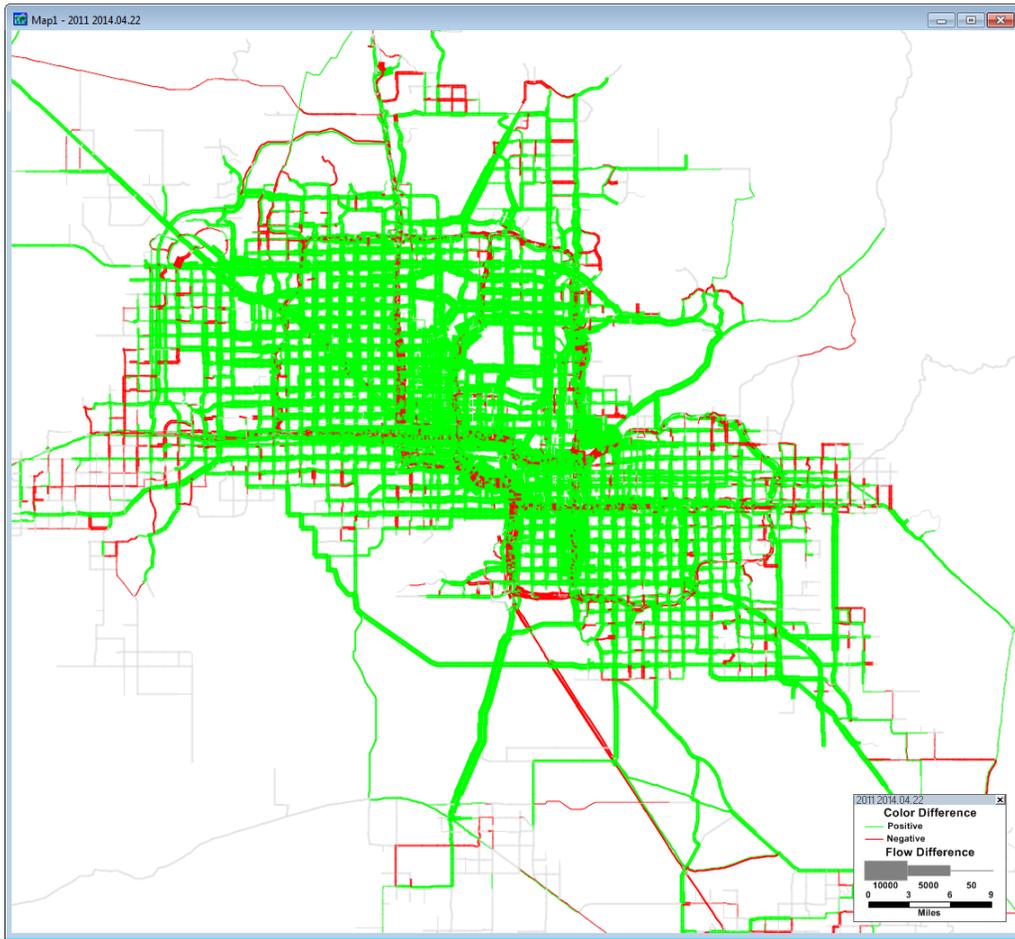
A different result, and a more plausible one, comes from the more highly converged traffic assignment. With the tighter convergence, there are positive VHT savings from the project and a more modest gain in highway trips suggesting that the results from the 1.E-4 analysis are not reliable.

### ***MAG single loop run with highway project added***

In this section, we compared the flows from running the full feedback base scenario to the flows obtained after adding a highway project to the network and running a single feedback loop. The MAG model typically begins with free flow auto travel speeds. If one uses free flow speeds instead of congested speeds, auto travel is greatly favored over transit, auto trips are longer, and we see flow increases almost everywhere in the network. This can be observed in the map that follows which, using our previous convention of color coding, reveals a sea of green reflecting increased auto trips. The few reds links are HOV lanes, which are practically unused due to the lack of congestion. The tabular results are quite dramatic with changes in VHT on the order of many hundreds of thousands of vehicle hours of travel.

Clearly this is not a recommended practice, but simply an illustration of how a mechanical application of the model might give rather strange results. This is due to a distortion of the trip distribution and mode split effects and not the traffic assignment itself.

**Figure 7-12 Highway Flow Differences in the MAG Network at 1.E-4 Convergence with Free-Flow Times**

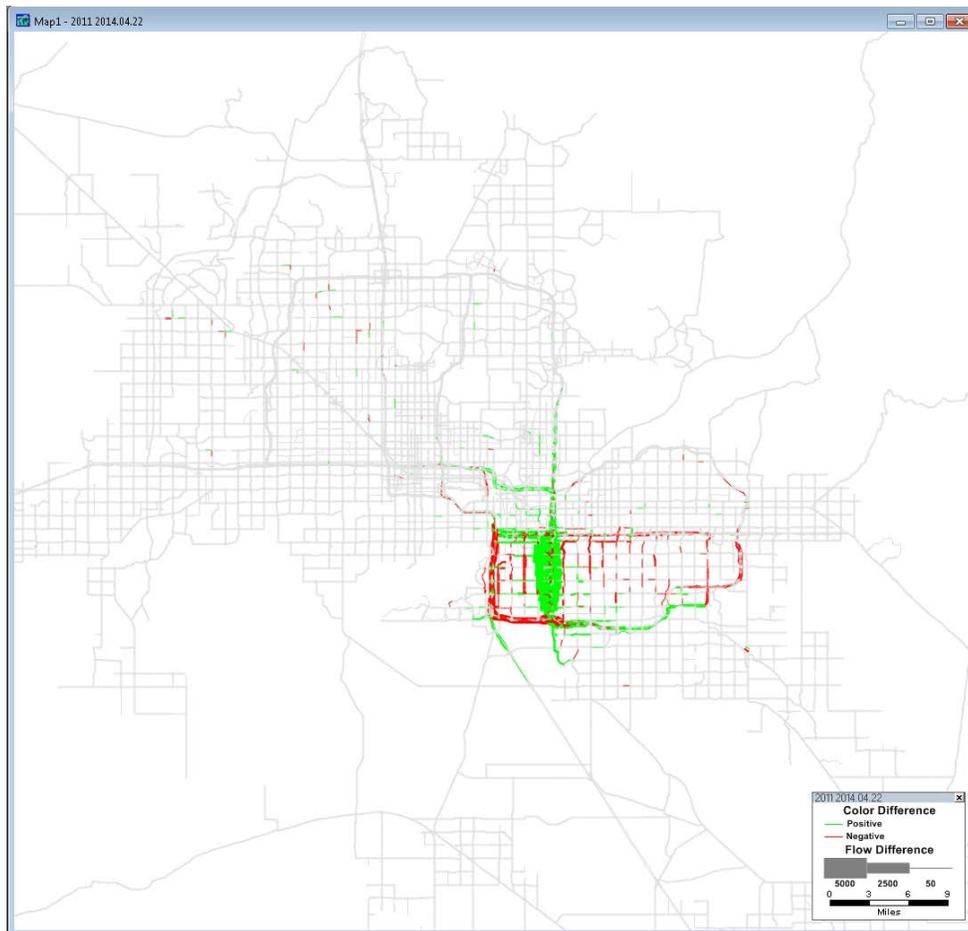


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	8938.53	784.76
Outside the vicinity of project	7615.94	431.10

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	34,069,394	992,337	3,654,724
$\Delta$ (Project-base)	+4,643,494	+100,968	+107,609

Repeating this analysis with **congested** travel speeds from the project, a single loop of the model runs trip distribution in addition to mode choice and traffic assignment. Below we show the results at a relative gap of 1.E-4.

**Figure 7-13 Highway Flow Differences in the MAG Network at 1.E-4 Convergence when Initialized with Congested Times**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	4382.48	78.10
Outside the vicinity of project	223.91	7.43

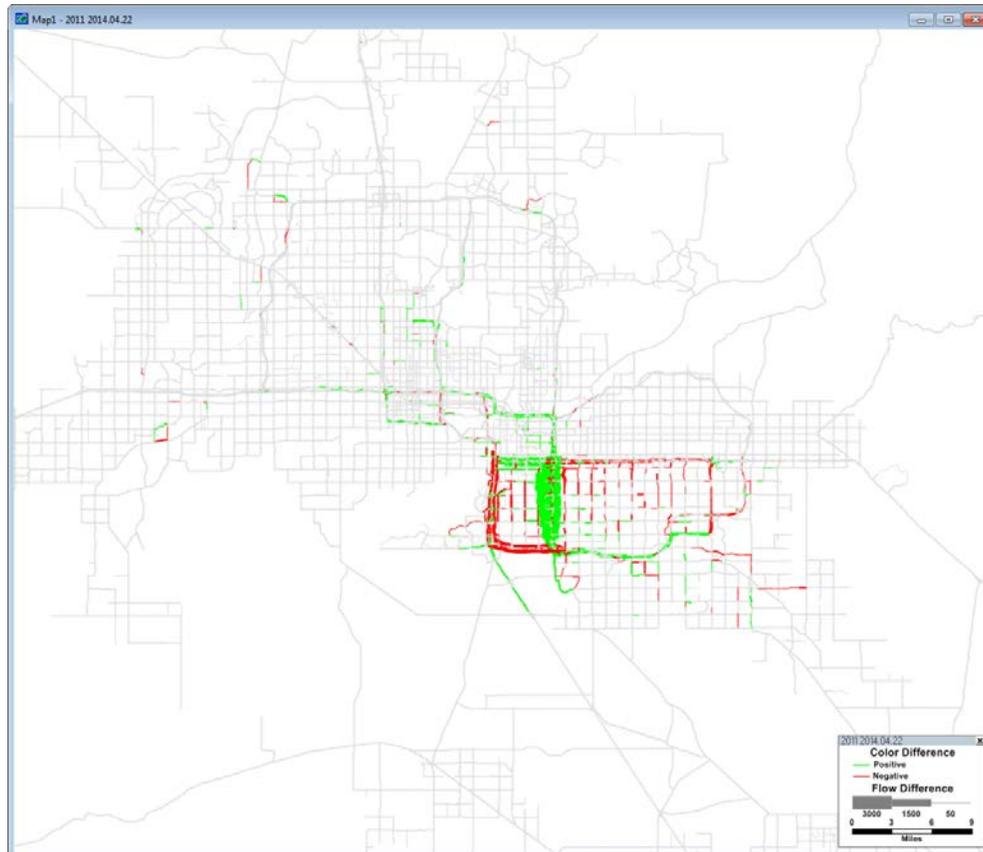
	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,632,997	902,876	3,552,792
After project added	29,696,159	904,913	3,554,100
Δ (Project-base)	+63,162	+2,037	+1,308

Note that there is still an increase in VHT due to the project. On further investigation it was revealed that the average trip length in the network goes up when a single loop is run with congested times from the project.

### **MAG full model run with highway project added**

To conclude the highway project analysis, we analyze the difference in flows when the full model with 5 feedback loops is run with the project added. The MPO uses a feedback convergence criterion of 3.8% applied to the maximum of the flow %RMSE and matrix %RMSE obtained at the end of the loop. In all of our model runs, this resulted in 4 feedback loops. We ran the full model with feedback at highway convergence levels of 1.E-4, 1.E-5 and 1.E-6.

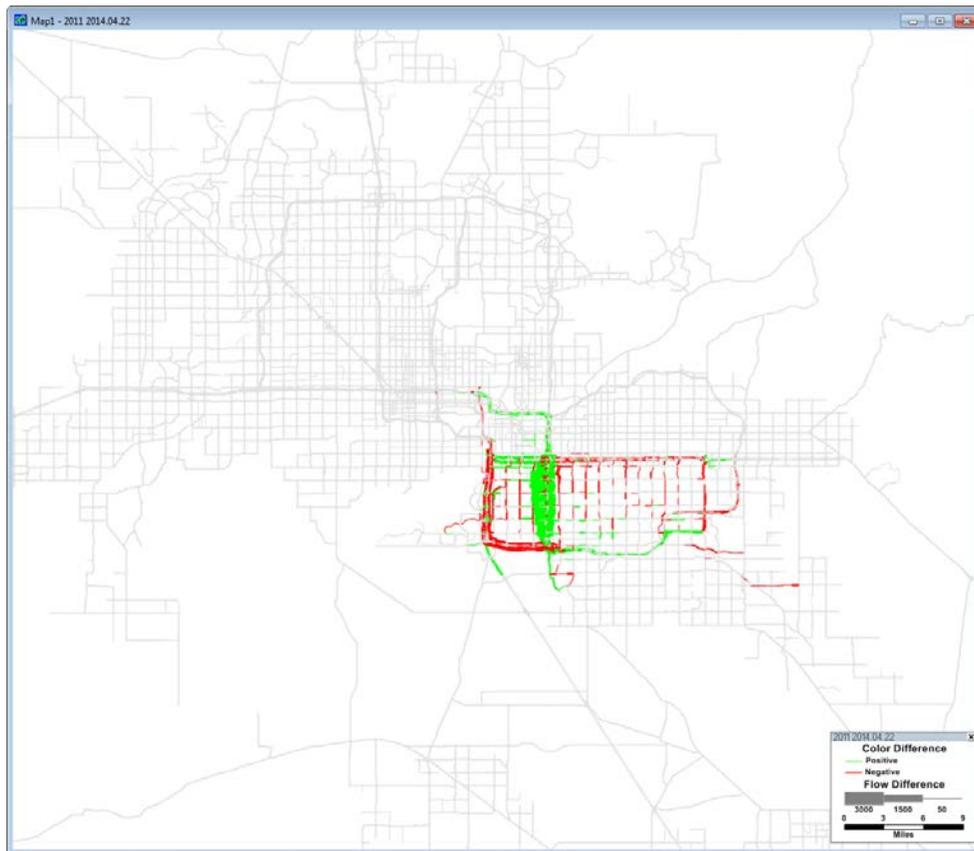
**Figure 7-14 Highway Flow Differences in the MAG Network at 1.E-4 Convergence and 4 Feedback Loops**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3752.74	84.61
Outside the vicinity of project	331.52	9.57

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	29,462,318	892,112	3,549,849
$\Delta$ (Project-base)	+36,418	+743	+2,734

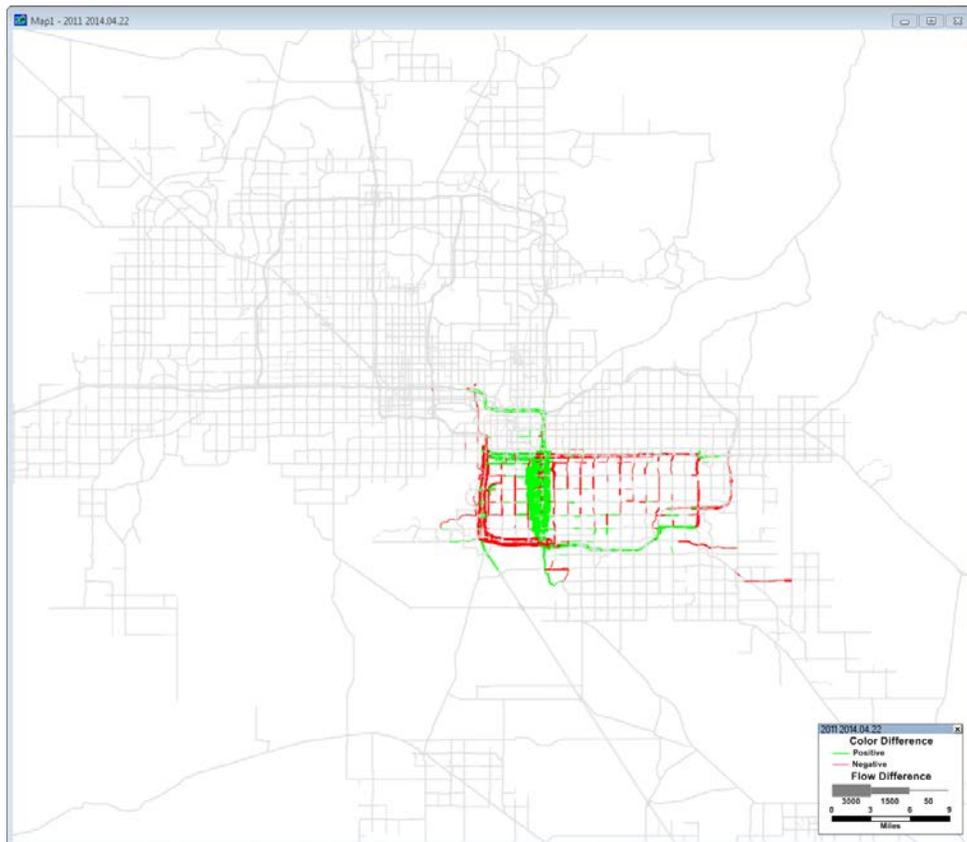
**Figure 7-15 Highway Flow Differences in the MAG Network at 1.E-5 Convergence and 4 Feedback Loops**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3717.92	82.17
Outside the vicinity of project	283.11	4.04

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,427,134	891,525	3,547,159
After project added	29,442,828	890,968	3,547,485
$\Delta$ (Project-base)	+15,694	-557	+326

**Figure 7-16 Highway Flow Differences in the MAG Network at 1.E-6 Convergence and 4 Feedback Loops**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	3713.10	62.89
Outside the vicinity of project	281.93	2.72

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,428,457	891,605	3,547,163
After project added	29,444,527	891,064	3,547,494
$\Delta$ (Project-base)	+16,070	-541	+331

It is important to note that the estimated impact of the project changes from negative to positive with the higher level of assignment convergence.

The following table summarizes the highway project impacts for all the scenarios examined above. The transit trips during PM were estimated by halving the peak period matrix total since the transit time period definitions were different from the highway definitions.

**Table 7-2 MAG Highway Project Impact Summary**

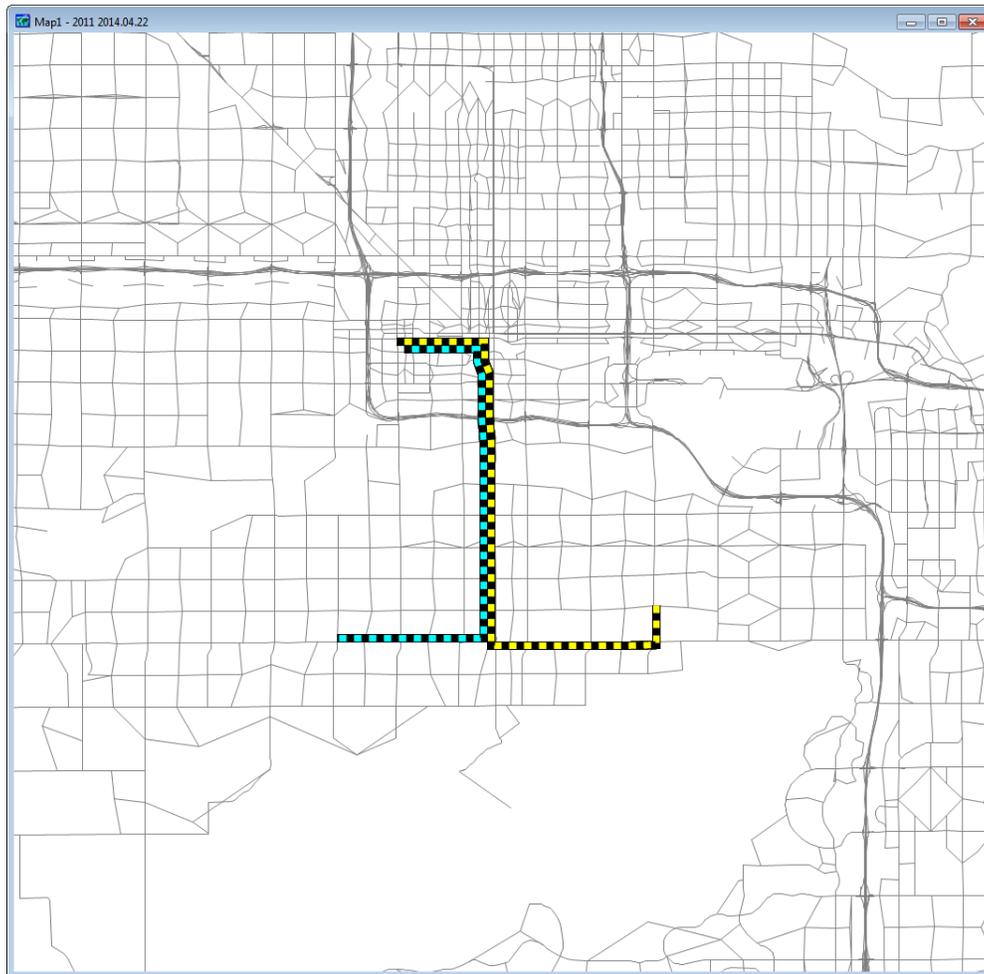
Highway assignment convergence	Type of model run	Δ PM VMT (Project-base)	Δ PM VHT (Project-base)	Δ PM Highway trips (Project-base)	Δ PM Transit trips (Project-base)
1.E-4	Highway PM assignment only	+2,827	-1,117	N/A (same O-D matrix)	N/A (no mode choice)
1.E-5	Highway PM assignment only	+2,665	-1,113	N/A (same O-D matrix)	N/A (no mode choice)
1.E-6	Highway PM assignment only	+2,239	-1,057	N/A (same O-D matrix)	N/A (no mode choice)
1.E-4	Modal split and assignment only	+33,412	+619	+2,350	-2,629
1.E-6	Modal split and assignment only	+5,812	-913	+216	-4
1.E-4	Single loop run starting with free-flow times	+4,643,494	+100,968	+107,609	-6107
1.E-4	Single loop run starting with congested times	+63,162	+2,037	+1,308	-32
1.E-4	Full model with feedback	+36,418	+743	+2,734	-2,875
1.E-5	Full model with feedback	+15,694	-557	+326	-5
1.E-6	Full model with feedback	+16,070	-541	+331	-2

Clearly different answers emerge from the different analysis protocols and convergence levels. Theory would suggest that there would be highway benefits from this highway project. If one focuses solely on the 1.E-6 results, we get a consistent positive benefit with a range of savings of between 541 to 1057 vehicle hours of travel. These particular scenarios are ones in which there is no significant negative impact on transit use in Phoenix, which we also find plausible.

## **Impact of a Transit Improvement Project in Phoenix**

Next we analyze the effect on both highway and transit flows when a transit project is added to the MAG 2011 base year scenario. The future-year transit project chosen in this case was taken from the MAG's 2025 route system and involves the addition of two peak period bus routes that are referred to as the South Central Rapid and the South Central Express services. Both routes start from the same point in the Phoenix Inner Loop and overlap for much of their length but serve different destinations. In the figure below, the route indicated by the dashed yellow line is the South Central Express, and the one indicated by the dashed blue line is the South Central Rapid.

**Figure 7-17 Transit Improvements in Phoenix**



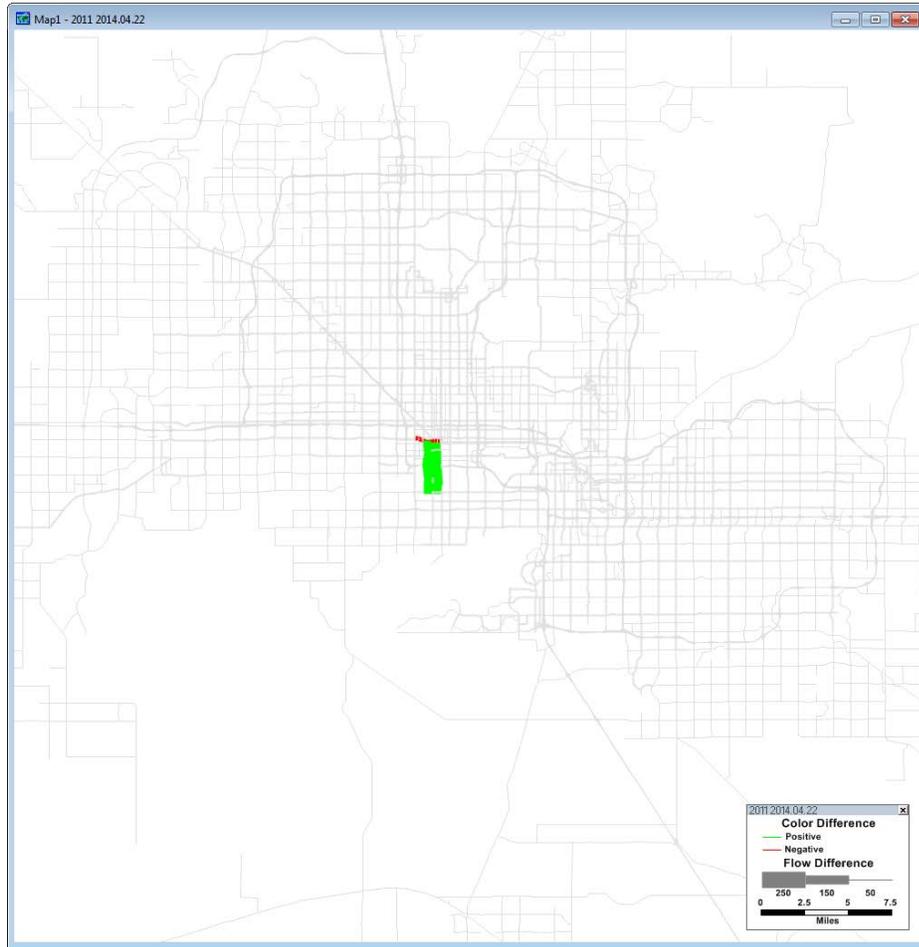
Introduction of two new transit routes would be expected to increase transit use to some degree. The magnitude of this effect is estimated by running the mode choice model. Changes in transit route choice are modeled using the Pathfinder transit assignment method in TransCAD.

### ***MAG mode choice and assignment with transit project added***

We first compared the changes in transit flows compared to the base year when only the mode choice and highway assignment steps of the model were run after the addition of the transit project. This was done using a convergence criterion of 1.E-4 relative gap for the highway assignment. For each scenario, the PM transit flows are assumed to be half of the peak period transit flows, since the MAG model does not explicitly output PM transit flows.

In the figures that follow, we show the transit and highway flow changes that the model associates with the project. The figure below shows the differences in transit ridership due to the project. There are 269 riders on the new routes, but a net gain of only 66 riders due to significant diversion from existing routes.

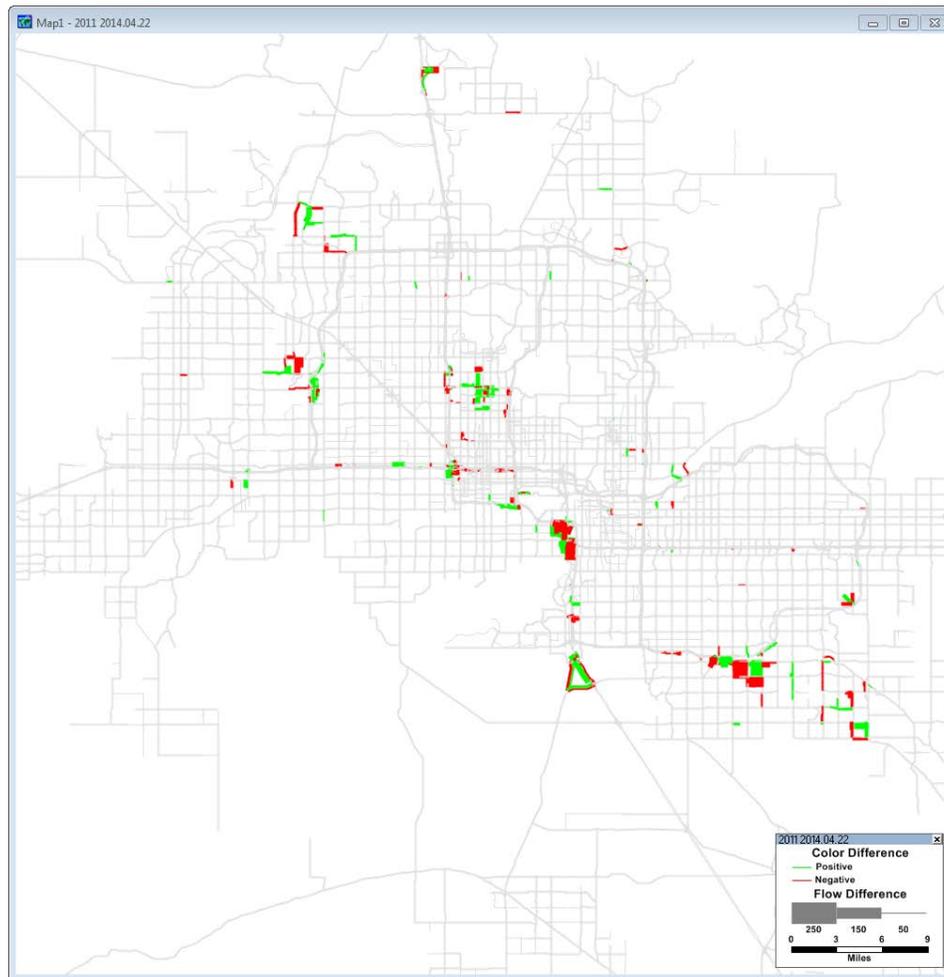
**Figure 7-18 Transit Flow Differences in the MAG Network at 1.E-4 RG Convergence**



	Assigned PM transit demand	PM Person-Hours (PHT)
Before project added	52,225	42,086
After project added	52,291	42,143
$\Delta$ (Project-base)	+66	+57

At a relative gap of 1.E-4 in the highway traffic assignment, there are widespread changes in link flows all over the network as shown in the figure below and not simply in the corridor served by the additional transit service. Many of these changes seem highly unlikely. There is an overall reduction in road traffic which is computed to be a VHT savings of 60.

**Figure 7-19 MAG Highway Flow Differences Due to the Transit Improvements at 1.E-4 Convergence**

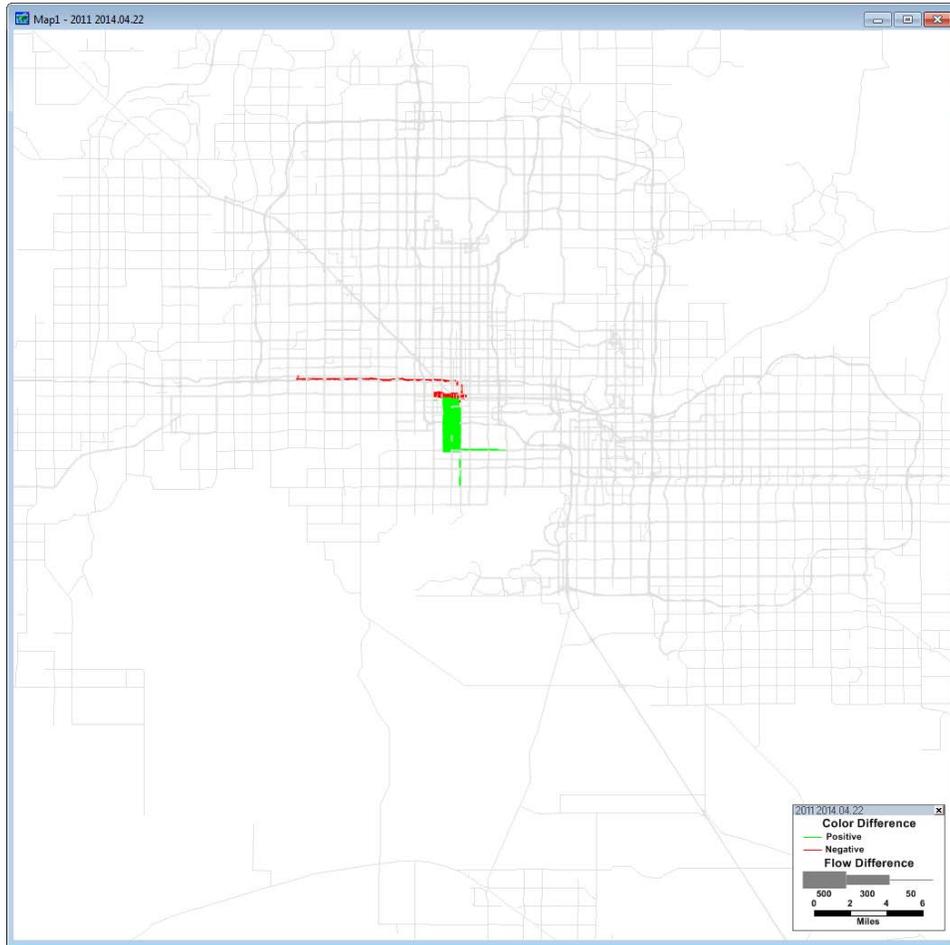


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	109.37	10.54
Outside the vicinity of project	225.50	6.96

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	29,425,490	891,309	3,547,071
$\Delta$ (Project-base)	-410	-60	-44

When the highway traffic assignment is run to a higher convergence level, there are differences in congested travel times that yield somewhat different results in mode shift as well as in the assignment. This yields a slight but noticeable difference in the transit flows as shown below.

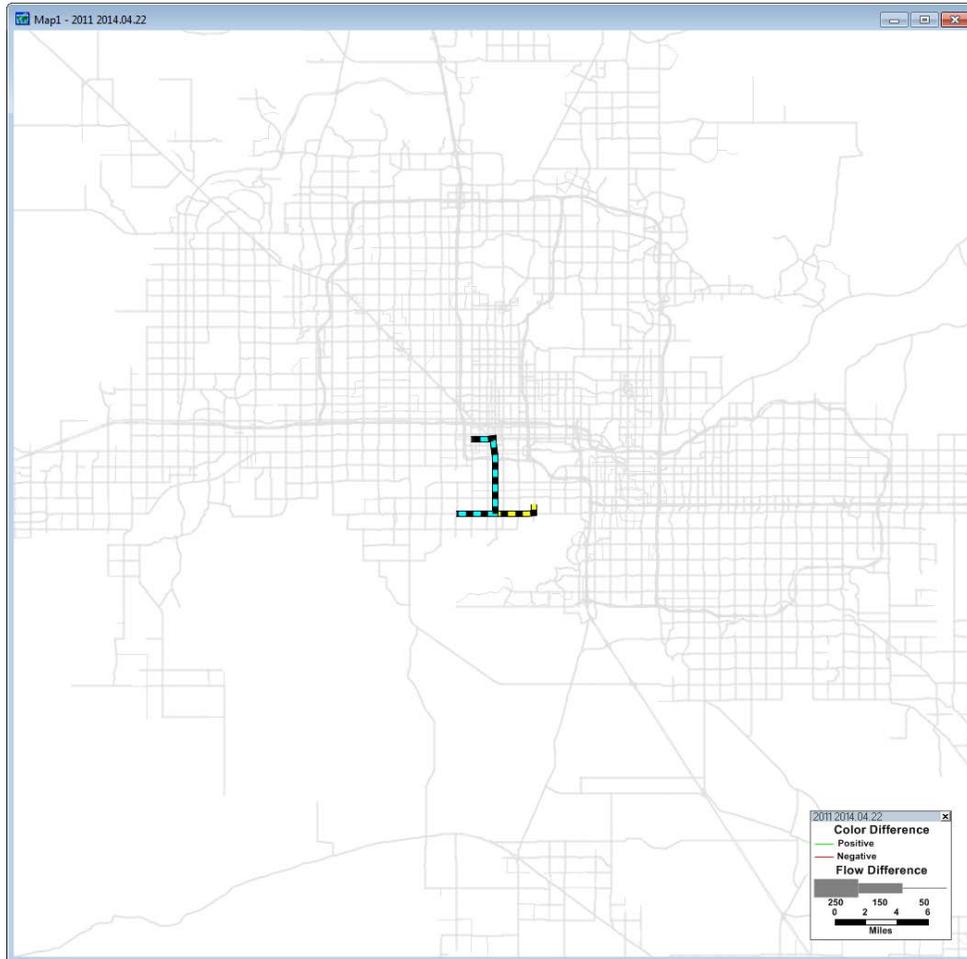
**Figure 7-20 Transit Flow Differences in the MAG Network at 1.E-6 RG Convergence**



	Assigned PM transit demand	PM PHT
Before project added	52,225	42,096
After project added	52,281	42,136
Δ (Project-base)	+56	+40

The PM ridership on new routes is 270, with net gain of only 56 riders overall. With tighter convergence in the traffic assignment, no highway link has a flow change of 50 or more as shown in the map that follows. This seems like a much more plausible result than the one computed at the lower convergence level.

**Figure 7-21 Highway Flow Differences in the MAG Network at 1.E-6 RG Convergence**



The corresponding statistics are given below for the traffic assignment converged to a 1.E-6 relative gap. As might be expected there is a small reduction in highway VHT due to the transit project. This is not implausible.

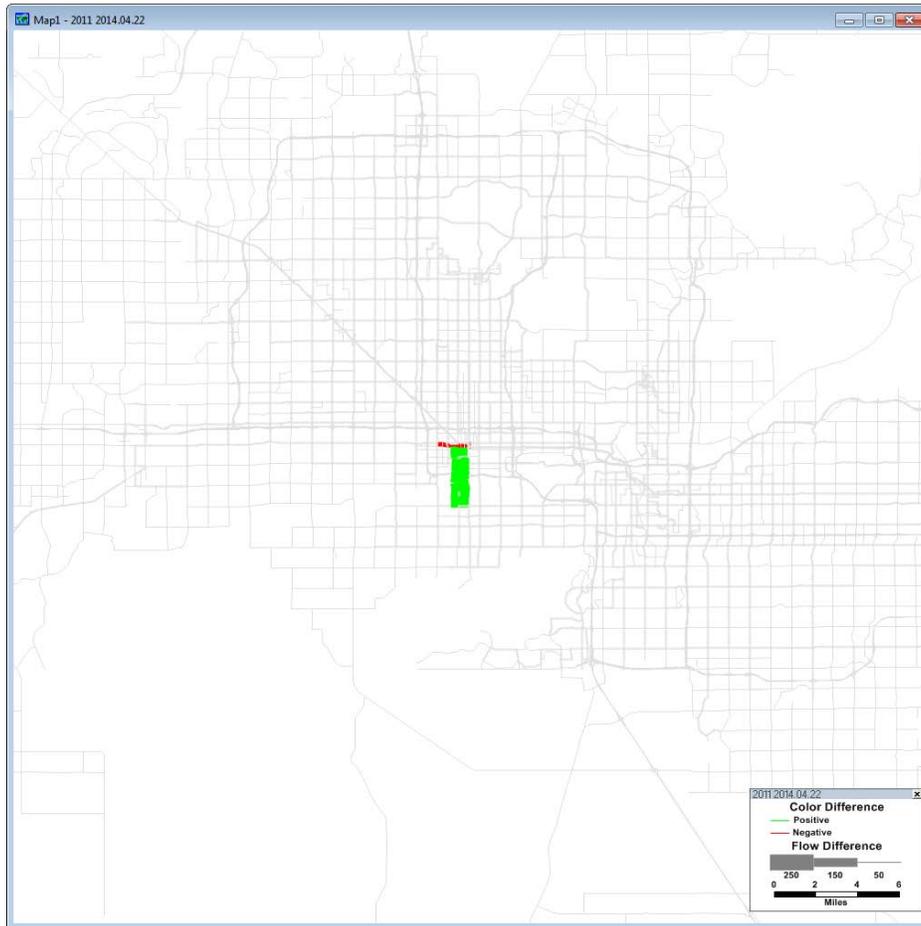
	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	15.66	0.87
Outside the vicinity of project	19.80	0.20

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,428,457	891,605	3,547,163
After project added	29,427,797	891,571	3,547,122
$\Delta$ (Project-base)	-660	-34	-41

### **Transit project impacts assessed with a MAG full model run**

Lastly, we analyze the changes on transit flows when the full feedback model with the transit project added is run to three different assignment convergence levels. As seen below, the transit flow difference maps at 1.E-4 and 1.E-5 are almost identical. This demonstrates that the highway convergence level has little to no effect on the transit flow differences. However, the highway flow differences as a result of the transit project are affected by the convergence level specified. At a 1.E-4 relative gap (RG), there are highway flow differences in areas far outside the transit project vicinity while at a 1.E-5 relative gap, these are reduced considerably and only a few links exhibit change in highway flows as a result of the transit project. At a highway convergence level of 1.E-4, the PM ridership on the new routes is 273 but there is a net gain of only 65 trips overall.

**Figure 7-22 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-4 Convergence**

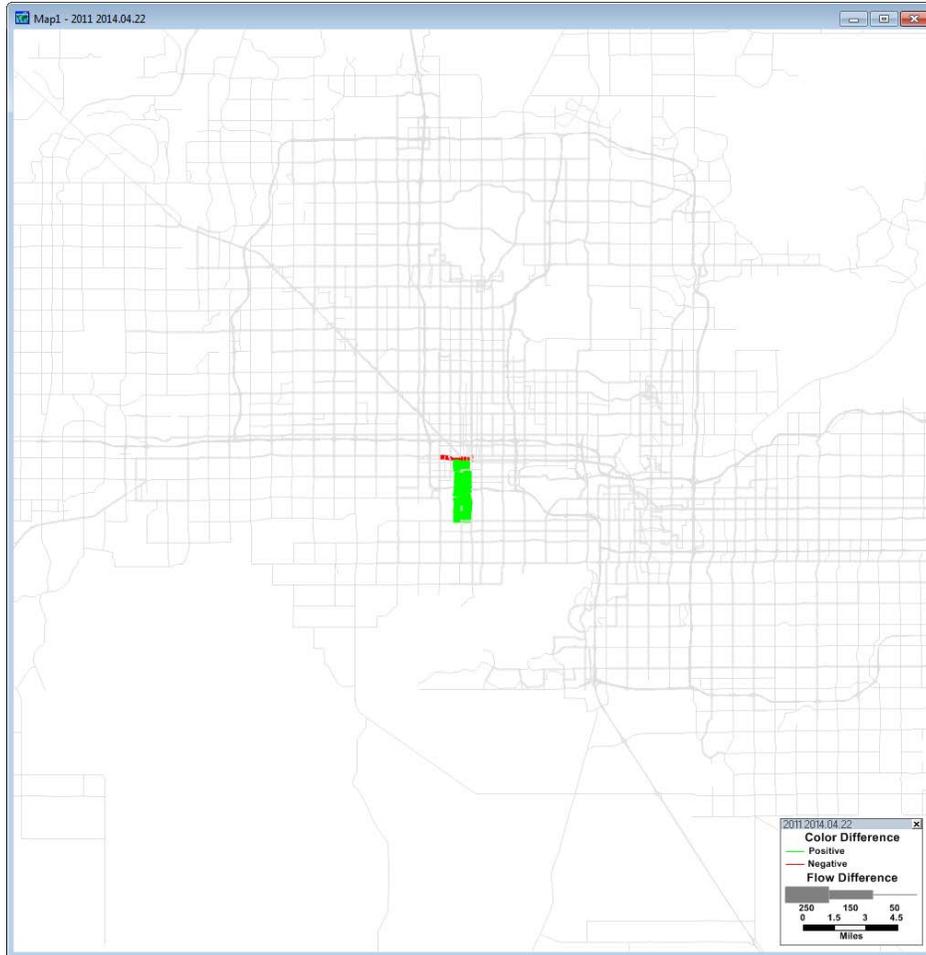


	Maximum PM transit flow difference	Average PM transit flow difference
In the vicinity of project	272.47	4.39
Outside the vicinity of project	30.07	0.20

	Assigned PM transit demand	PM PHT
Before project added	52,225	42,086
After project added	52,290	42,140
$\Delta$ (Project-base)	+65	+54

At higher convergence the PM ridership on new routes is nearly identical at 274 trips and a net gain of 57 riders.

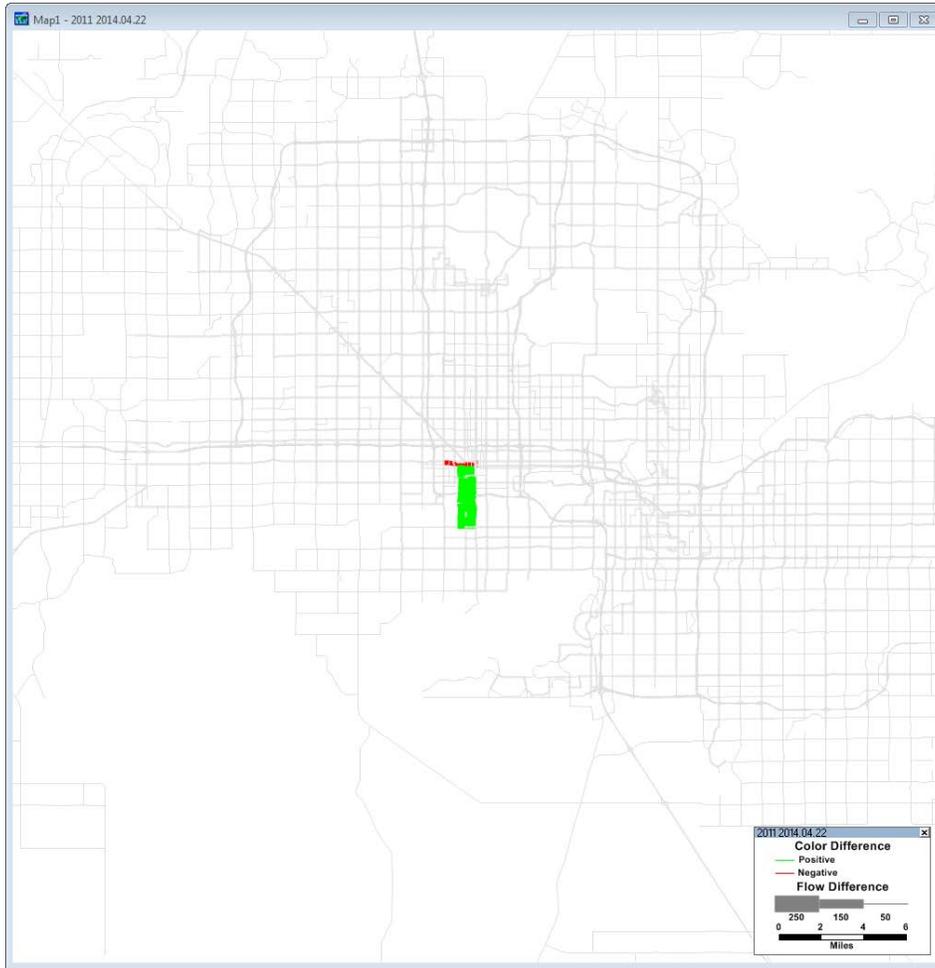
**Figure 7-23 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-5 Convergence**



	Maximum PM transit flow difference	Average PM transit flow difference
In the vicinity of project	273.49	4.38
Outside the vicinity of project	30.87	0.16

	Assigned PM transit demand	PM PHT
Before project added	52,225	42,096
After project added	52,282	42,129
$\Delta$ (Project-base)	+57	+33

**Figure 7-24 Transit Flow Differences in the MAG Network with a Full Model Run at 1.E-6 RG**



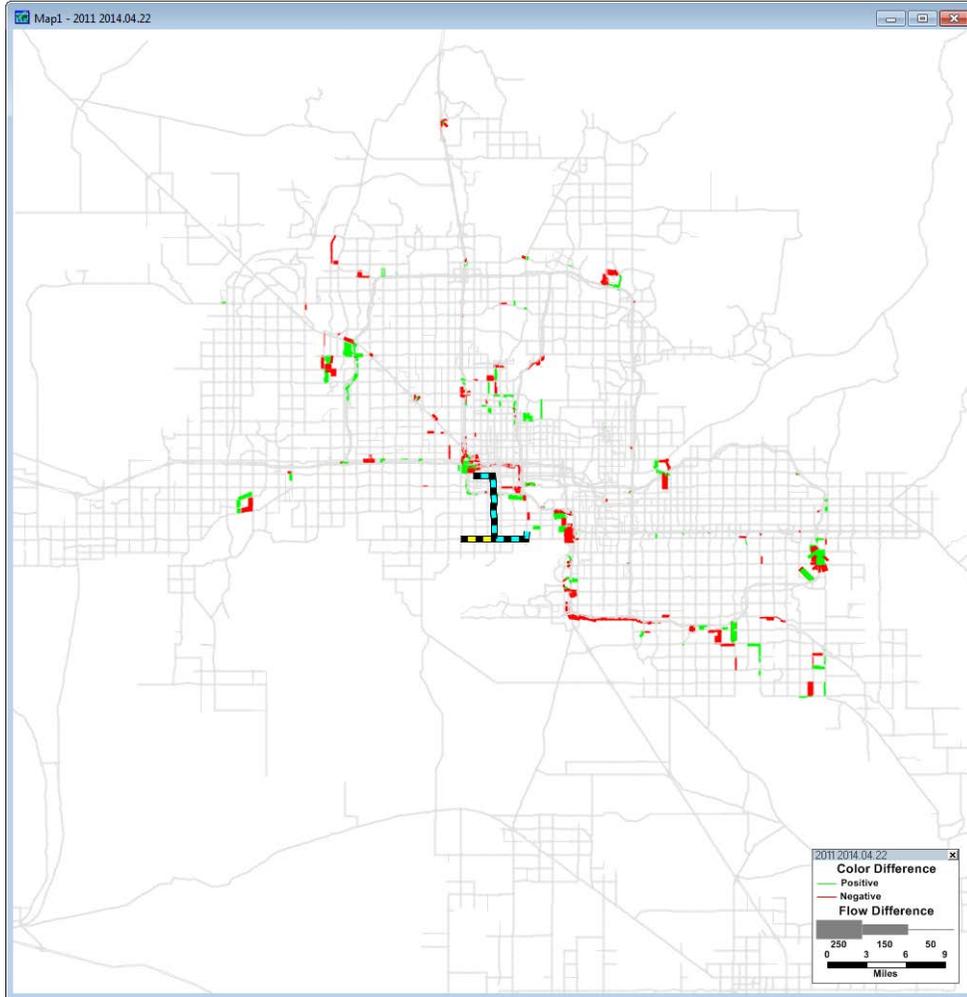
Similarly, at a relative gap of 1.E-6, ridership on the new route is 274 and there is a net gain of 59.

	Maximum PM transit flow difference	Average PM transit flow difference
In the vicinity of project	273.61	3.26
Outside the vicinity of project	30.71	0.12

	Assigned PM transit demand	PM PHT
Before project added	52,226	42,096
After project added	52,285	42,135
Δ (Project-base)	+59	+39

As observed previously, at a relative gap of 1.E-4 in the traffic assignment and with a full model run, there are changes in highway traffic all over the region and in locations in which little or no impact of the project would be expected. This is illustrated in the flow map that follows.

**Figure 7-25 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-4 RG**

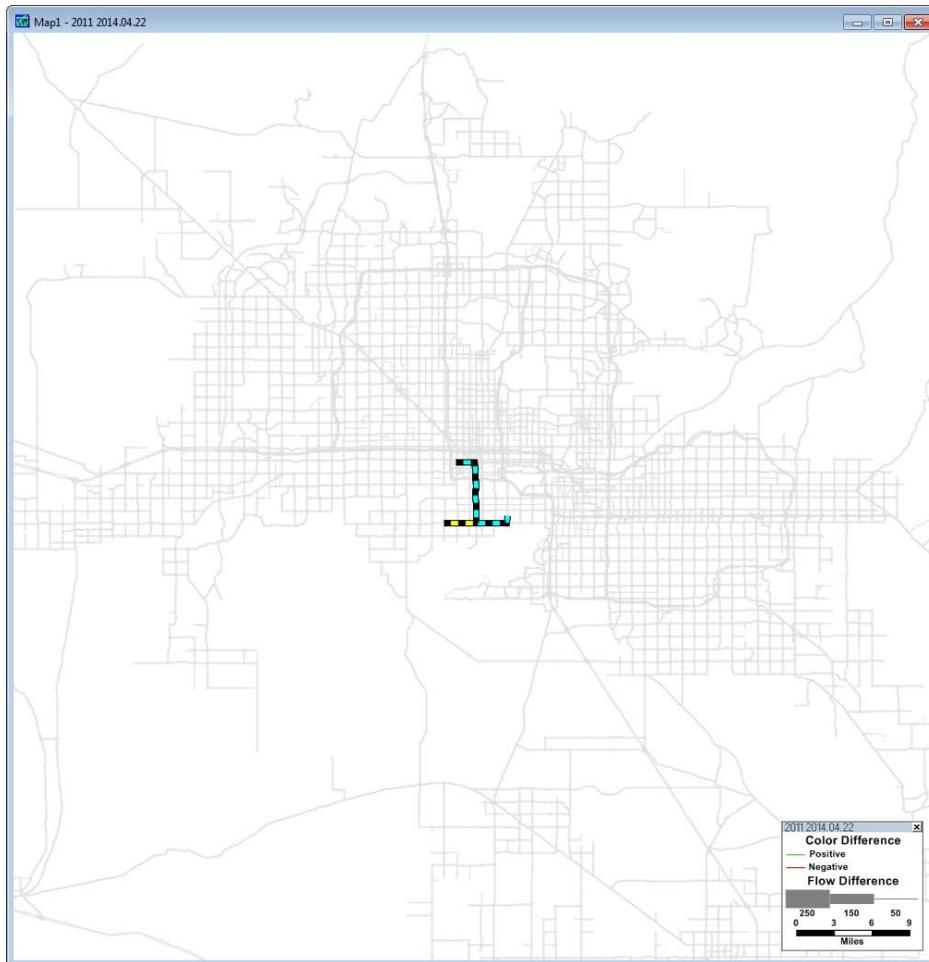


	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	173.77	12.19
Outside the vicinity of project	247.30	7.41

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,425,900	891,369	3,547,115
After project added	29,423,710	891,262	3,547,034
$\Delta$ (Project-base)	-2190	-107	-81

In the next figure, we map the changes in link flows with the full model run at a relative gap of 1.E-5. As one can see, there are no link changes greater than or equal to 50 vehicles.

**Figure7-26 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-5 RG**



	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	25.28	1.96
Outside the vicinity of project	38.54	1.03

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,427,134	891,525	3,547,159
After project added	29,426,480	891,487	3,547,123
$\Delta$ (Project-base)	-654	-38	-36

Not surprisingly, the same clear map is obtained with the full model run and with the traffic assignment converged to a relative gap of 1.E-6. There are small differences in the tabulated project impact statistics.

**Table 7-3 Highway Flow Differences in the MAG Network with a Full Model Run at 1.E-6 RG**

	Maximum PM highway flow difference	Average PM highway flow difference
In the vicinity of project	13.86	0.85
Outside the vicinity of project	19.73	0.23

	PM VMT	PM VHT	Assigned PM highway demand
Before project added	29,428,457	891,605	3,547,163
After project added	29,427,842	891,573	3,547,124
$\Delta$ (Project-base)	-615	-32	-39

The following table summarizes the transit project impacts for all the runs examined above.

**Table 7-4 MAG Transit Project Impact Run Summary**

Highway assignment convergence	Type of model run	$\Delta$ PM VMT (Project-base)	$\Delta$ PM VHT (Project-base)	$\Delta$ PM Highway trips (Project-base)	$\Delta$ PM Transit trips (Project-base)	$\Delta$ PM PHT (Project-base)
1.E-4	Mode choice and assignment only	-410	-60	-44	+66	+57
1.E-6	Mode choice and assignment only	-660	-34	-41	+56	+40
1.E-4	Full model with feedback	-2,190	-107	-81	+65	+54
1.E-5	Full model with feedback	-654	-38	-36	+57	+33
1.E-6	Full model with feedback	-615	-32	-39	+59	+39

From this tabulation, it can be seen that tighter highway convergence impacts the highway results with all analysis protocols. Importantly, from this analysis, it appears that it is possible to produce plausible estimates of the highway benefits of transit projects. It is also clear that these benefit estimates will vary based upon the analysis protocol that is employed. In general, it seems that higher convergence in the traffic assignment will give better results. In all cases, the 1.E-4 results seem less plausible than those obtained from analysis with a more highly converged traffic assignment, at least for the MAG model.

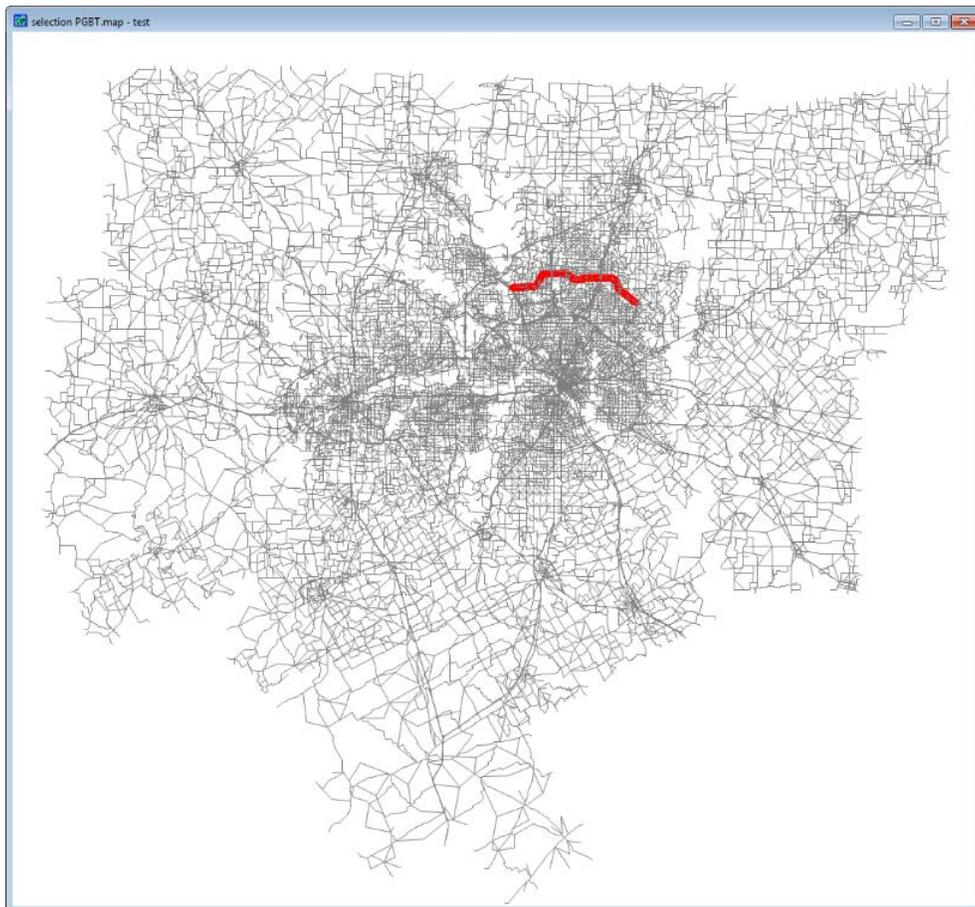
This analysis illustrates that a range of project impact estimates results from applying different forecasting protocols. Quite obviously, it rests with the analyst's judgment about which modeling protocol is appropriate for project impact analysis. For a small highway project, it is unlikely that there would be any significant draw away from transit to highway modes, suggesting that the highway assignment-only analysis would be the most correct.

## Impact of a Roadway Project in Dallas-Ft. Worth

---

Next, we analyzed a roadway project in the Dallas-Ft. Worth region. Our analysis was conducted with a version of the NCTCOG model that we updated to the latest version of TransCAD for our convenience in testing. We chose a road widening project, which simply added an extra lane in each direction on sections of the President George Bush Turnpike. There was no change in network geography. This project was taken from the MPO's 2035 Mobility plan and its location is shown in the map below.

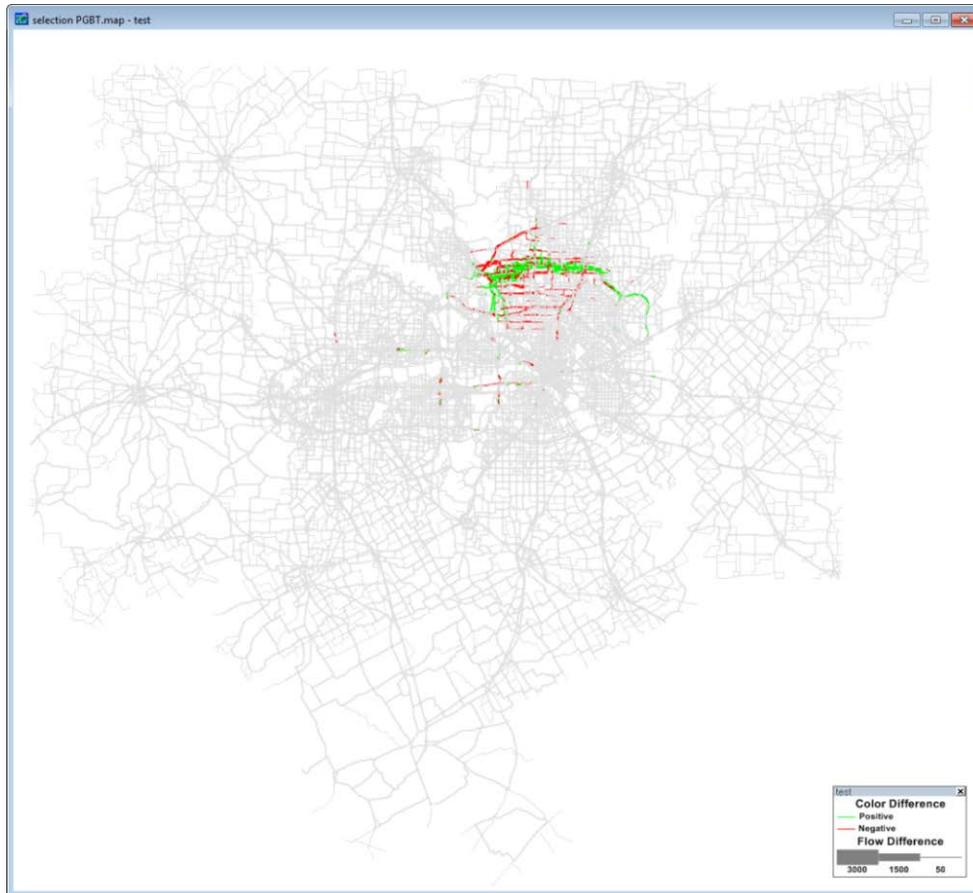
**Figure 7-27 Roadway Project Scope in NCTCOG Network**



## ***NCTCOG AM highway assignment-only results with highway project added***

We applied the same analysis protocol as before running the assignment-only comparisons first. As shown below for the assignment converged to a relative gap of 1.E-4, there were changes in the link flows both in the project corridor and elsewhere in the network. Some of these changes were rather far away from the area served by the project. Quite substantial travel time savings were computed for the project.

**Figure 7-28 Flow Differences in the NTCOG Network at 1.E-4 Highway Convergence**

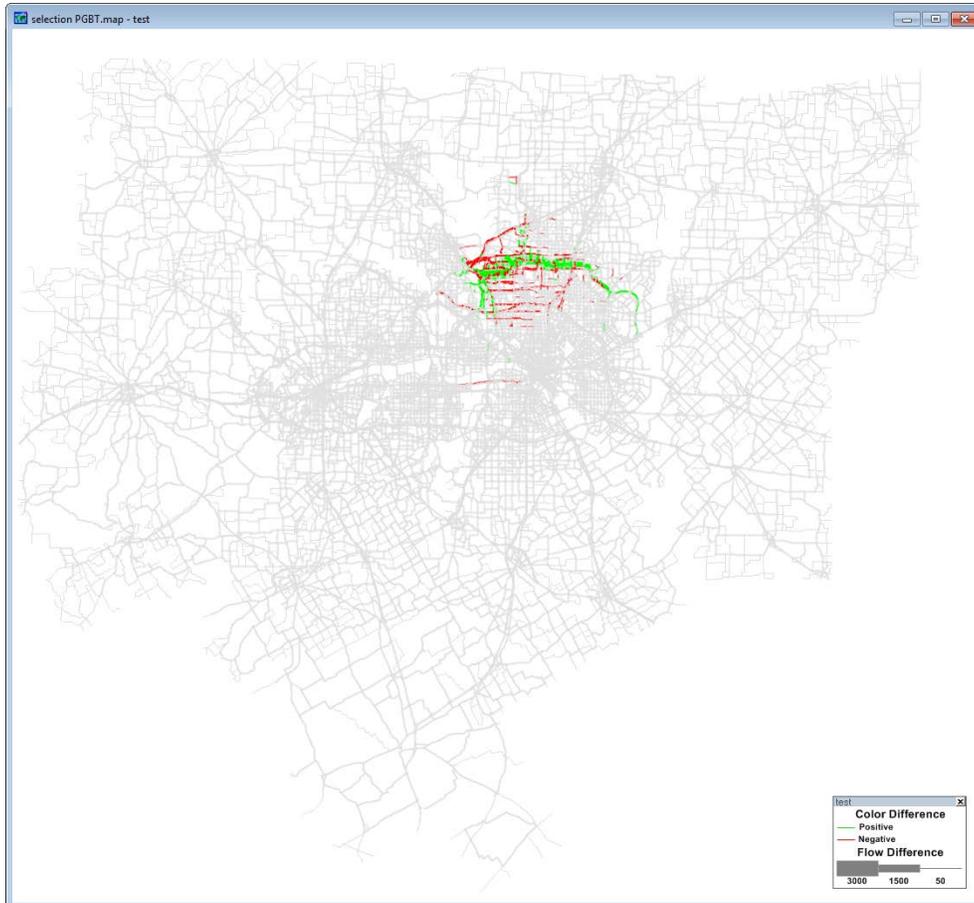


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3377.10	27.93
Outside the vicinity of project	163.72	2.23

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	35,261,168	1,092,819	3,135,788
After project added	35,267,071	1,091,195	3,135,788
$\Delta$ (Project-base)	+5,903	-1,624	0

We next re-ran the assignment-only analysis with higher levels of traffic assignment convergence. As can be observed, the changes were somewhat more localized and there were small differences in the estimated VHT savings.

**Figure 7-29 Flow Differences in the NCTCOG Network at 1.E-5 Relative Gap**

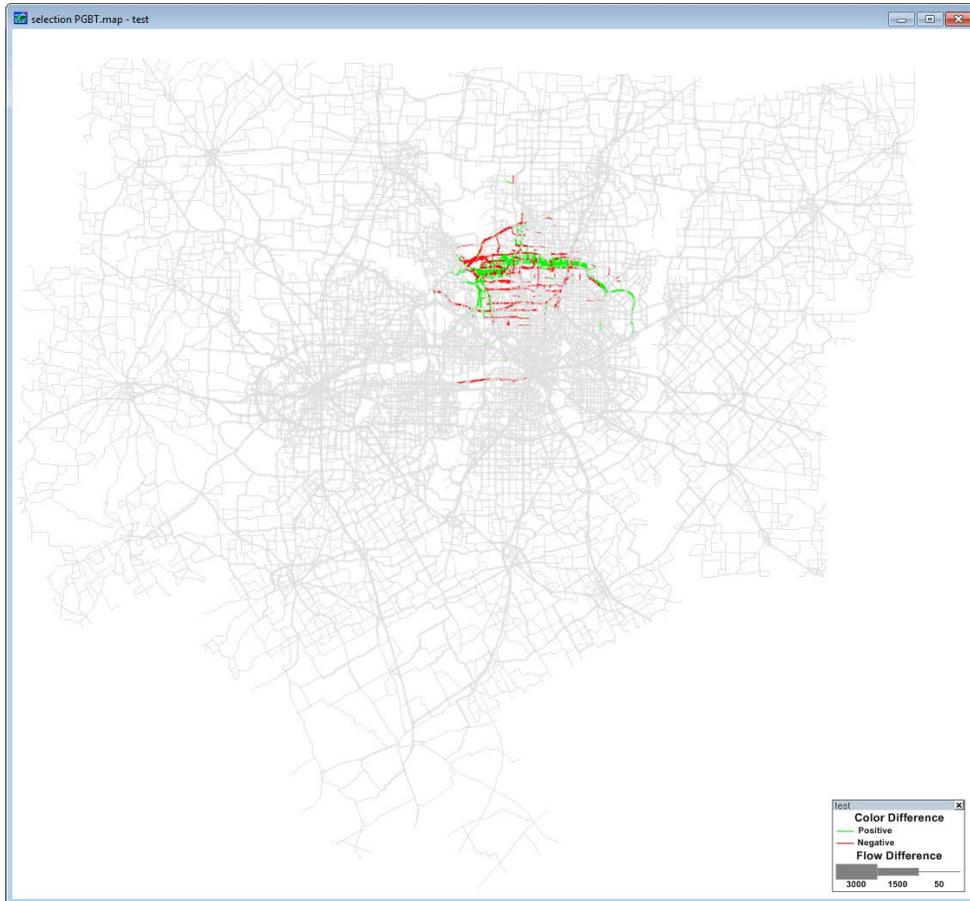


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3377.79	27.87
Outside the vicinity of project	135.69	1.38

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	35,260,436	1,092,850	3,135,788
After project added	35,266,248	1,091,276	3,135,788
$\Delta$ (Project-base)	+5,812	-1,574	0

As shown below, the estimated impacts of the project were rather similar for the two higher levels of assignment convergence.

**Figure 7-30 Flow Differences in the NCTCOG Network at 1.E-6 Relative Gap**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3376.83	27.99
Outside the vicinity of project	133.40	1.41

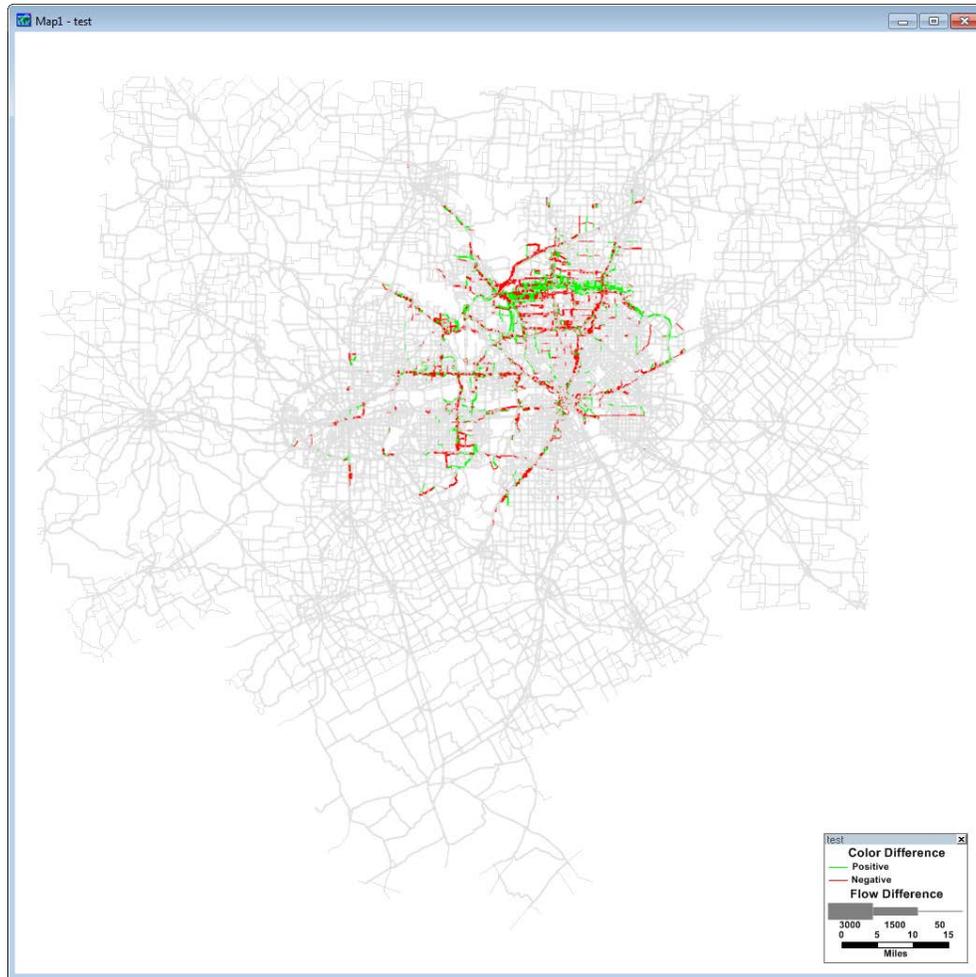
	AM VMT	AM VHT	Assigned AM highway demand
Before project added	35,244,755	1,092,325	3,135,788
After project added	35,250,653	1,090,718	3,135,788
$\Delta$ (Project-base)	+5,898	-1,607	0

***Added lanes assessed with the NCTCOG mode choice and assignment models***

Here we analyze the change in flows when the analysis is performed by running only the mode choice and assignment steps. The congested travel time skims from addition of the project to the network were used as inputs to the mode choice step. The highway assignment convergence was set to a 1.E-4 relative gap.

This analysis protocol produced a broader set of impacts throughout the region than observed with the assignment-only tests. However, when we increased the traffic assignment convergence level, the impacts were once again more localized.

**Figure 7-31 Flow Differences in the NCTCOG Network Evaluated with Mode Choice and at 1.E-4 Assignment Convergence**

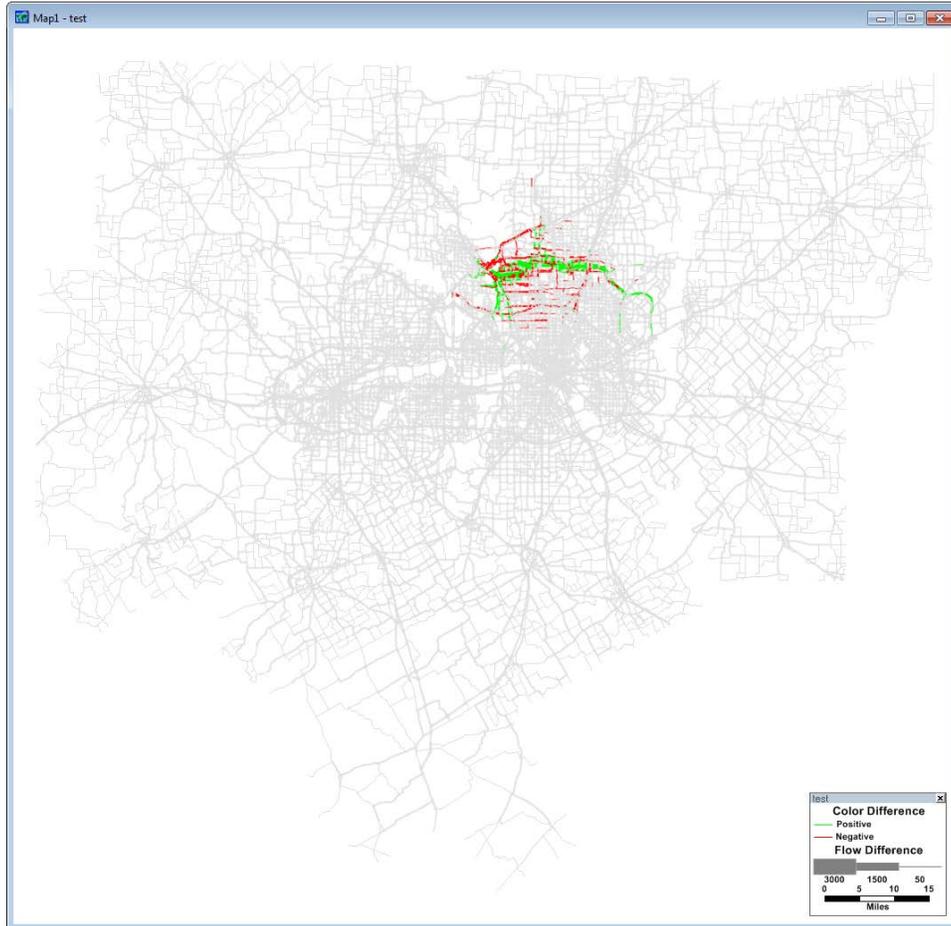


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3363.40	47.50
Outside the vicinity of project	737.43	11.51

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,872,483	1,094,330	3,135,788
After project added	34,875,018	1,092,780	3,135,865
$\Delta$ (Project-base)	+2,535	-1,550	+77

At both the 1.E-4 and 1.E-6 assignment convergence levels, highway trips increase as we would expect. At 1.E-4 however, large flow changes were observed outside the vicinity of the project while at 1.E-6 the pattern of flow changes is more concentrated geographically as shown in the Figure below.

**Figure 7-32 Flow Differences in the NCTCOG Network Evaluated with Mode Choice at 1.E-6 Assignment Convergence**



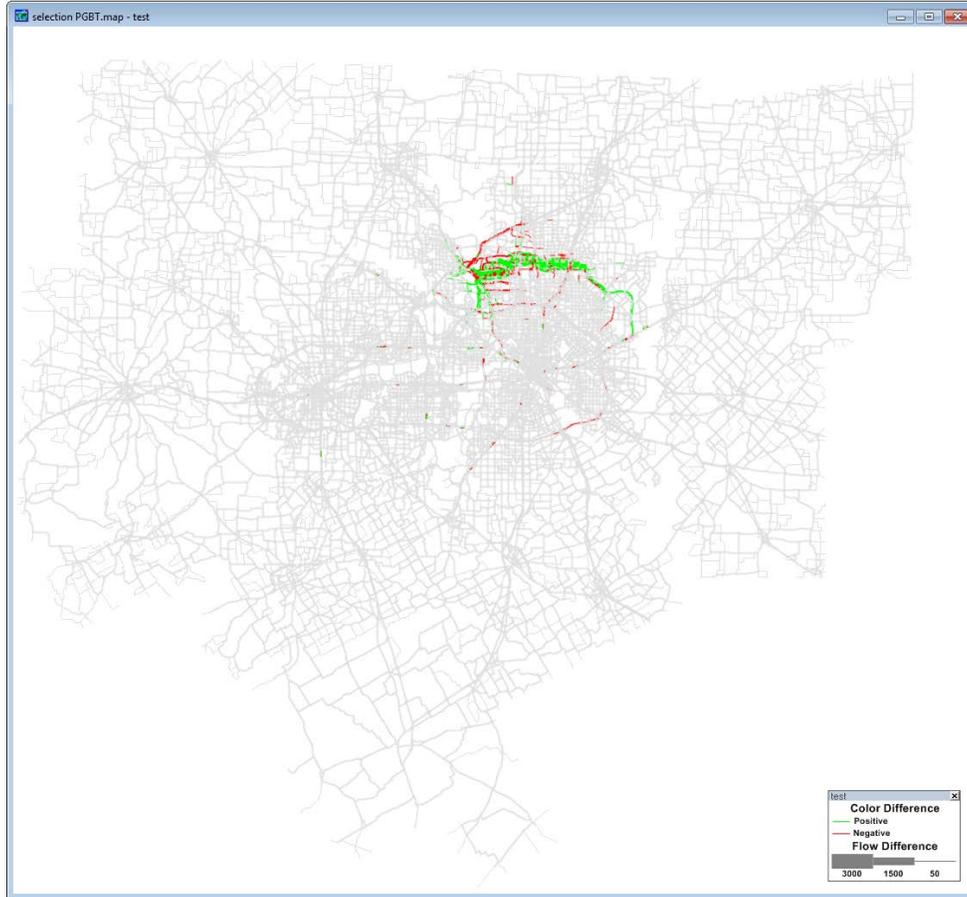
	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3386.40	27.27
Outside the vicinity of project	100.28	1.18

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,857,823	1,093,928	3,135,850
After project added	34,863,022	1,092,379	3,135,872
$\Delta$ (Project-base)	+5,199	-1,549	+22

### ***Lane expansion evaluated with a full NCTCOG model run***

Lastly, we examine the impacts of the lane expansion using the full model run with feedback and varying the traffic assignment convergence level.

**Figure 7-33 Flow Differences from Lane Expansion in the NCTCOG Network at 1.E-4 Assignment Convergence**

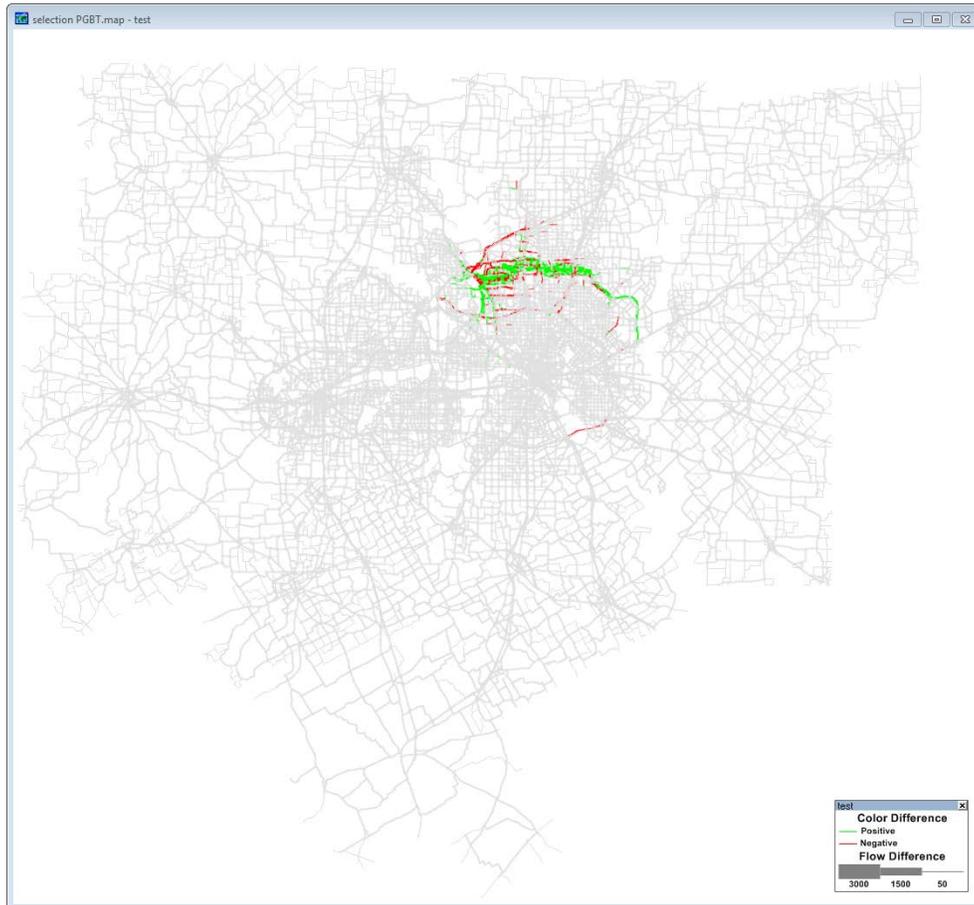


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3500.11	27.38
Outside the vicinity of project	158.59	2.70

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,872,483	1,094,330	3,135,788
After project added	34,902,621	1,094,019	3,135,860
$\Delta$ (Project-base)	+31,094	-460	+72

The travel time benefits from the lane expansion project in the full model run to an assignment relative gap of 1.E-4 are more modest than those predicted by the mode choice and assignment runs presumably due to a redistribution of trip patterns. We also see below that the estimates do not change much even at higher convergence levels for this project. The mode shift favoring highways is slightly less optimistic at higher convergence levels though.

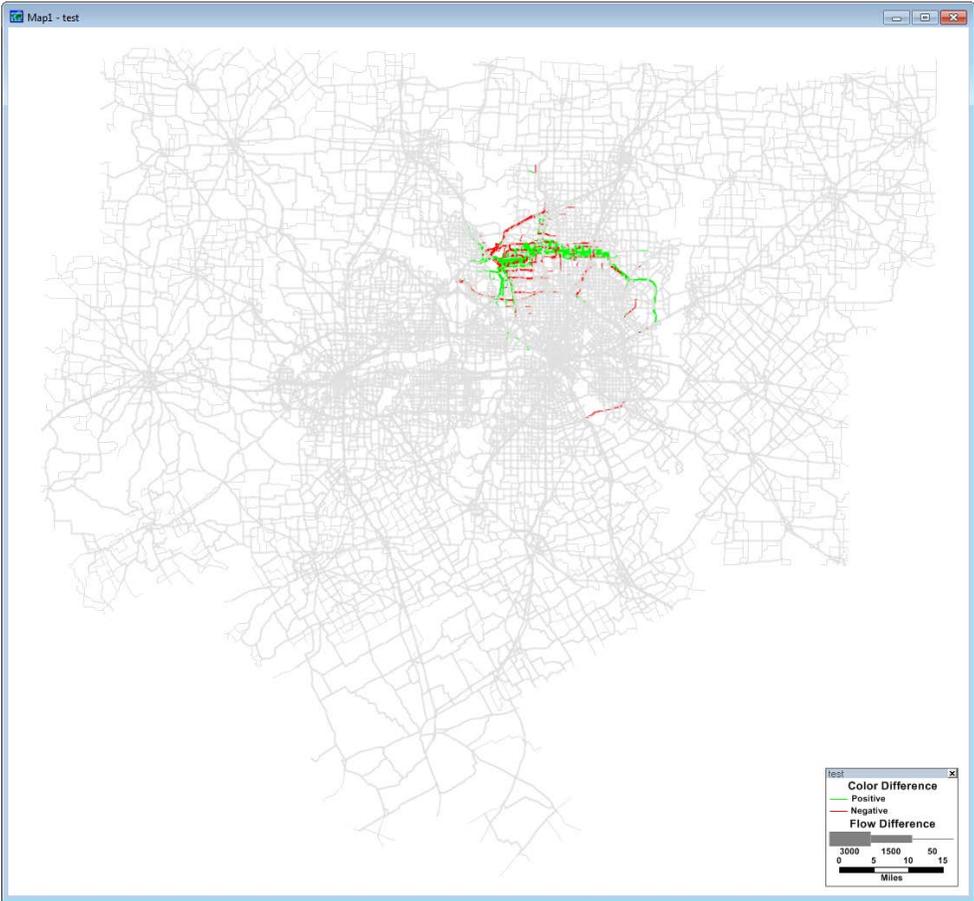
**Figure 7-34 Flow Differences in the Network Evaluated with a Full Model Run at 1.E-5 Assignment Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3500.11	27.33
Outside the vicinity of project	112.31	1.815997

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,866,047	1,094,196	3,135,803
After project added	34,896,578	1,093,803	3,135,856
Δ (Project-base)	+30,531	-393	+53

**Figure 7-35 Flow Differences in the NCTCOG Network Evaluated with a Full Model Run at 1.E-6 Assignment Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	3500.24	24.16
Outside the vicinity of project	164.33	1.69

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,857,823	1,093,928	3,135,850
After project added	34,887,629	1,093,475	3,135,877
$\Delta$ (Project-base)	+29,806	-453	+27

The following table summarizes the highway project impacts for all the analyses described above. The transit trips during AM were estimated by halving the peak period matrix total since the transit time period definitions were different from the highway definitions.

**Table 7-5 Summary of Model Runs Evaluating Changes Due to Added Lanes in the NCTCOG Network**

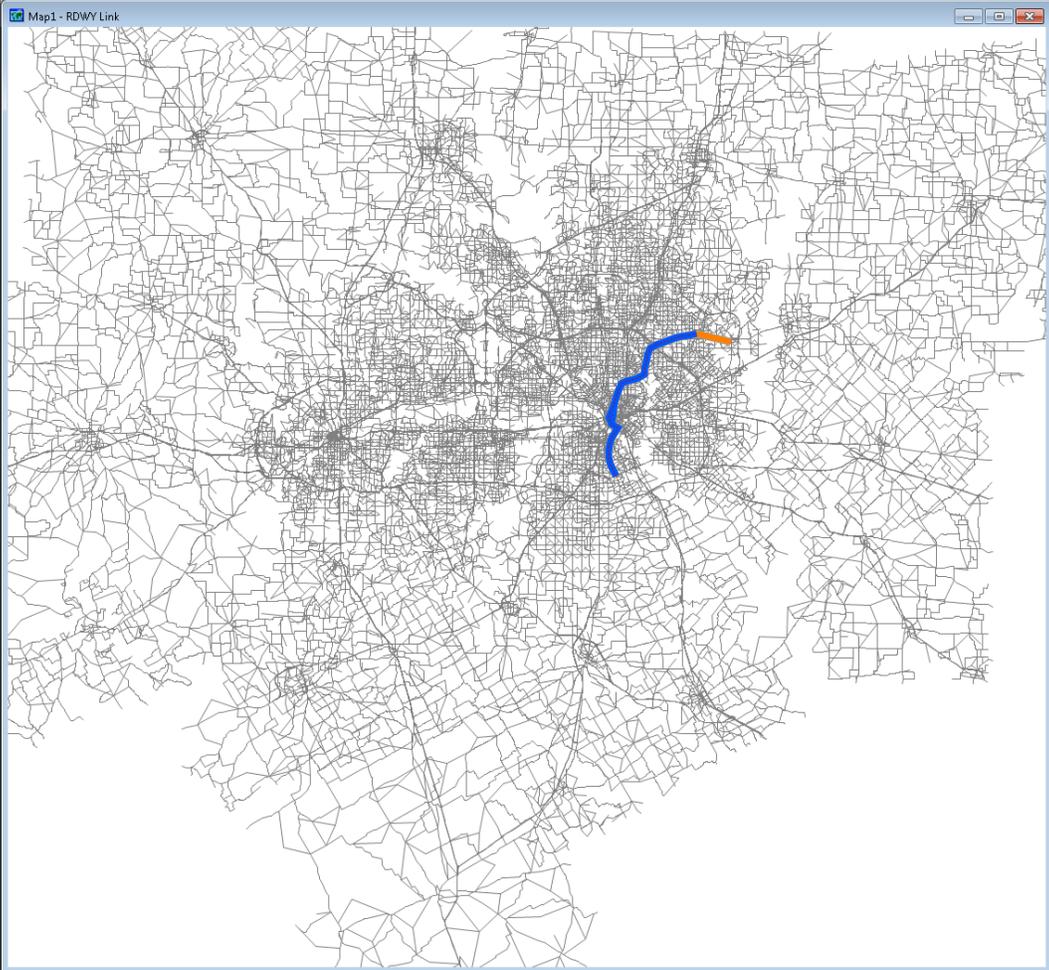
Highway assignment convergence	Type of model run	Δ AM VMT (Project-base)	Δ AM VHT (Project-base)	Δ AM Auto trips (Project-base)	Δ AM Transit trips (Project-base)
1.E-4	Highway AM assignment only	+5,903	-1,624	N/A (same O-D matrix)	N/A (no transit assignment)
1.E-5	Highway AM assignment only	+5,812	-1,574	N/A (same O-D matrix)	N/A (no transit assignment)
1.E-6	Highway AM assignment only	+5,898	-1,607	N/A (same O-D matrix)	N/A (no transit assignment)
1.E-4	Mode choice and assignment only	+3,491	-1,699	-29	-1
1.E-6	Mode choice and assignment only	+5,199	-1,549	+22	+2
1.E-4	Full model with feedback	+31,094	-460	+72	+7
1.E-5	Full model with feedback	+30,531	-393	+53	+152
1.E-6	Full model with feedback	+29,806	-453	+27	+10

Looking across these results, there are relatively small differences as a function of convergence level, but larger differences depending upon the modeling approach. The mode choice changes are plausible, and the analyst's judgment would be required to decide whether or not trip distribution changes as represented by the full model runs would be appropriate impacts of this project. At least in this case, there are positive benefits to the project irrespective of the modeling approach.

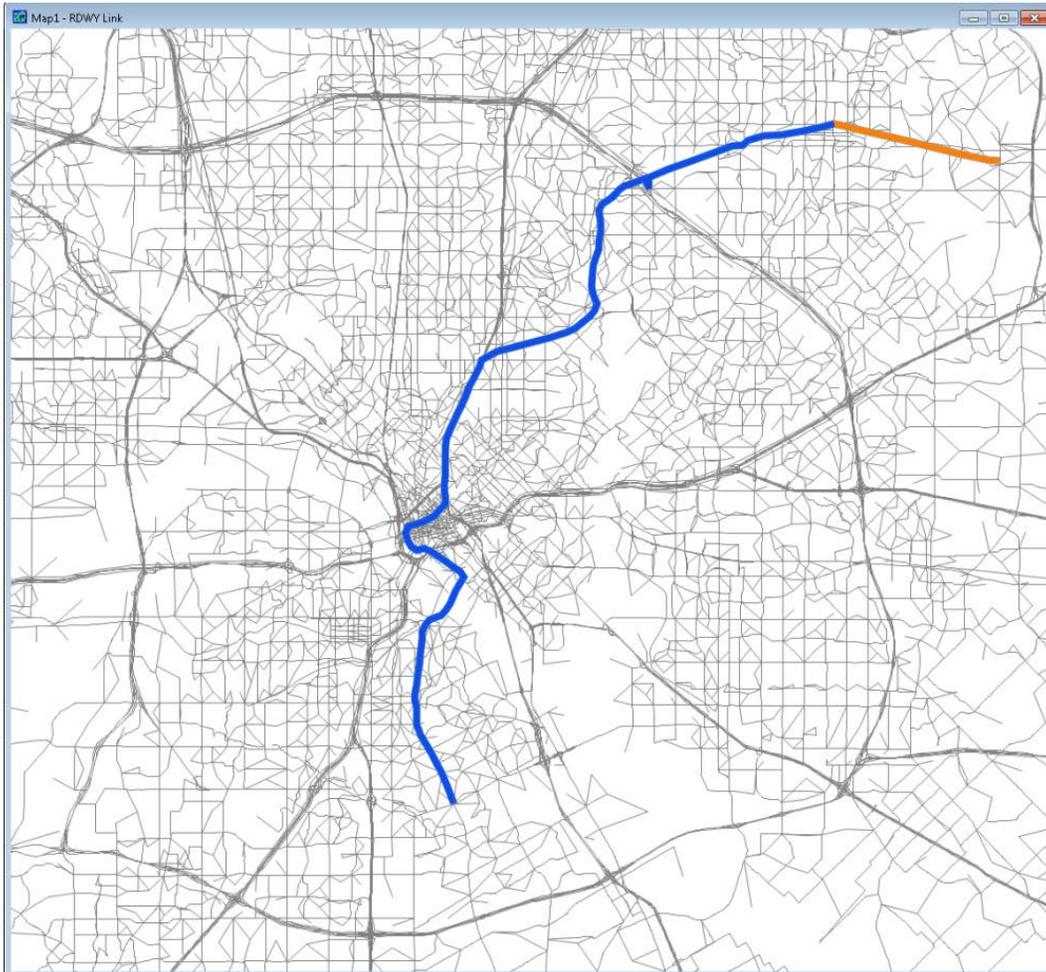
# Impact of a Light Rail Extension in Dallas-Ft. Worth

We next consider the impact of a transit project in the NCTCOG region. The future-year transit project was selected from the MPO's 2013 transit network and involved an extension of the Blue Line LRT by one station. In the figure below, the blue line represents the existing LRT line in the base year, and the orange line represents the extension.

Figure 7-36 Light-Rail Extension in the NCTCOG Region



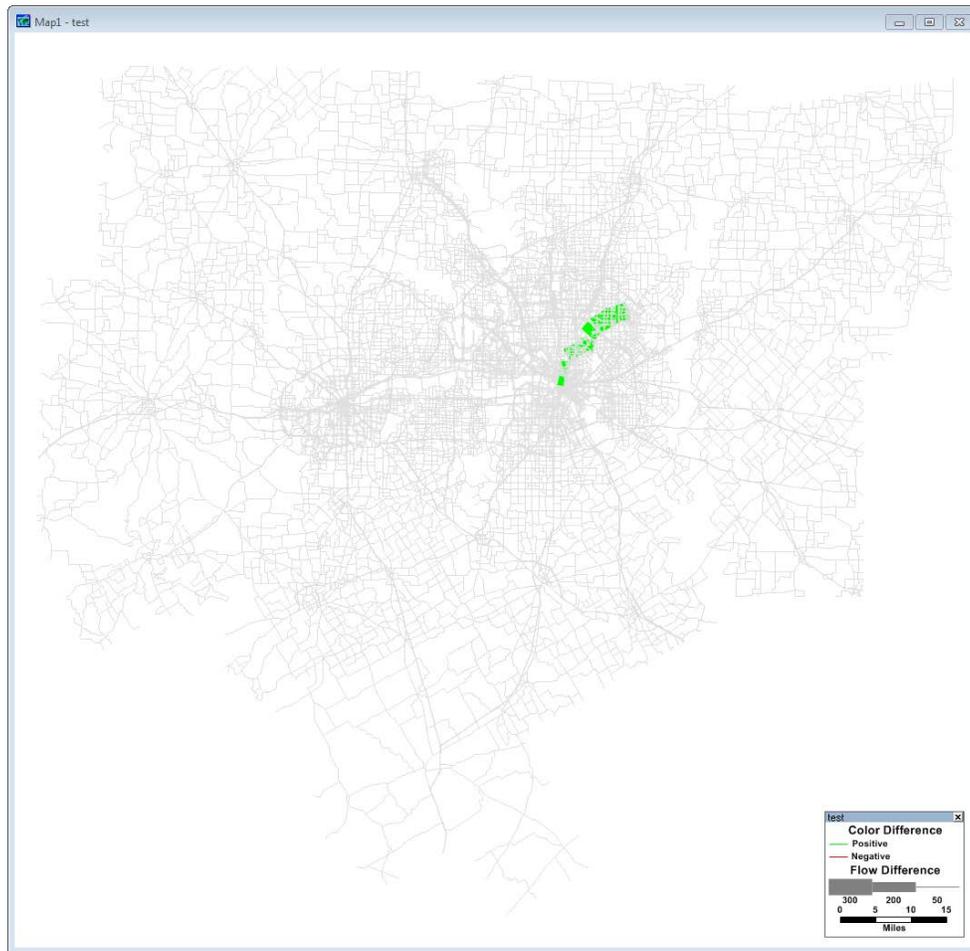
**Figure 7-37 Zoomed-In View of NCTOCG Transit Line Extension Project**



## ***Light rail extension impact with the NCTCOG mode choice and assignment models***

We compared the changes in transit flows compared to the base year shown in the Figure below when only the mode choice and assignment steps of the model were run after the addition of the transit project. This was first done using a convergence criterion of 1.E-4 relative gap for the highway assignment.

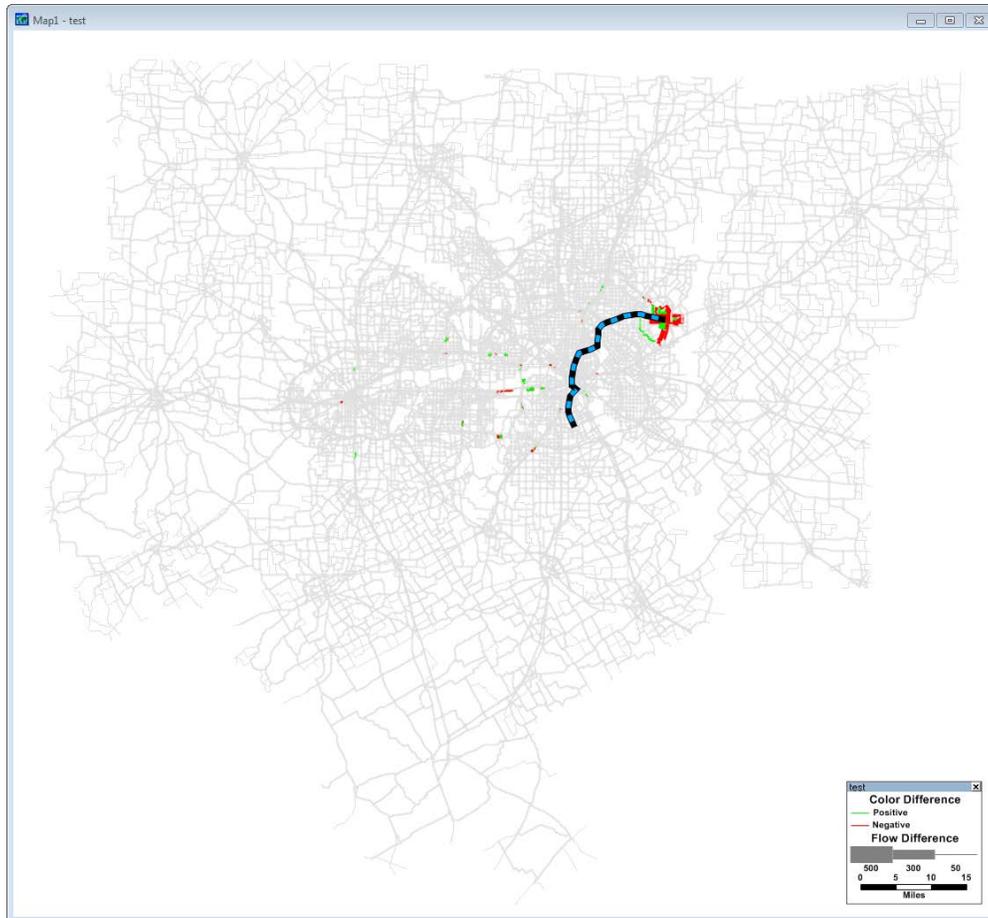
**Figure 7-38 Light Rail Transit Flow Differences in the NCTCOG Network at 1.E-4 RG Convergence**



	Assigned AM transit demand	AM passenger hours traveled (PHT)
Before project added	42,150	17,241
After project added	42,280	17,345
$\Delta$ (Project-base)	+130	+104

The projected change in ridership was a net gain of 130 riders. The highway flow differences are shown below. Some of the differences are rather far away from the project and the project corridor.

**Figure 7-39 Highway Flow Differences at 1.E-4 Convergence as a Result of the Light Rail Extension**



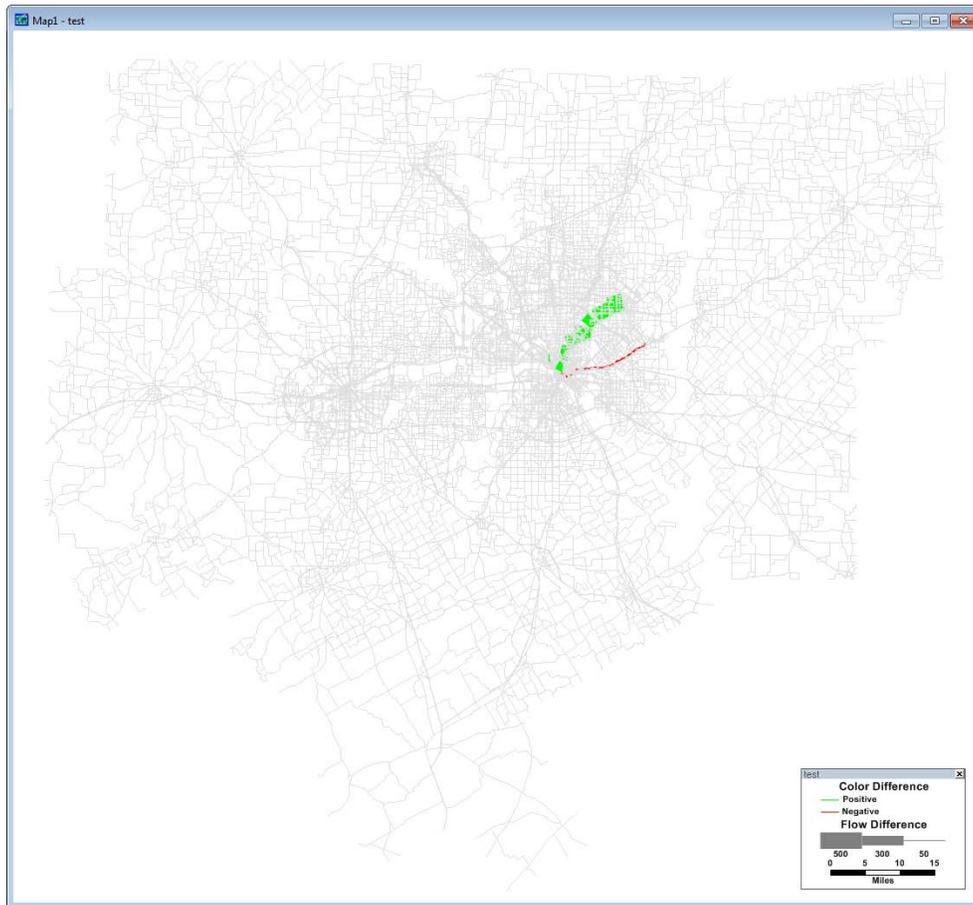
	Maximum AM hwy flow difference	Average AM hwy flow difference
In the vicinity of project	532.63	5.51
Outside the vicinity of project	123.07	1.43

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,870,375	1,094,384	3,135,888
After project added	34,869,151	1,094,308	3,135,797
$\Delta$ (Project-base)	-1,224	-76	-91

Roadway AM VHT is projected to decline by 76 vehicle hours in response to the light rail extension.

With a higher convergence set to 1.E-6, the transit ridership gains are larger as are the corresponding roadway VHT savings. Also, the transit assignment difference map shows a small diversion of flows from an alternate route.

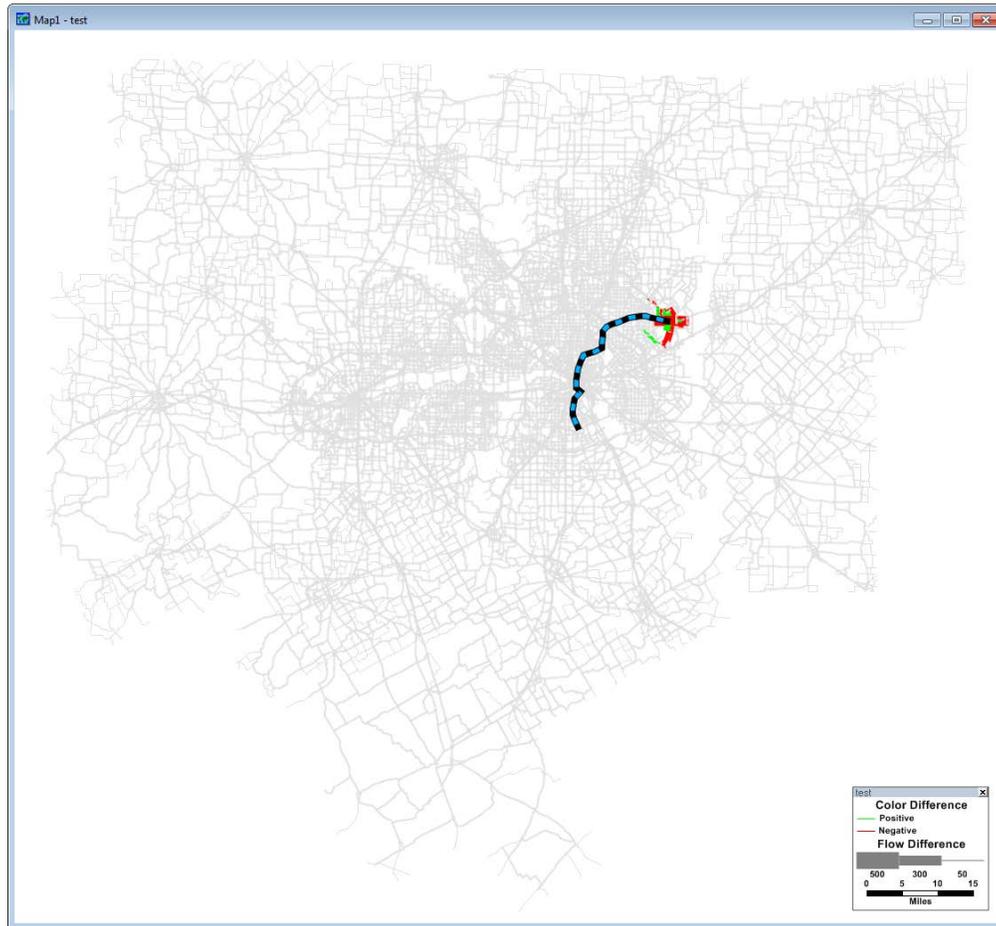
**Figure 7-40 Transit Flow Differences in the Network at 1.E-6 Convergence**



	Assigned AM transit demand	AM PHT
Before project added	42,141	17,272
After project added	42,321	17,372
$\Delta$ (Project-base)	+180	+100

At the higher level of convergence, the ridership gain is 180. Interestingly, there is a lower ratio of person hours of travel to the ridership gain that suggests that either more short trips are served, or that shorter trips on the project are replacing longer trips from other routes. The highway flow differences are more concentrated in the area of the transit improvement, which is more logical.

**Figure 7-41 Highway Flow Differences at 1.E-6 Convergence as a Result of the NCTCOG Region Transit Project**



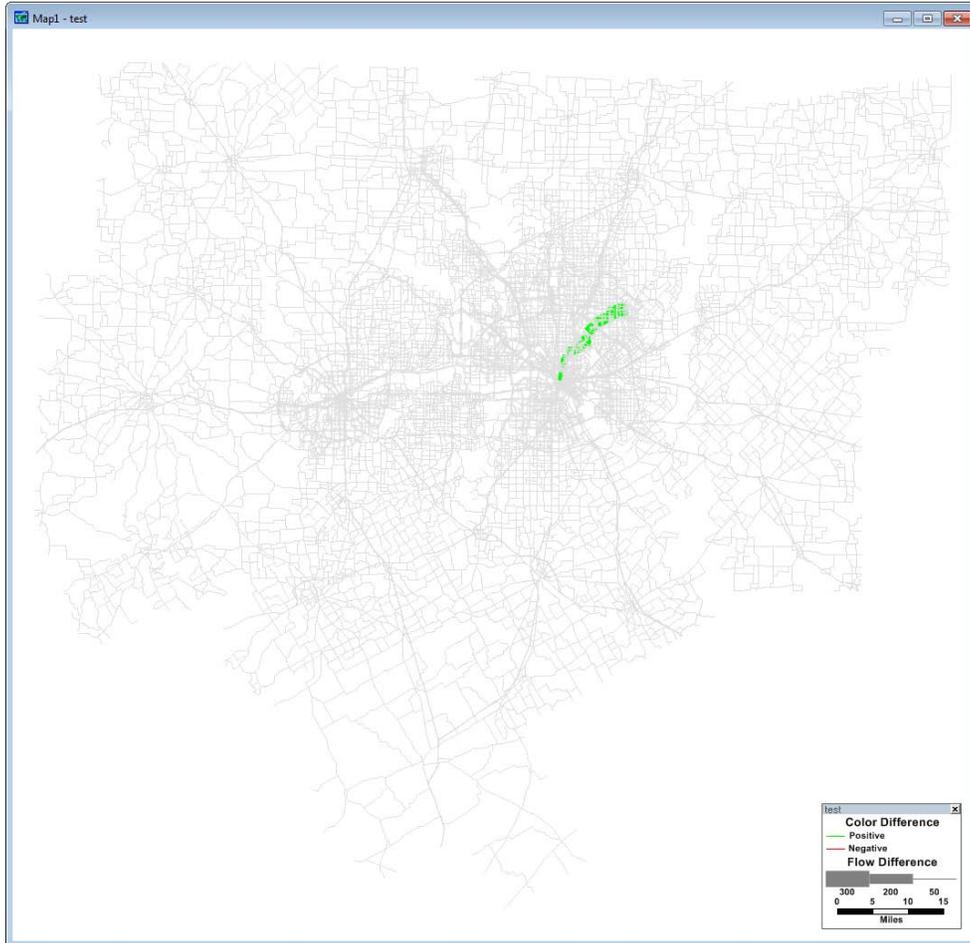
	Maximum AM hwy flow difference	Average AM hwy flow difference
In the vicinity of project	526.23	1.77
Outside the vicinity of project	16.95	0.33

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,857,883	1,093,916	3,135,852
After project added	34,856,421	1,093,820	3,135,752
$\Delta$ (Project-base)	-1,462	-96	-100

**Light rail extension impact assessed with an NCTCOG full model run**

Lastly, we perform the same project evaluation using a full run of the NCTCOG model. As seen below, the transit flow difference at relative gaps of 1.E-4, 1.E-5 and 1.E-6 are similar, but do vary a bit in terms of the total ridership gain.

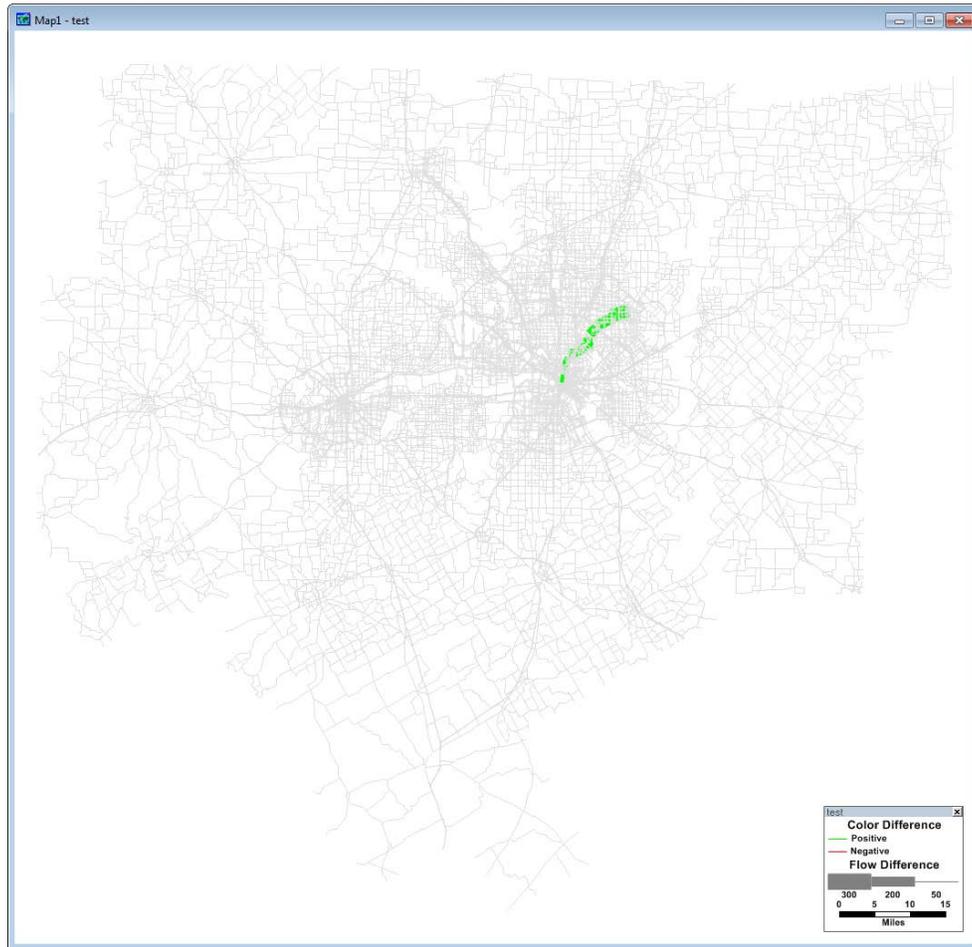
**Figure 7-42 Transit Flow Differences with a Full NCTCOG Model Run at 1.E-4 Convergence**



	Assigned AM transit demand	AM PHT
Before project added	42,150	17,241
After project added	42,279	17,344
Δ (Project-base)	+129	+103

With the project there is an estimated gain of 129 trips at 1.E-4 RG.

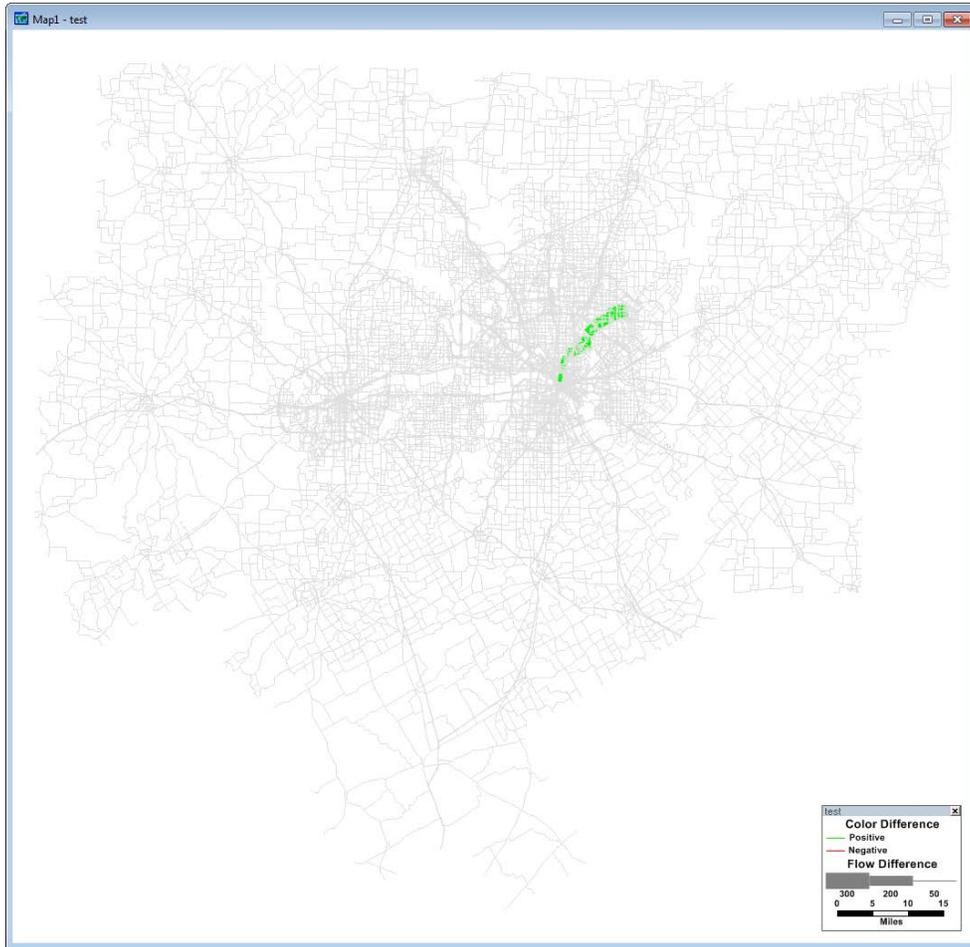
**Figure 7-43 Transit Flow Differences with a Full NCTCOG Model Run at 1.E-5 Assignment Convergence**



	Assigned AM transit demand	AM PHT
Before project added	42,007	17,275
After project added	42,328	17,376
Δ (Project-base)	+321	+101

At the assignment convergence level of a 1.E-5 relative gap, the estimated transit ridership increase is 321 trips. At a relative gap of 1.E-6 and with a full model run, the estimated ridership gain is 180 trips. The results for that run are in the figure below.

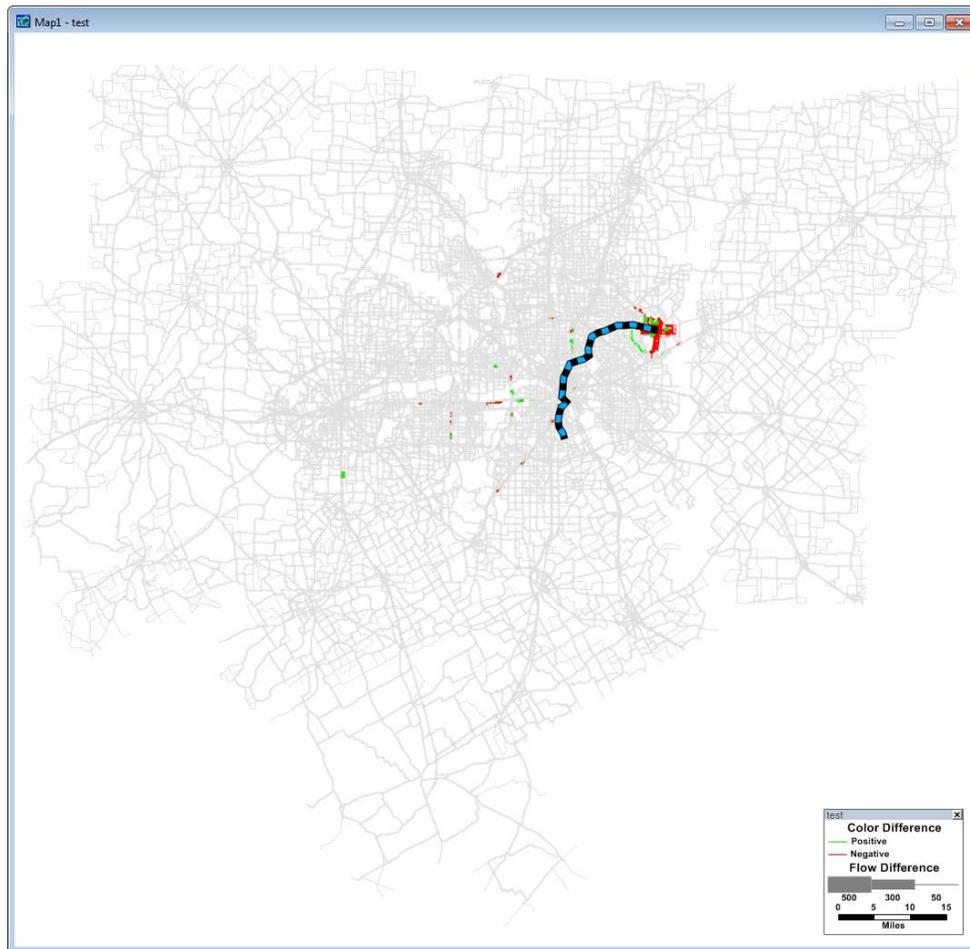
**Figure 7-44 Transit Flow Differences in the NCTCOG Network at 1.E-6 Convergence**



	Assigned NCTCOG AM transit demand	AM PHT
Before project added	42,141	17,272
After project added	42,321	17,372
Δ (Project-base)	+180	+100

The introduction of a transit line extension project has an effect on highway flows. Overall highway flow decreases in the project vicinity. The highway differences are also sensitive to the level of highway convergence specified. At 1.E-4 RG, there are links outside the vicinity of the transit project that have flow differences. At 1.E-5 RG, there are almost no roadway flow differences outside the vicinity of the transit project.

**Figure 7-45 NCTCOG highway Flow Differences at 1.E-4 Convergence as a Result of the Transit Project**

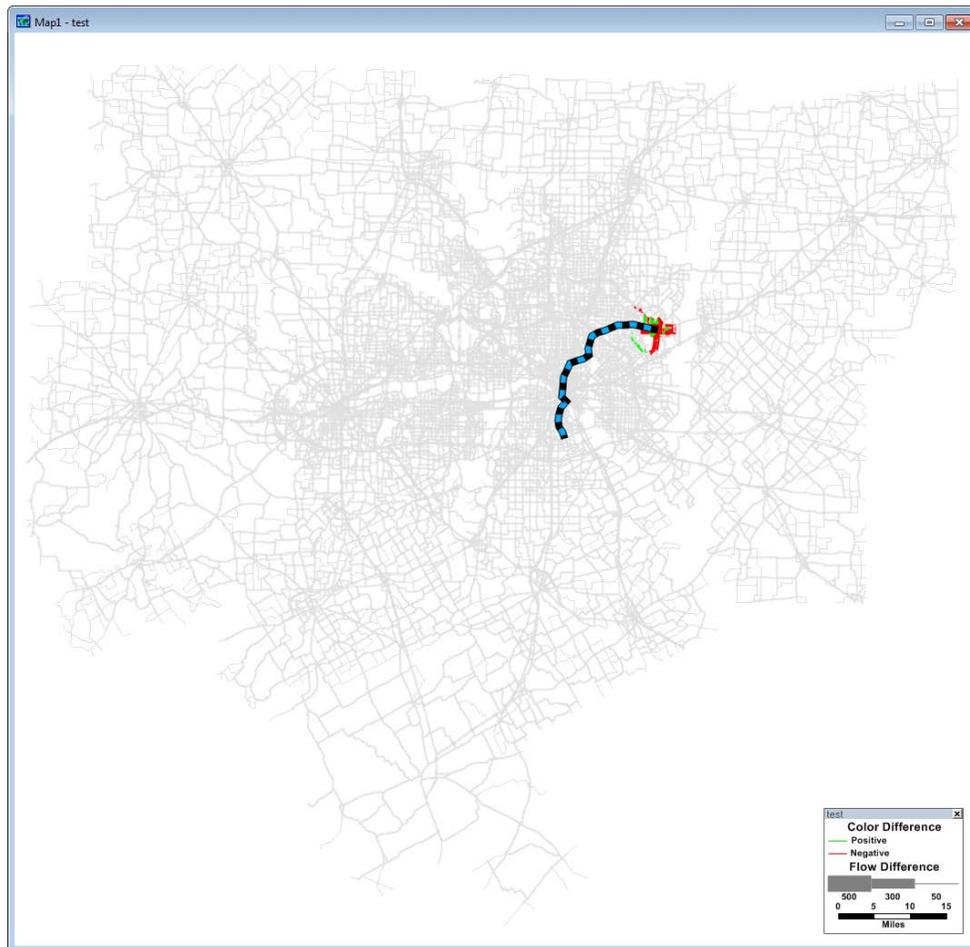


	Maximum flow difference	Average flow difference
In the vicinity of project	555.32	6.24
Outside the vicinity of project	147.37	2.42

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,870,375	1,094,384	3,135,888
After project added	34,873,691	1,094,566	3,135,781
$\Delta$ (Project-base)	+3316	+182	-113

We see that at a lower convergence level, the transit project seems detrimental to highway travel times but this is resolved at higher convergence levels where there are VHT savings from the transit project.

**Figure 7-46 Highway Flow Differences Assessed with a Full Model Run at 1.E-5 Convergence as a Result of the NCTCOG Transit Project**

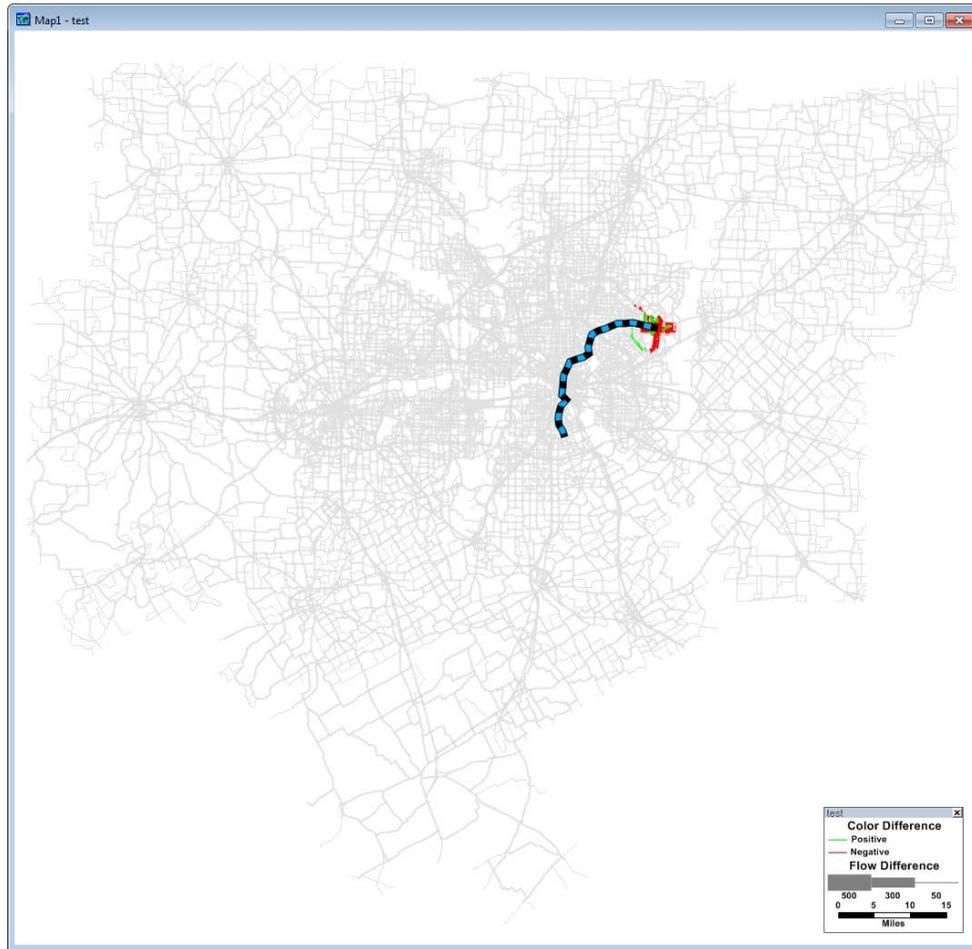


	Maximum flow difference	Average flow difference
In the vicinity of project	550.59	2.73
Outside the vicinity of project	18.05	0.81

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,867,093	1,094,249	3,135,802
After project added	34,865,335	1,094,144	3,135,702
$\Delta$ (Project-base)	-1758	-105	-100

The estimated impacts of the transit line extension at 1.E-6 RG are similarly concentrated geographically, but the VHT savings are somewhat different than that at 1.E-5.

**Figure 7-47 Highway Flow Differences at 1.E-6 Convergence as a Result of the NCTCOG Transit Project**



	Maximum flow difference	Average flow difference
In the vicinity of project	548.80	2.32
Outside the vicinity of project	22.53	0.29

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	34,857,883	1,093,916	3,135,852
After project added	34,856,970	1,093,844	3,135,739
$\Delta$ (Project-base)	-913	-72	-113

The following table summarizes the project impacts for all the runs described above.

**Table 7-6 NCTCOG Transit Line Extension Model Run Summary**

Highway assignment convergence	Type of model run	Δ AM VMT (Project-base)	Δ AM VHT (Project-base)	Δ AM Auto trips (Project-base)	Δ AM Transit trips (Project-base)	Δ AM PHT
1.E-4	Mode choice and assignment only	-1,224	-76	-91	+130	+104
1.E-6	Mode choice and assignment only	-1,462	-96	-100	+180	+100
1.E-4	Full model with feedback	+3,316	+182	-113	+129	+103
1.E-5	Full model with feedback	-1,758	-105	-100	+321	+101
1.E-6	Full model with feedback	-913	-72	-113	+180	+100

In general we find consistent results for the project impacts except in the case of the full model run with the 1.E-4 highway convergence. We also can see the gain in ridership does vary with convergence levels, once again suggesting that higher convergence would be the best modeling approach.

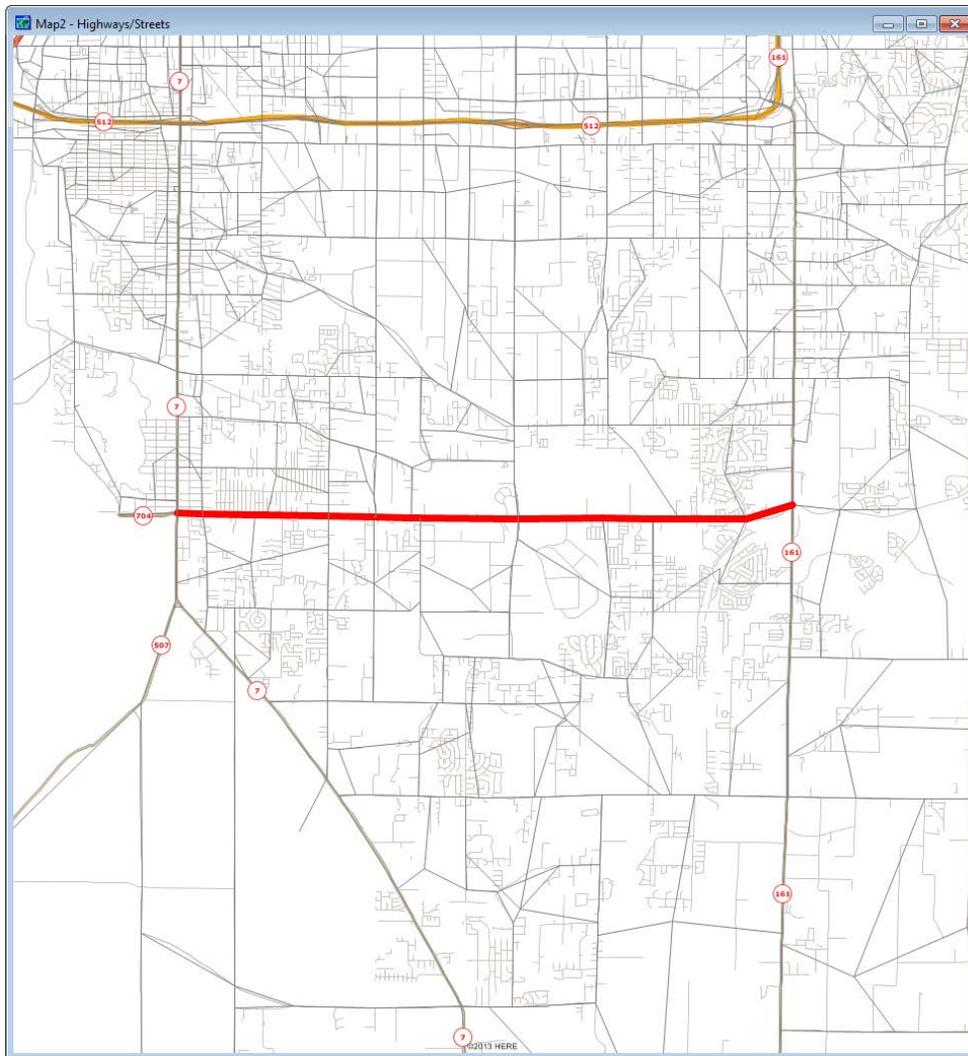
## Impact of a Roadway Project in the Puget Sound Region

We obtained the assignment scripts, networks, matrices, and output flows for the base year scenario from PSRC and proceeded to implement the highway assignment in TransCAD. Once we had achieved a reasonably close match with the flows obtained by the MPO, we coded a future year highway project into the network. PSRC's base year is 2010 and the project chosen was from the 2014 network. It involved the widening of 176th St, an arterial, from 1 to 2 lanes in each direction on the section connecting SR161 and SR7.

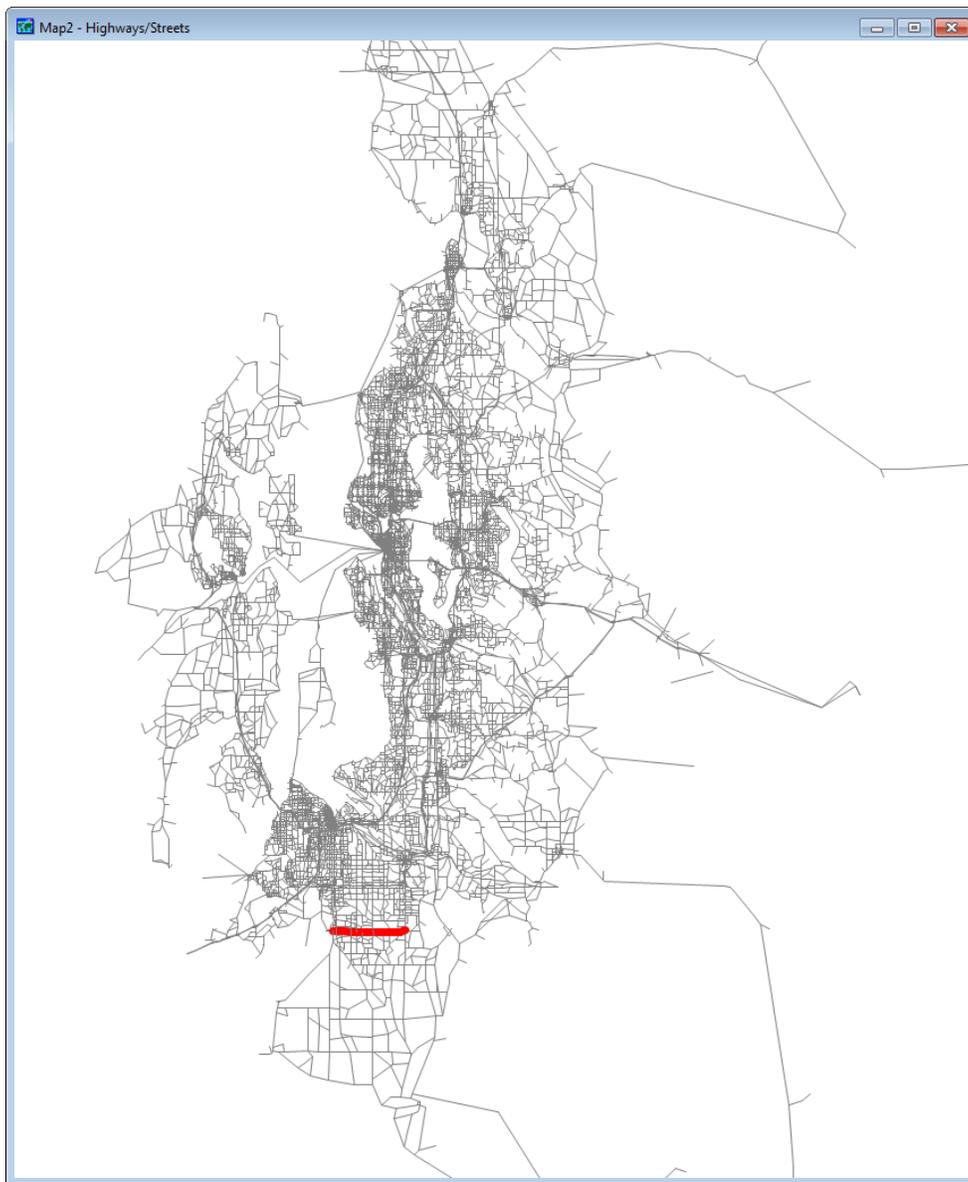
### ***Impact of a widened arterial in the PSRC region***

We performed an AM assignment-only evaluation of the project, which is displayed in red in the map that follows.

**Figure 7-48 Roadway Project on 176 St Connecting SR161 and SR7**



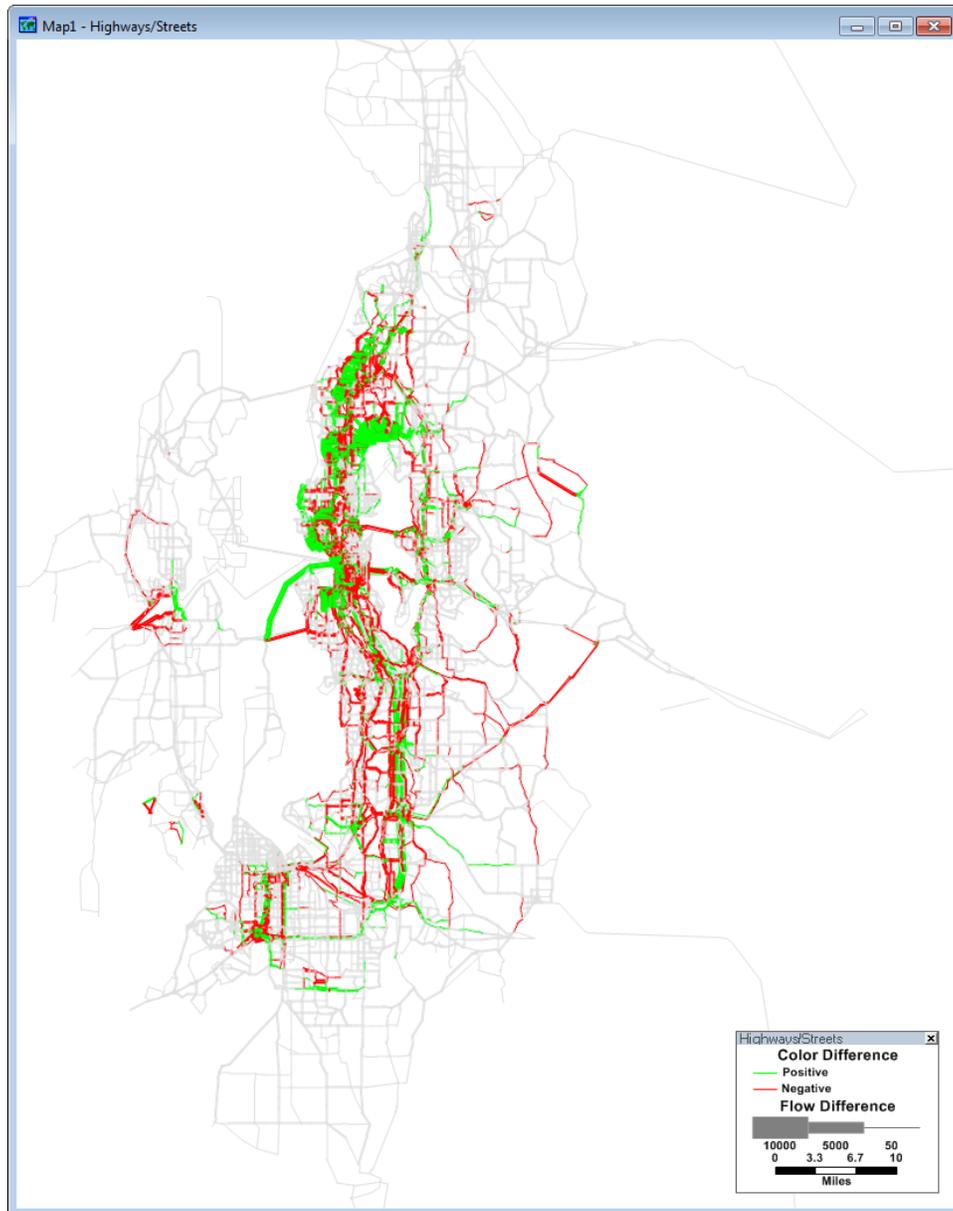
**Figure 7-49 Roadway Project Location and Limits in PSRC Network**



Since the MPO model assignment uses a path-based algorithm, all the analysis was performed using the path-based algorithm in TransCAD. The evaluation was performed at three convergence levels with relative gaps of 1.E-4, 1.E-5, and 1.E-6, respectively.

At a relative gap of 1.E-4 there were impacts all over the region including many that were far away from the project corridor. Curiously, the largest impacts were not in the vicinity of the improvement project.

**Figure 7-50 Flow Differences in the PSRC Network at 1.E-4 Convergence**



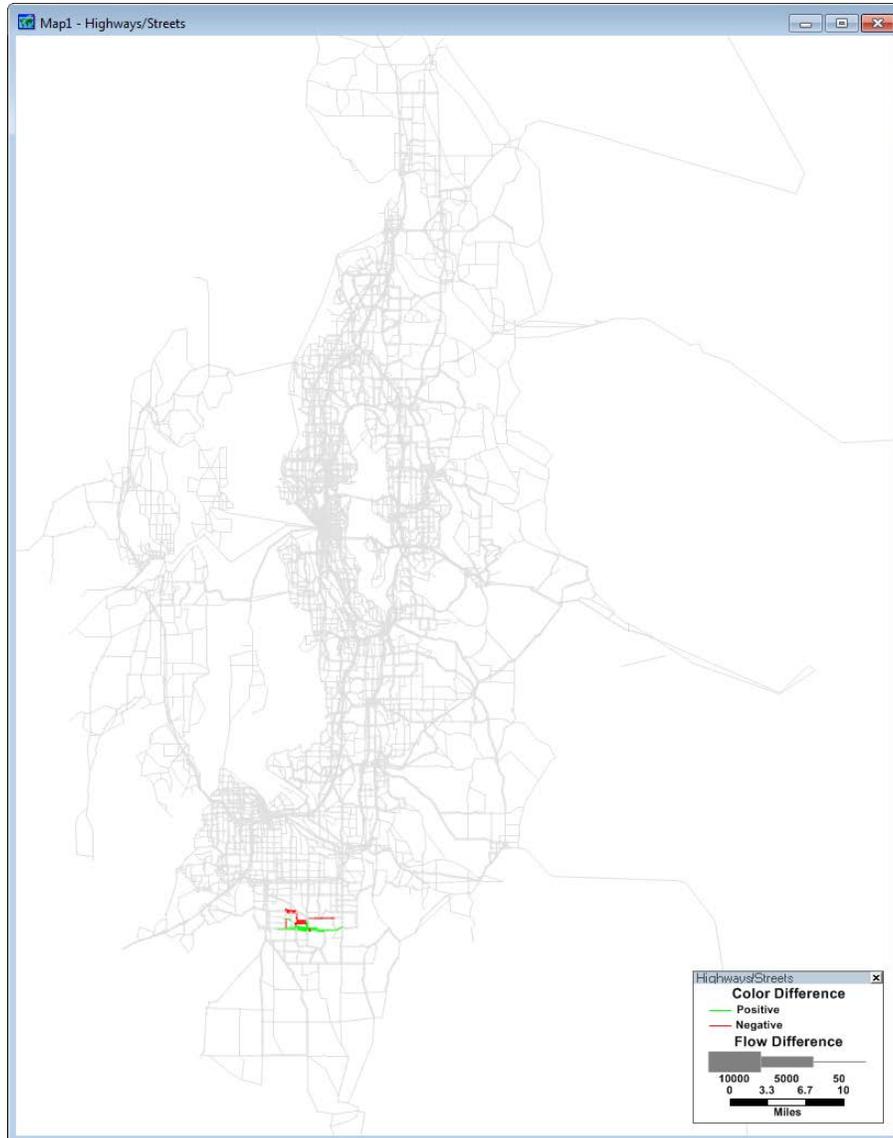
Overall there was a lessening of VHT calculated as shown in the Table below.

	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	2,018.84	55.61
Outside the vicinity of project	10,562.82	122.36

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	13,122,321	447,167	1,350,163
After project added	13,121,917	446,816	1,350,163
$\Delta$ (Project-base)	-404	-351	0

In contrast, at a relative gap of 1.E-5 virtually all of the link differences away from the project disappeared. There was also a drop in the estimated VHT benefits. As indicated below, the effect of tighter convergence is rather startling.

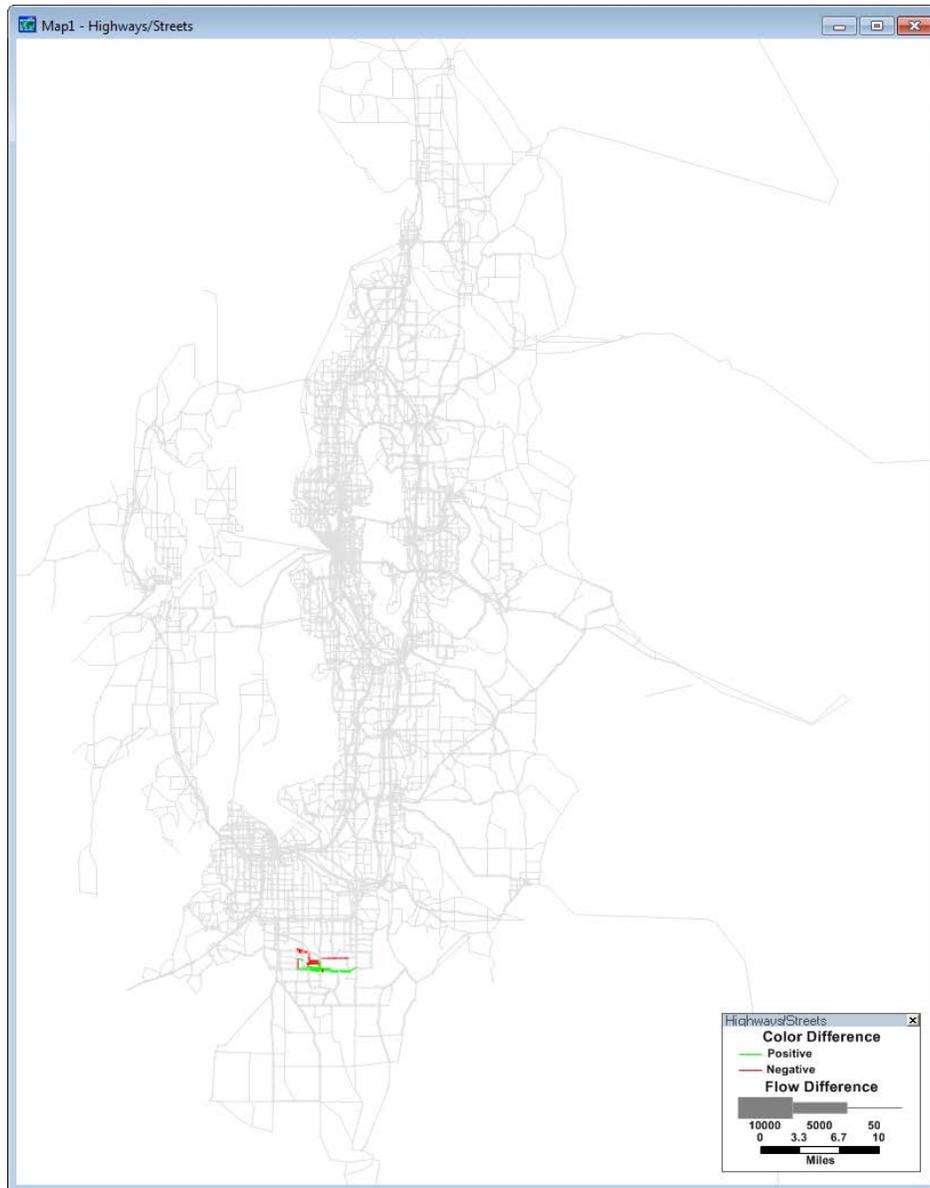
**Figure 7-51 Flow Differences in the PSRC Network at 1.E-5 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	467.27	9.69
Outside the vicinity of project	36.96	0.66

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	13,122,030	447,028	1,350,163
After project added	13,122,021	446,970	1,350,163
$\Delta$ (Project-base)	-9	-58	0

**Figure 7-52 Flow Differences in the Network at 1.E-6 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	468.269747	9.63643
Outside the vicinity of project	36.834	0.334689

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	13,121,905	447,018	1,350,163
After project added	13,121,962	446,979	1,350,163
$\Delta$ (Project-base)	+57	-39	0

The following table summarizes the analysis from the PSRC assignment runs with a highway project added.

**Table 7-7 PSRC Network Highway Project Impact Summary**

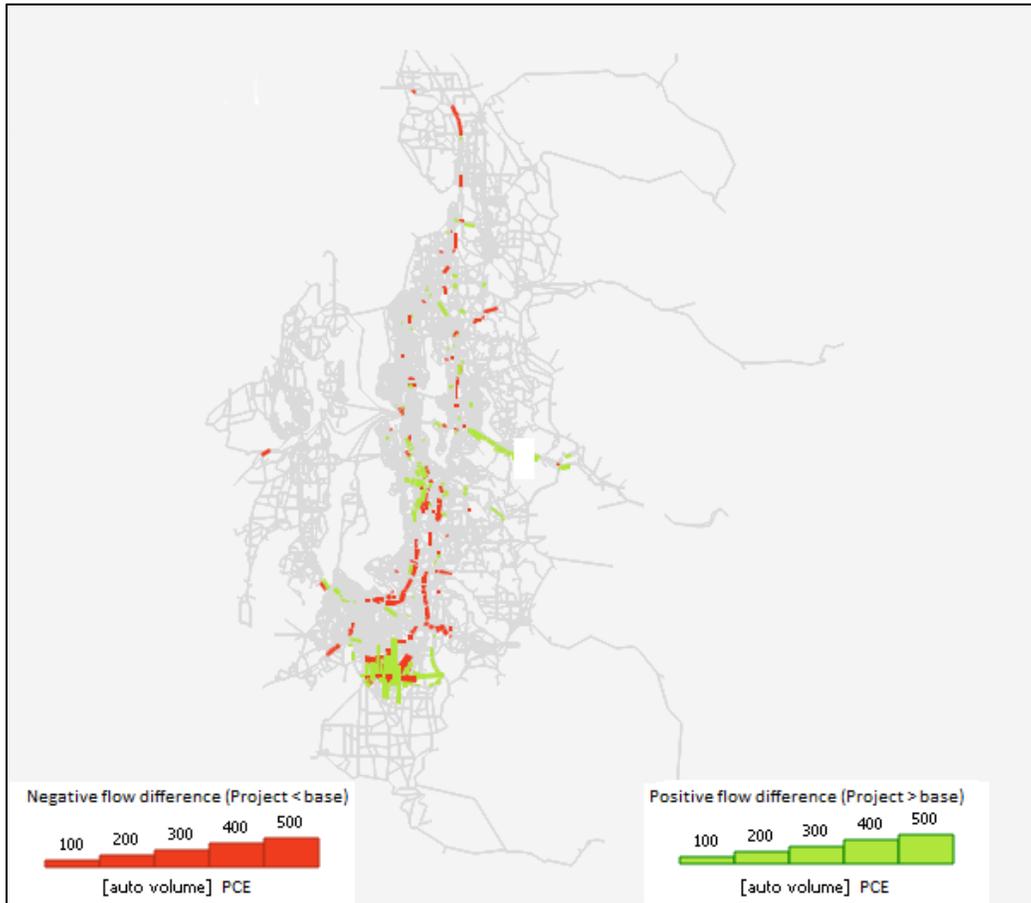
Highway assignment convergence	Type of model run	$\Delta$ AM VMT (Project-base)	$\Delta$ AM VHT (Project-base)	$\Delta$ AM Highway trips (Project-base)
1.E-4	Highway AM assignment only	-404	-351	0
1.E-5	Highway AM assignment only	-9	-58	0
1.E-6	Highway AM assignment only	+57	-39	0

Quite obviously there are different estimated benefits based upon the relative gap computed. Once again, we see that gross errors can result from limiting the relative gap to 1.E-4.

### ***PSRC full model run with highway project added***

We asked PSRC to make some full feedback model runs for the no-build and build scenarios of the same roadway project. The PSRC model uses a fixed number (5) of feedback loops using skim averaging between loops.

**Figure 7-53 Flow Differences in the PSRC Network with a Full Model Run at 1.E-4 Convergence**



**Max link flow increase = 817 PCE**  
**Max link flow decrease = 538 PCE**

	AM VMT	AM VHT
Before project added	13,204,727	461,682
After project added	13,202,370	461,513
$\Delta$ (Project-base)	-2,357	-169

**Figure 7-54 Flow Differences in the PSRC Network at 1.E-5 Convergence**

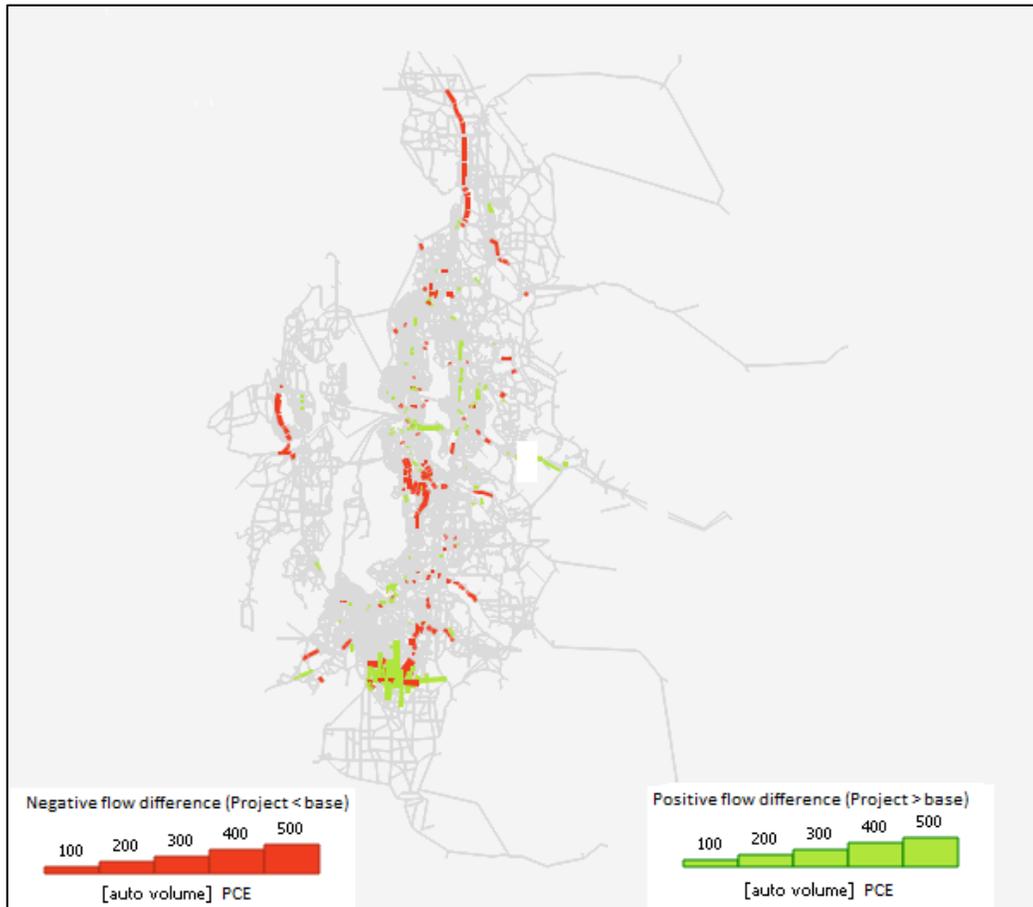


**Max link flow increase = 815 PCE**  
**Max link flow decrease = 527 PCE**

	AM VMT	AM VHT
Before project added	13,205,110	461,706
After project added	13,205,362	461,709
$\Delta$ (Project-base)	+252	+3

It is interesting to note that in the assignment-only tests performed by Caliper, the flow differences outside the project impact area are considerable in the 1.E-4 scenario but become negligible in the assignments to 1.E-5 and 1.E-6. However in the full model runs performed by the MPO, there doesn't seem to be any appreciable clearance of random changes when you go from 1.E-4 to 1.E-5 and 1.E-6.

**Figure 7-55 Flow Differences in the PSRC Network at 1.E-6 Convergence**



**Max link flow increase = 810 PCE**  
**Max link flow decrease = 512 PCE**

	AM VMT	AM VHT
Before project added	13,205,174	461,599
After project added	13,200,363	461,452
$\Delta$ (Project-base)	-4,811	-147

Below we summarize the results for the full model runs at different levels of convergence.

**Table 7-8 Summary of PSRC Full Model Runs for a Highway Project**

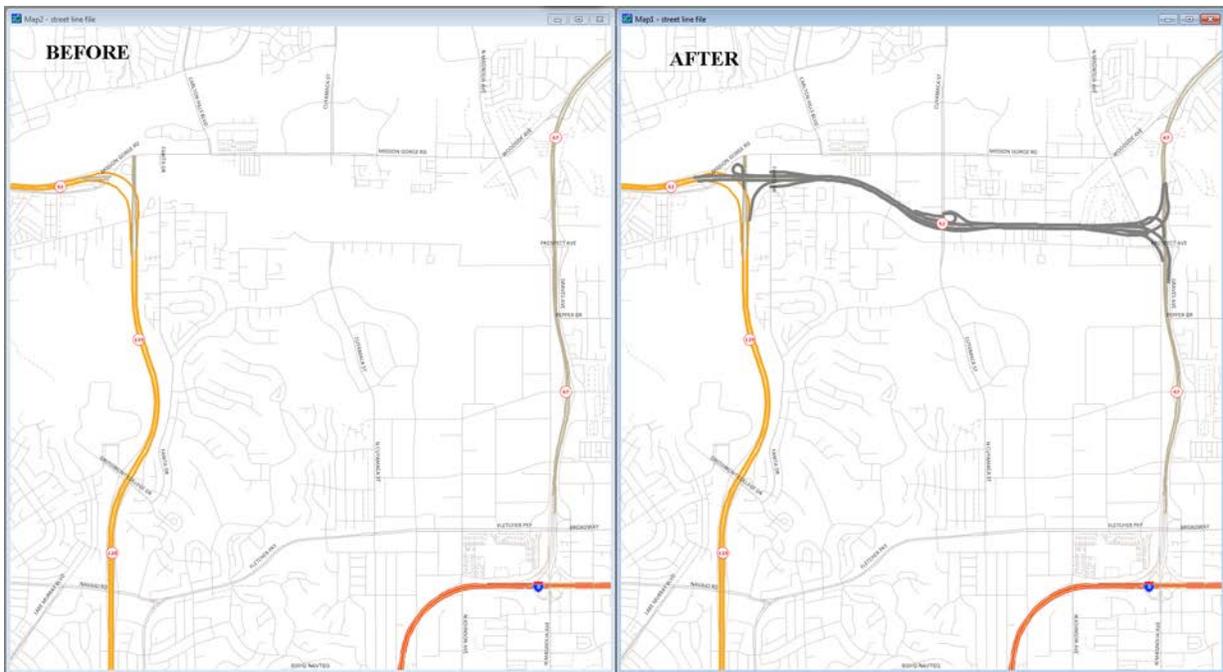
Highway assignment convergence	Type of model run	$\Delta$ AM VMT (Project-base)	$\Delta$ AM VHT (Project-base)
1.E-4	Full model run with feedback	-2,357	-169
1.E-5	Full model run with feedback	+252	+3
1.E-6	Full model run with feedback	-4,811	-147

The full model runs show changes all over the PSRC region at all levels of convergence. We were not able to attempt a diagnosis of the reasons why this happens although it may be attributable to the skim averaging between loops and/or the matrix trip rounding performed as part of the assignment process. Nevertheless, we find evidence here, too, that different levels of assignment convergence lead to difference modeling results.

## Impact of a Roadway Project in San Diego

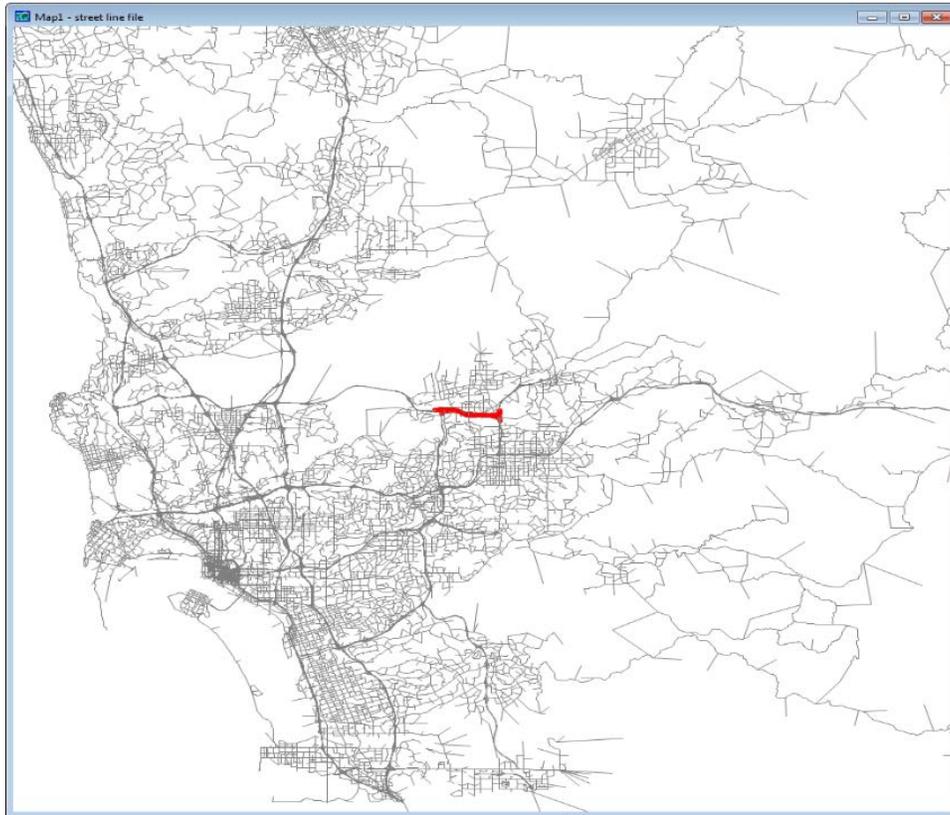
In the following section, we analyze the effect on flows of adding a highway project to the SANDAG base year 2010 network. The future-year highway project chosen was from the MPO's 2050 plan network and involves the addition of a new section on SR-52 connecting SR-125 and SR-67 as shown below. This analysis was conducted using the SANDAG ABM model.

**Figure 7-56 Roadway Project Introducing a New Section of Highway on SR-52 in the SANDAG Region**



The location of the project in the SANDAG region is highlighted in red in the next figure.

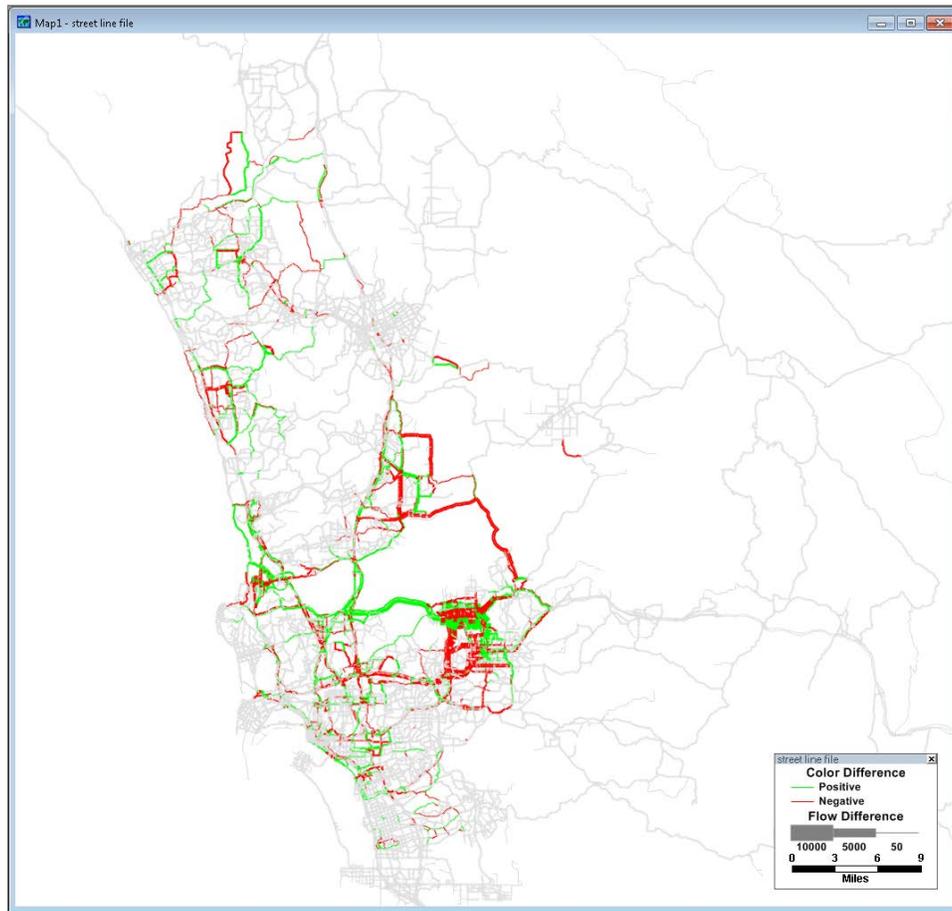
**Figure 7-57 Roadway Project Location in the SANDAG Regional Network**



### ***Assignment-only analysis***

We ran the SANDAG AM traffic assignment that is part of the ABM model with and without the project added using the same input base year O-D trip matrix. The AM highway assignment was chosen to enable better comparison with the results from the full model run, which uses the AM flows to determine feedback convergence. The assignment was performed to three convergence levels at relative gaps of 5.E-4 (which is the convergence specified by the MPO), 1.E-5 and 1.E-6. As before, we color code the links that have increased by 50 or more vehicles in green and those that have decreased by 50 or more vehicles in red. At 5.E-4, the travel time savings are dramatically higher than those estimated at higher convergence levels.

**Figure 7-58 Flow Differences in the SANDAG Network at 5.E-4 RG with Assignment-Only Analysis**



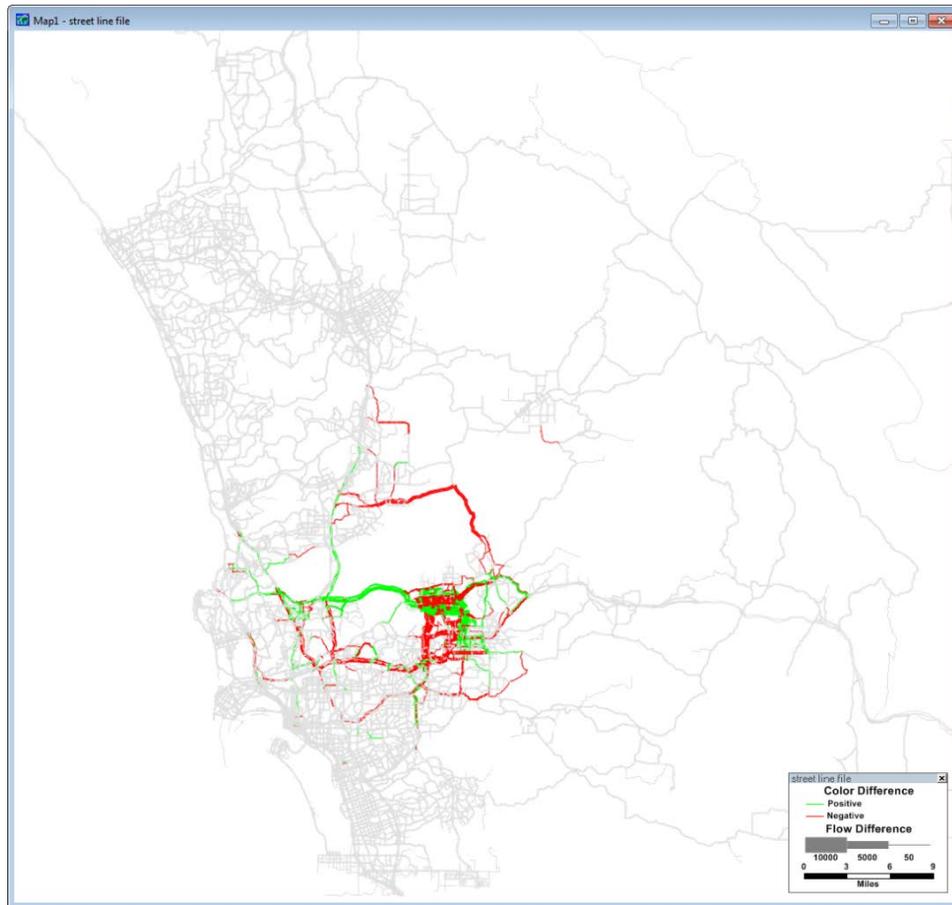
	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	11,106.64	186.08
Outside the vicinity of project	2,336.50	37.02

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,927,509	490,231	1,803,507
After project added	16,894,149	476,196	1,803,507
$\Delta$ (Project-base)	-33,360	-14,035	0

The map illustrates that the new link attracts increased flow that is diverted from alternate routes.

The project reduces VHT and also VMT due to the direct connection now available to some O-D pairs. This project has a significant impact in that at least one link has a flow difference in the vicinity of the project of more than 11,000 vehicles. In the map of flow differences above, there are some impacts far away from the project. Some of these disappear at higher levels of convergence as shown in the next Figures.

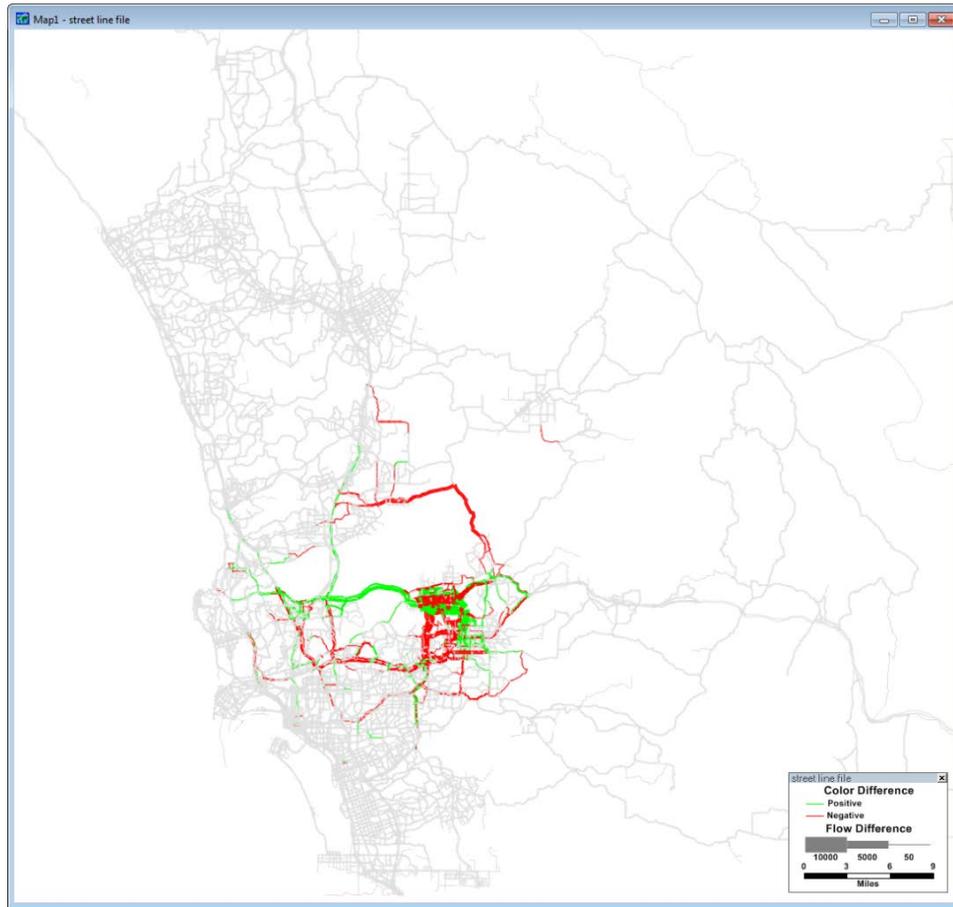
**Figure 7-59 Flow Differences in the SANDAG Network at 1.E-5 RG with Assignment-Only Analysis**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	11,393.16	293.13
Outside the vicinity of project	2,289.94	13.20

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,539	490,586	1,803,507
After project added	16,877,589	487,414	1,803,507
$\Delta$ (Project-base)	-56,950	-3,172	0

**Figure 7-60 Flow Differences in the SANDAG Network at 1.E-6 RG with Traffic Assignment-Only Analysis**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	11,392.62	293.05
Outside the vicinity of project	2,290.45	13.11

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,392	490,591	1,803,507
After project added	16,877,542	487,412	1,803,507
$\Delta$ (Project-base)	-56,850	-3,179	0

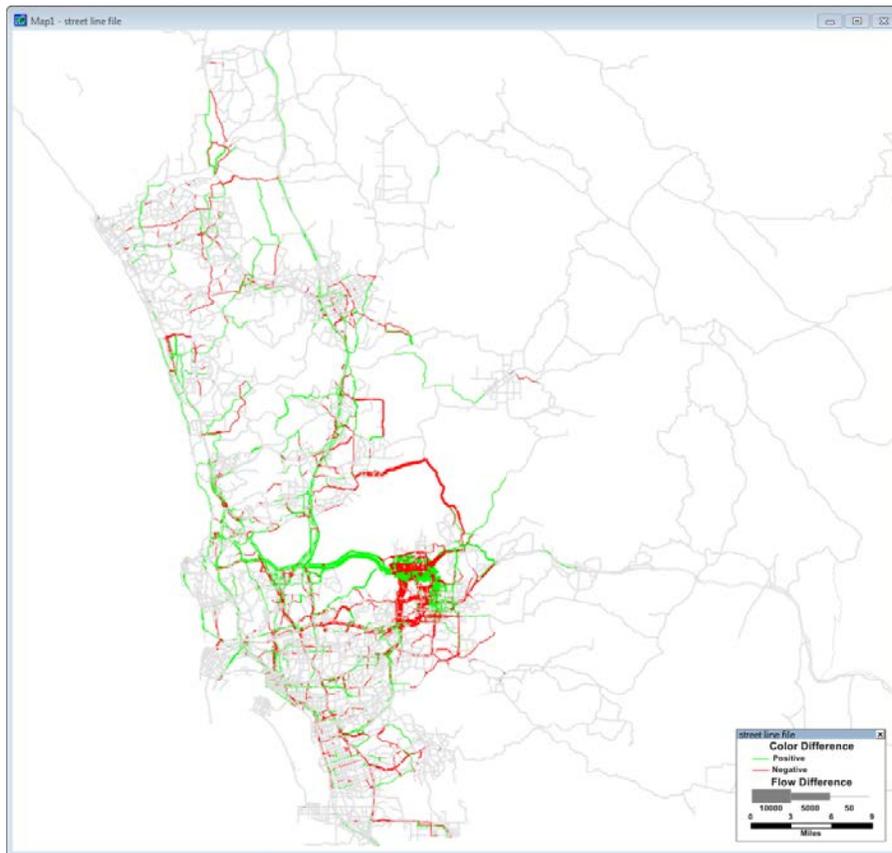
The plots and numerical results for convergence levels of 1.E-5 and 1.E-6 are quite similar. Both indicate a fairly substantial impact of the project.

### **Impacts assessed with a single model loop**

We conducted a single loop run of the ABM using updated skims from the addition of the roadway project to the network. A 100% sample for the population was used in the single loop run and thus the comparisons below are with the final feedback loop of the base scenario which also uses a 100% sample. The project impact evaluation was done at two highway convergence levels of 5.E-4 and 1.E-6 relative gaps.

In the figures that follow, there are notable differences in the plots and VHT savings associated with the different relative gaps. At 5.E-4, flow changes are observed all over the region. At a tighter relative gap of 1.E-6, the changes are more localized but still range far from the project.

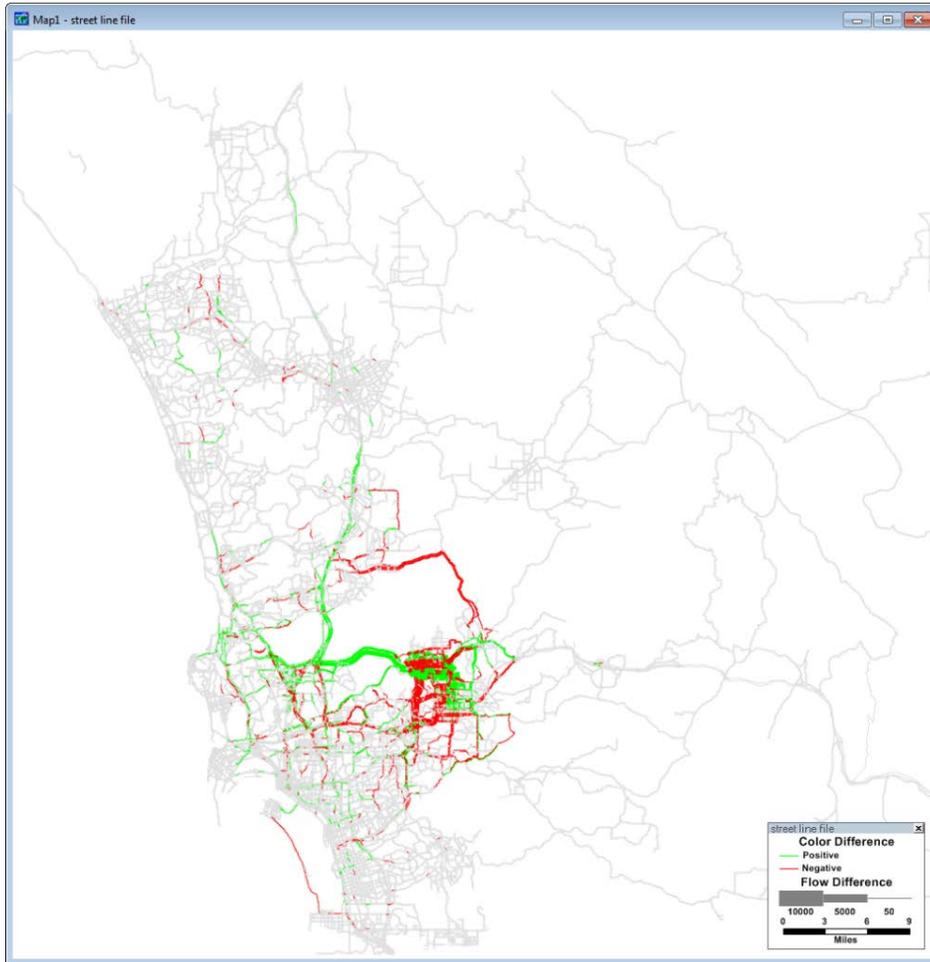
**Figure 7-61 Flow Differences in the SANDAG Network at 5.E-4 RG with a One Loop Model Run**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	12,068.74	308.78
Outside the vicinity of project	2,351.83	33.53

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,936,493	490,802	1,803,507
After project added	16,918,169	489,540	1,804,207
$\Delta$ (Project-base)	-18,324	-1,262	+700

**Figure 7-62 Flow Differences in the SANDAG Network at 1.E-6 RG with One Model Loop**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	12122.54	252.13
Outside the vicinity of project	2116.80	22.13

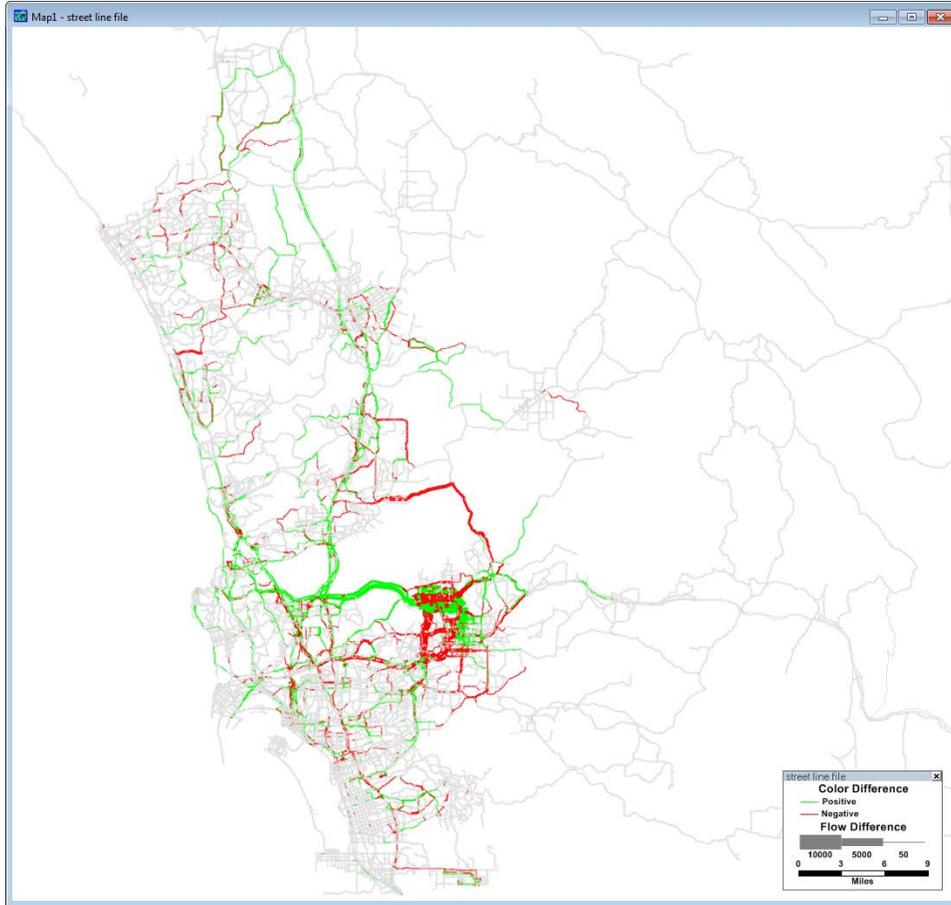
	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,563	490,529	1,803,829
After project added	16,906,044	488,885	1,804,104
$\Delta$ (Project-base)	-28,519	-1,644	+275

Clearly, the project impacts are different and more localized at the tighter convergence level. We note however that the VHT decreases are lower than the decreases estimated with the assignment-only analysis.

### **SANDAG full model run with highway project added**

To conclude the highway project analysis, we analyzed the difference in flows when the full model with feedback is run with the project added. The MPO fixes the number of feedback loops at 3. The sampling percentages for the population synthesis model within the ABM are set at 20%, 50%, and 100% for the first, second and third feedback loops respectively (a sampling percentage of 20 means that only one in five people in the synthetic population are modeled but each of them is assigned a weight of 5). We analyze three full feedback scenarios at highway convergence levels of 5.E-4, 1.E-5 and 1.E-6 relative gaps.

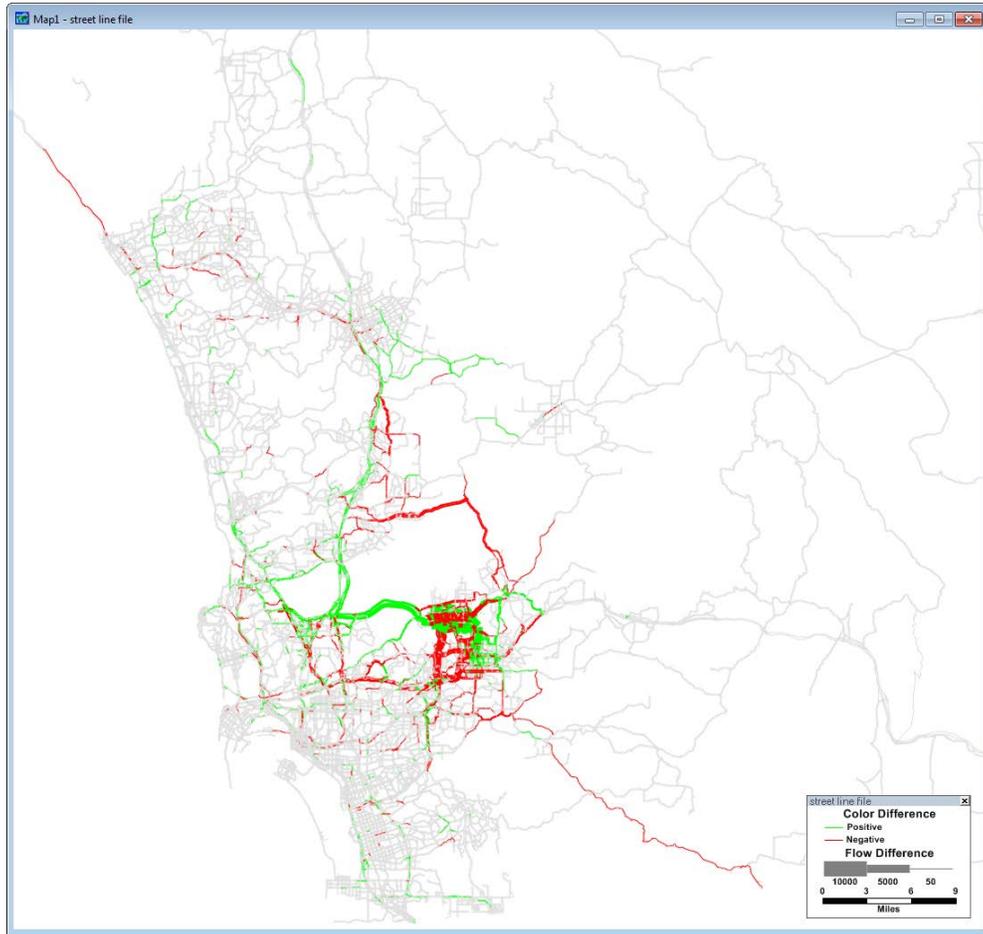
**Figure 7-63 Flow Differences in the SANDAG Network at 5.E-4 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	12,077.36	308.05
Outside the vicinity of project	2,389.94	32.72

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,936,493	490,802	1,803,507
After project added	16,918,911	489,588	1,804,165
$\Delta$ (Project-base)	-17,582	-1,214	+658

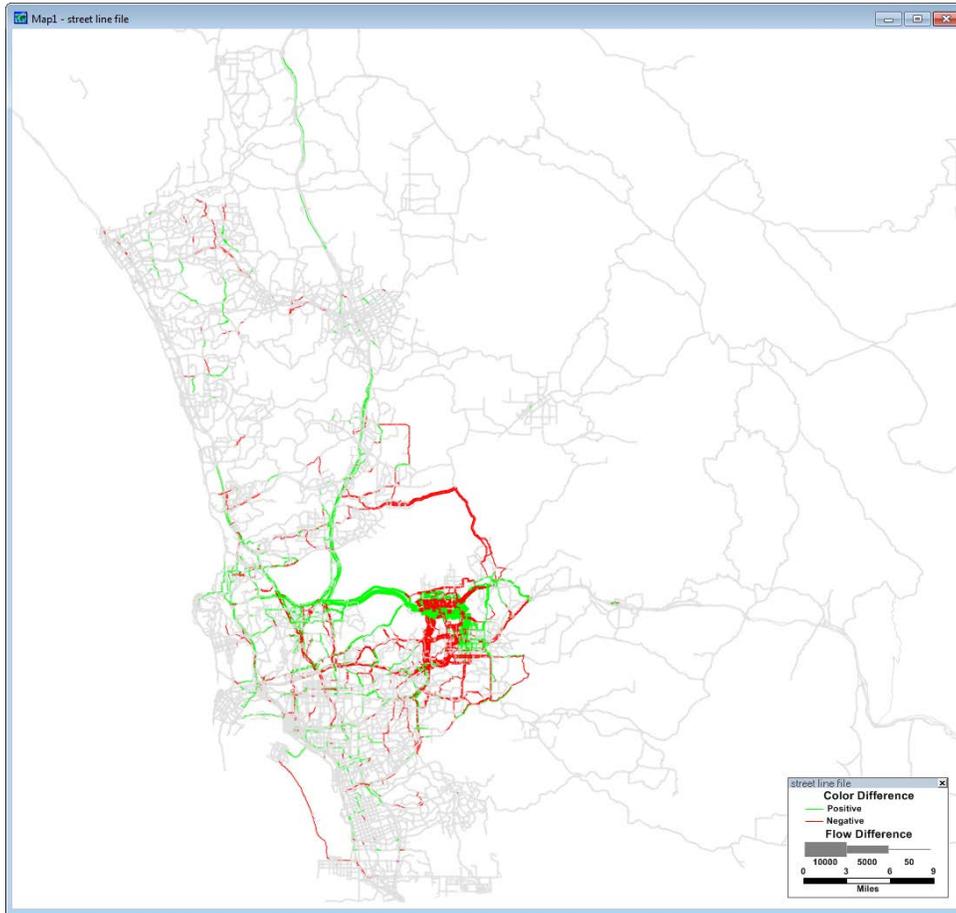
**Figure 7-64 Flow Differences in the SANDAG Network at 1.E-5 RG**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	12,053.24	309.70
Outside the vicinity of project	2,320.69	26.12

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,933,101	490,462	1,803,372
After project added	16,899,327	488,508	1,803,460
$\Delta$ (Project-base)	-33,774	-1,952	+88

**Figure 7-65 Flow Differences in the SANDAG Network at 1.E-6 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	12,122.85	310.48
Outside the vicinity of project	2,246.45	25.13

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,563	490,529	1,803,829
After project added	16,908,366	488,964	1,804,219
$\Delta$ (Project-base)	-26,197	-1,565	+390

Each level of convergence yields a different estimate of the VHT savings with the one from the most converged being midway between the two prior estimates. In all cases, the impacts were more geographically widespread than we would expect.

The following table summarizes the highway project impacts for all the model runs discussed previously.

**Table 7-9 SANDAG Highway Project Impact Summary**

Highway assignment convergence	Type of model run	Δ AM VMT (Project-base)	Δ AM VHT (Project-base)	Δ AM Highway trips (Project-base)	Δ AM Transit trips (Project-base)
5.E-4	Highway AM assignment only	-33,360	-14,035	0	N/A (no transit assignment)
1.E-5	Highway AM assignment only	-56,950	-3,172	0	N/A (no transit assignment)
1.E-6	Highway AM assignment only	-56,850	-3,179	0	N/A (no transit assignment)
5.E-4	Single loop run with 100% sampling of activity-based model	-18,324	-1,262	+700	+1167
1.E-6	Single loop run with 100% sampling of activity-based model	-28,519	-1,644	+275	+30
5.E-4	Full model with feedback	-17,582	-1,214	+658	+1161
1.E-5	Full model with feedback	-33,774	-1,952	+88	+1004
1.E-6	Full model with feedback	-26,197	-1,565	+390	+43

In all of the model runs, this fairly significant highway improvement yields VHT and VMT savings. We observe significant differences in the benefits based upon the analysis protocol and the level of convergence that is achieved. Since higher convergence is presumptively superior due to noise reduction, we can conclude that a better numerical assessment of VMT and VHT changes results from the model runs to a relative gap of 1.E-6.

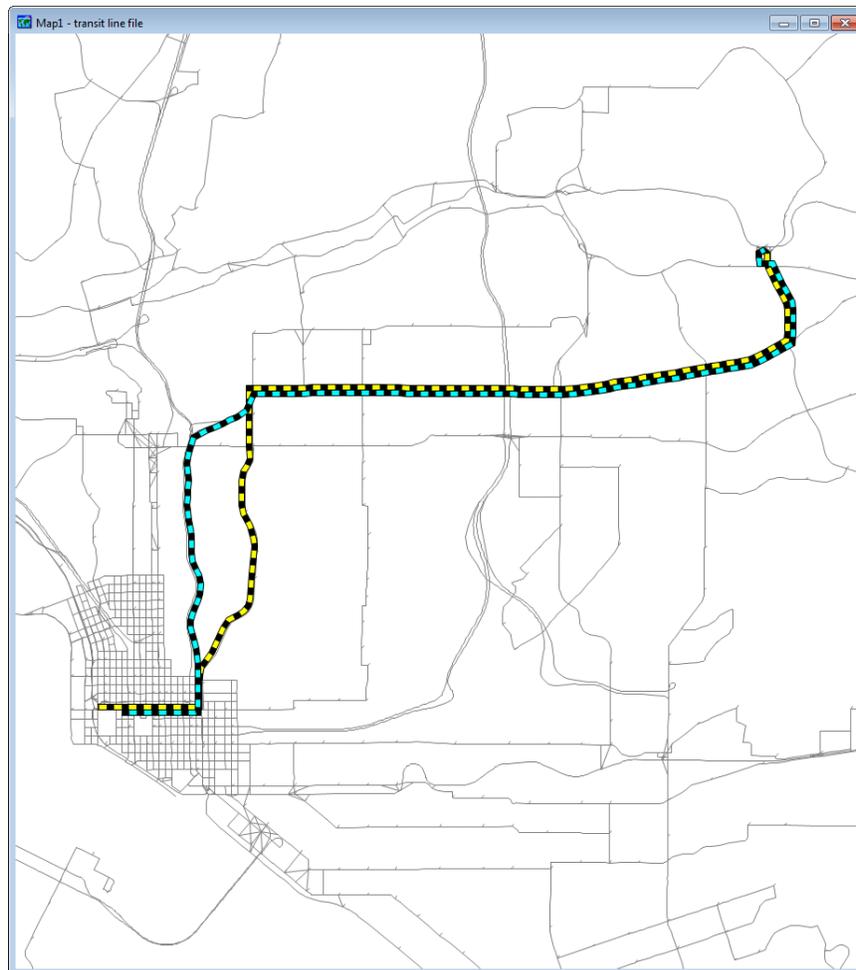
The fact that there are widespread changes in the network may be due to some characteristic of the activity model and an inherent sensitivity to congested travel times. This might be expected since trips are more interdependent in a tour-based formulation than in a trip-based model. Further diagnosis of the forecast impact would certainly be warranted but was beyond our scope of analysis.

We do not have any particular evidence to choose among the three alternative analysis methods. The assignment-only results would probably be the most reasonable in the short term and absent any likely trip distribution or mode choice effects might be most reasonable in the long term. It is also possible that the improved accessibility might lead to higher trip frequencies as opposed to other effects. We suggest that before and after studies of highway project impacts might be needed to help resolve these types of modeling questions.

## Impact of a Transit Project in San Diego

In this section, we analyze the impact on both highway and transit flows when a transit project is added to the 2010 SANDAG base year model. The future-year transit project chosen in this case was from the MPO's 2050 transit network and involved the replacement of a local bus route (MTS Route 15) with a Bus Rapid Transit route, the Mid-City Rapid. The new route begins and ends at the same points as the old route, but has a higher frequency and a different set of stops. In the figures below, the blue dashes show the old route and the yellow dashes show the new route.

**Figure 7-66 Transit Project in the SANDAG Network**



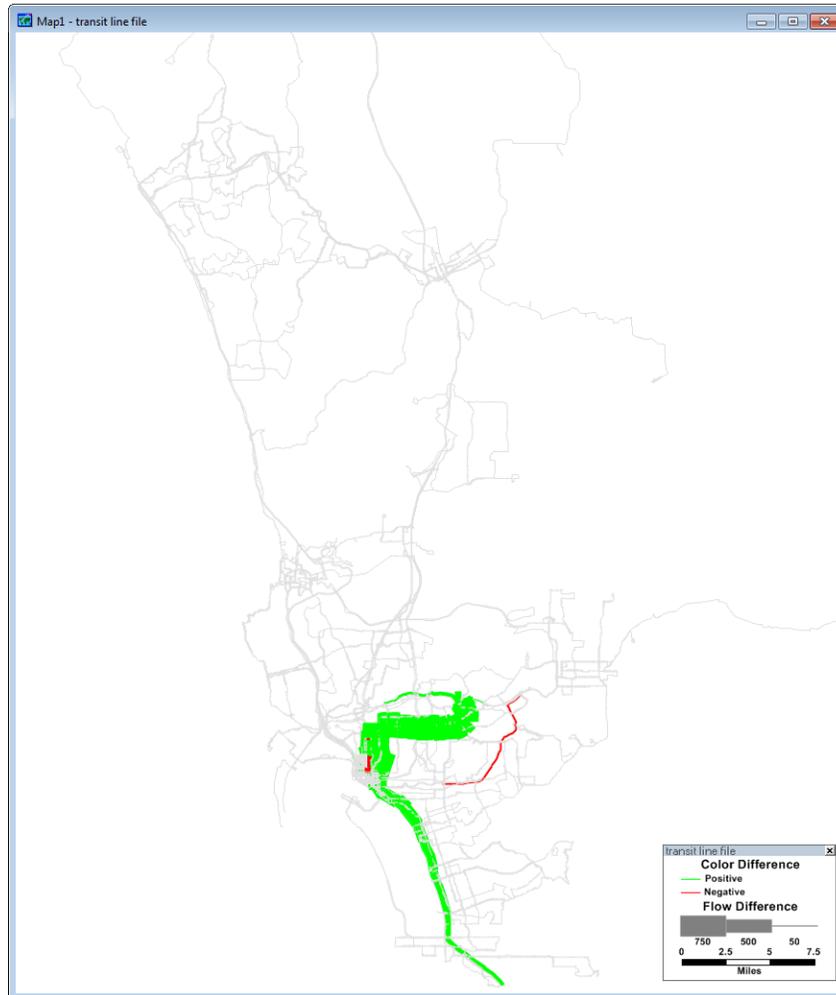
The project is expected to increase the attractiveness of transit service. In the first analysis, we run a single loop of the SANDAG ABM since there is no way to isolate the mode choice model from the other ABM model components and the mode shift to transit is hypothesized to be the major impact of this change. It should also be noted that buses are pre-loaded on the network in the SANDAG model, so there is a small increase in road traffic due to the higher frequency of the project route. In addition, the mode choice logsum that is re-computed with the project will make some destinations near the project more attractive as the logsum is comprised of both transit and auto elements.

### **Transit project impacts with a SANDAG single loop model run**

We conducted a single loop run of the ABM using updated skims from the addition of the transit project to the network. A 100% sample for the population was used in the single loop run and thus the comparisons below are with the final feedback loop of the base scenario, which also uses a 100% sample. The project impact evaluation was done at two highway convergence levels of 5.E-4 and 1.E-6 relative gaps.

The increase in trips due to the attractiveness of the new service is shown in green below. These gains are offset a little due to small trip losses on parallel routes.

**Figure 7-67 Transit Flow Differences in the Network at 5.E-4 RG**

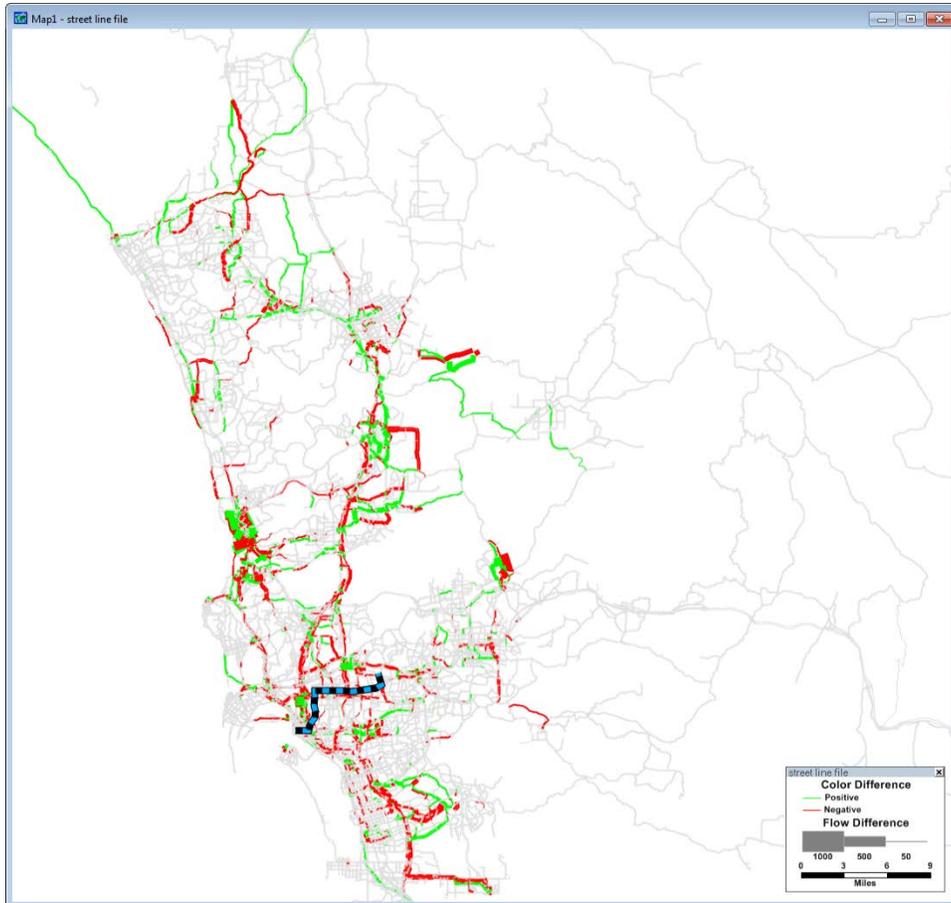


	Assigned AM transit demand	AM PHT
Before project added	19,031	4,118
After project added	20,514	4,731
$\Delta$ (Project-base)	+1,483	+613

As a result of the transit project, the model predicts 2,026 AM boarding trips on the new route and an overall net gain of 1,483 AM trips. The highway impacts are a mode shift loss of 1,133 auto trips and almost no impact on VHT.

The specific road network impacts are shown at relative gaps of 5.E-4 and 1.E-5. At 5.E-4, the changes are widespread and no doubt spurious when far removed from the improved transit service.

**Figure 7-68 Highway Flow Differences in the Network at 5.E-4 Convergence**



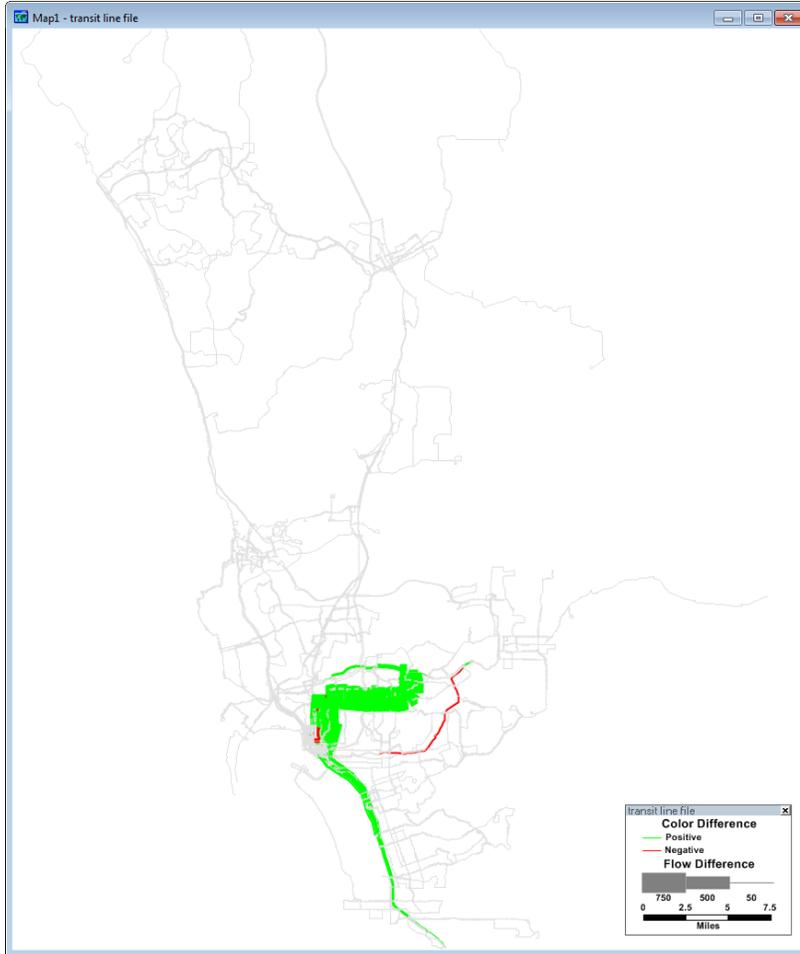
	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	610.33	29.13
Outside the vicinity of project	829.36	24.25

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,936,493	490,802	1,803,507
After project added	16,920,722	490,798	1,802,374
Δ (Project-base)	-15,771	-4	-1,133

The loss in highway VHT is less than expected given the decrease in highway demand. The loss in VHT is offset by a small VHT increase caused by additional bus preload flows associated with the service frequency increase.

At higher convergence of the highway assignment, the transit flow differences are rather similar to those shown previously. However, there is a slightly smaller estimate of the transit ridership gain and a very small difference in the number of boardings on the new route.

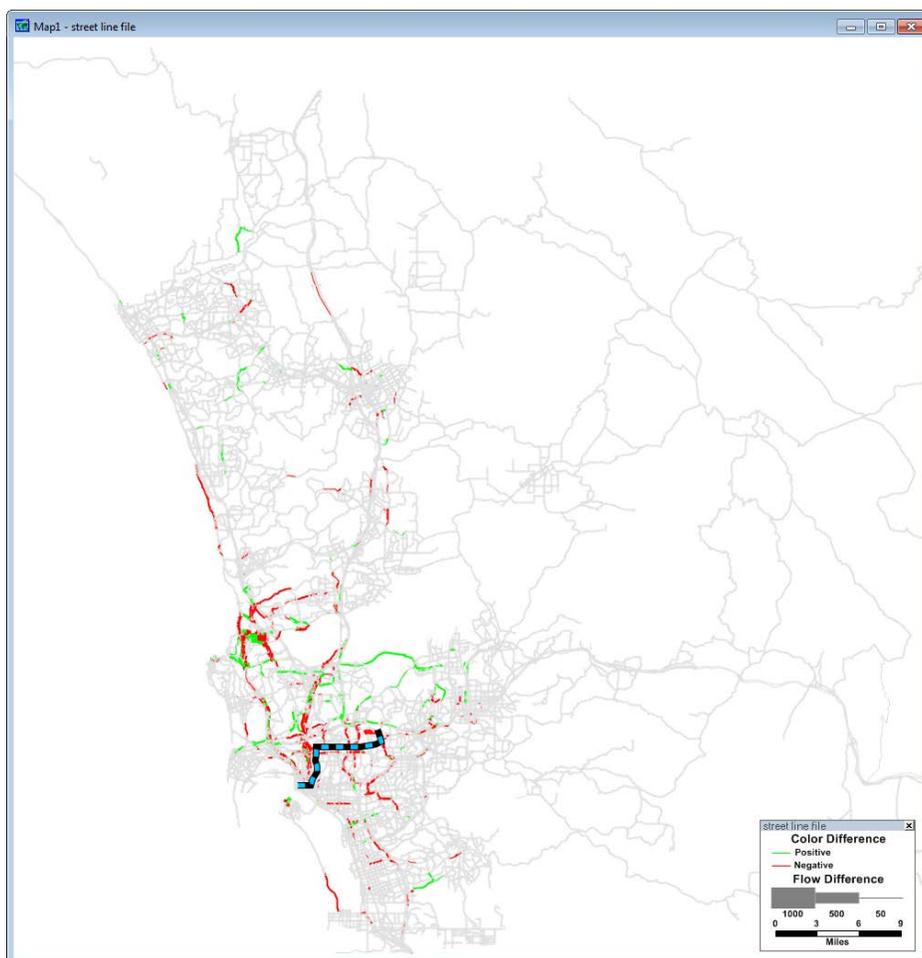
**Figure 7-69 Transit Flow Differences in the SANDAG Network at 1.E-6 Convergence**



	Assigned AM transit demand	AM PHT
Before project added	19,087	4,161
After project added	20,443	4,703
Δ (Project-base)	+1,356	+542

At this level of convergence, the number of AM boardings on the new route is 2,057. The pattern of highway flow differences is much cleaner with tighter convergence but there are still changes in locations where one would not reasonably expect them. Perhaps even higher convergence would be useful in cleaning up the analysis further.

**Figure 7-70 Highway Flow Differences in the SANDAG Network at 1.E-6 Convergence**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	389.32	20.32
Outside the vicinity of project	319.23	13.93

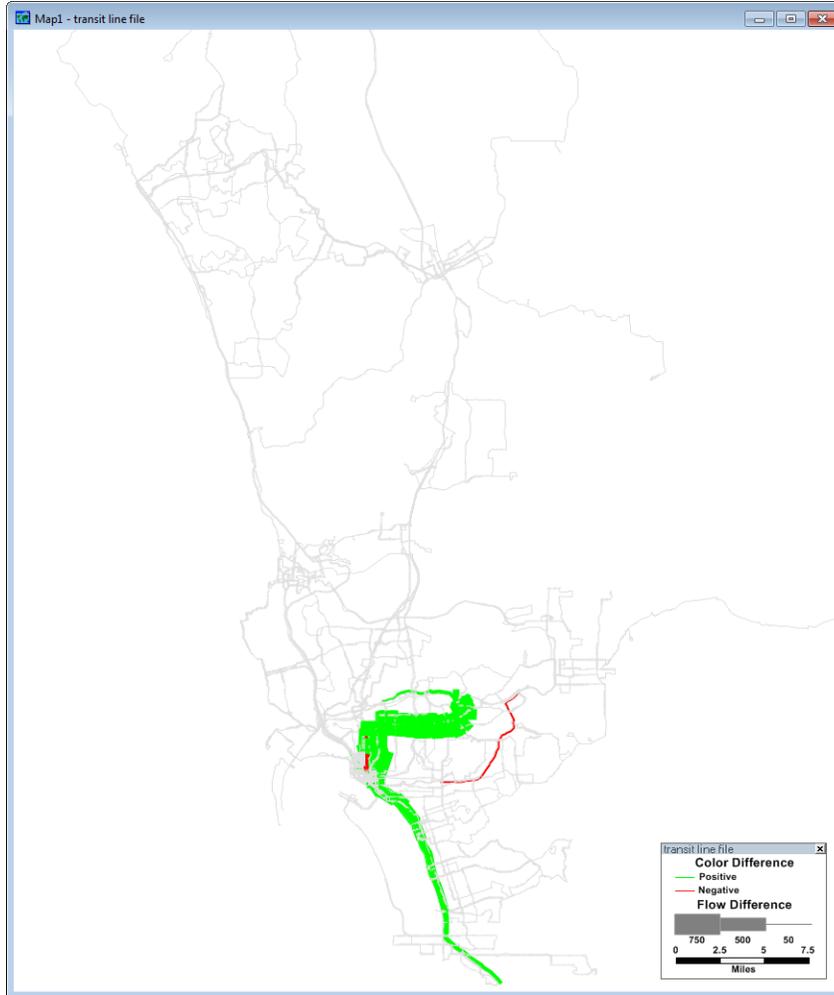
	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,563	490,529	1,803,829
After project added	16,920,812	490,651	1,802,548
$\Delta$ (Project-base)	-13,751	+122	-1,281

At the higher traffic assignment convergence level, the VMT savings are in the same range as assessed previously but there is a negligible gain in VHT (~0.01% of network VHT) as indicated above. Some of the link volume changes are rather far away from the project.

### ***Transit project impacts from a full SANDAG model run***

In this section we analyze the changes on transit flows when the full model with the transit project added is run with three loops and to three different assignment convergence levels. As seen below, the transit flow difference maps at different convergence levels are almost identical. This demonstrates that the highway convergence level has little to no effect on the transit flow differences. The first map illustrates the transit flow differences at 5.E-4 relative gap and reflects AM Ridership on the new route of 2,029 trips and a net gain of 1472 riders overall.

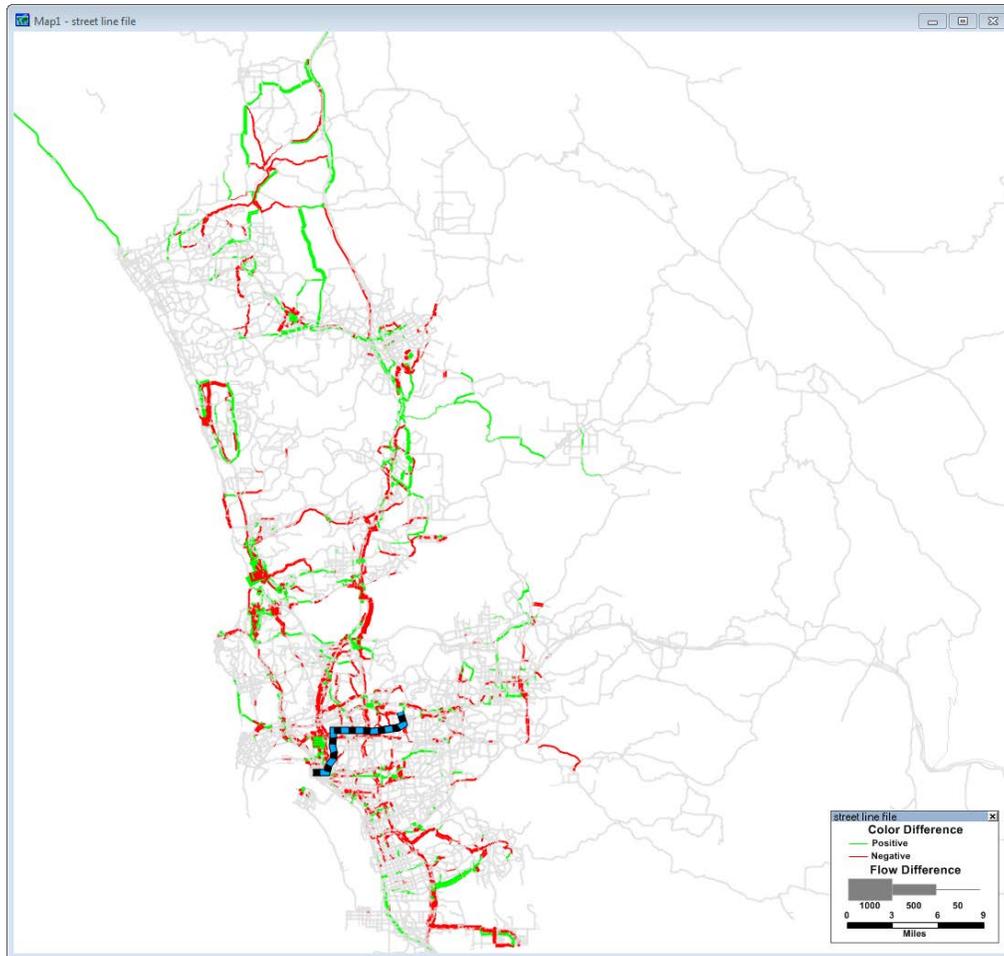
**Figure 7-71 Transit Flow Differences in the Network at 5.E-4 Convergence**



	Assigned AM transit demand	AM PHT
Before project added	19,031	4,118
After project added	20,503	4,727
Δ (Project-base)	+1,472	+609

The next figure shows the highway flow differences, which are fairly widespread.

**Figure 7-72 SANDAG Highway Flow Differences at 5.E-4 Convergence as a Result of the Transit Project**



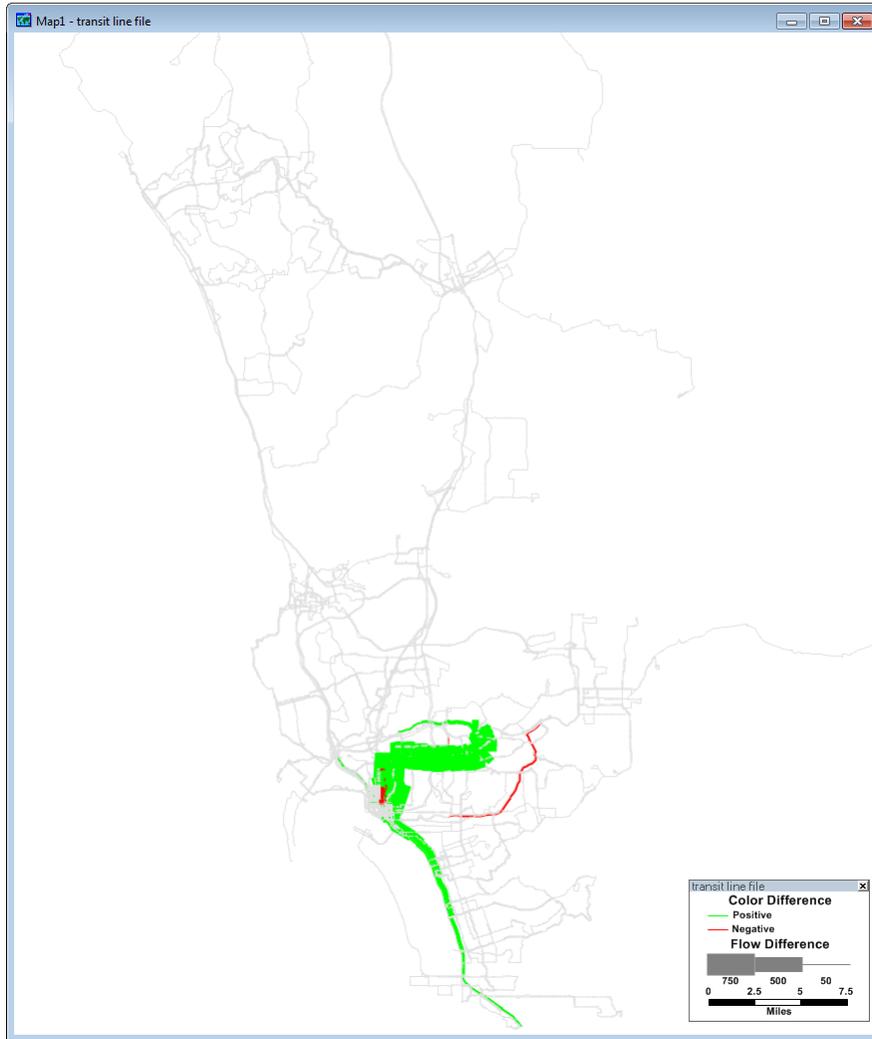
	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	438.23	28.29
Outside the vicinity of project	849.75	22.86

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,936,493	490,802	1,803,507
After project added	16,921,625	490,805	1,802,468
Δ (Project-base)	-14,868	+3	-1,039

Here there is no meaningful decrease in VHT but a thousand plus fewer highway trips and a savings of VMT on the order of 14 miles per trip.

At a 1.E-5 relative gap, AM Ridership on the new route is 2,062 and there is a net gain of 1,572 riders.

**Figure 7-73 Transit Flow Differences in the Network at 1.E-5 RG**

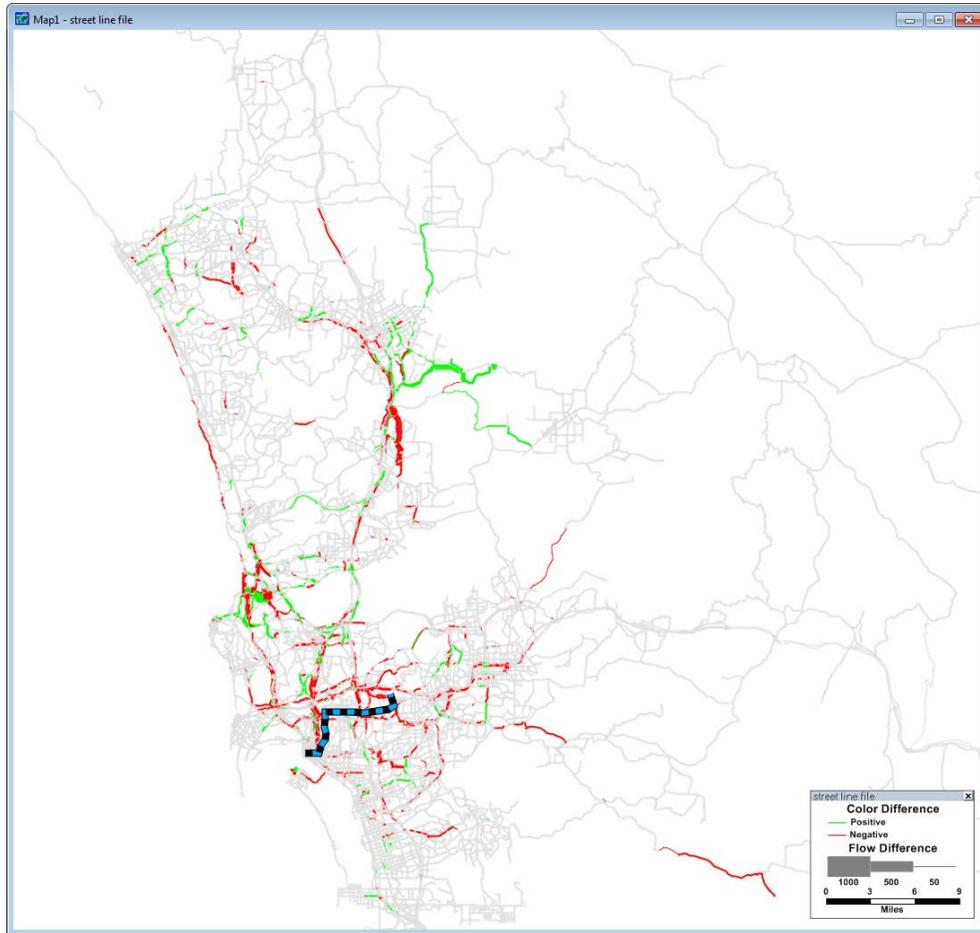


	Maximum AM transit flow difference	Average AM transit flow difference
In the vicinity of project	687.00	15.61
Outside the vicinity of project	245.00	1.48

	Assigned AM transit demand	AM PHT
Before project added	19,068	4,150
After project added	20,640	4,709
$\Delta$ (Project-base)	+1,572	+559

The highway flow differences are still fairly widespread, but there is a VHT reduction instead of a gain as indicated in the Figure below.

**Figure 7-74 Highway Flow Differences at 1.E-5 RG as a Result of the Transit Project**

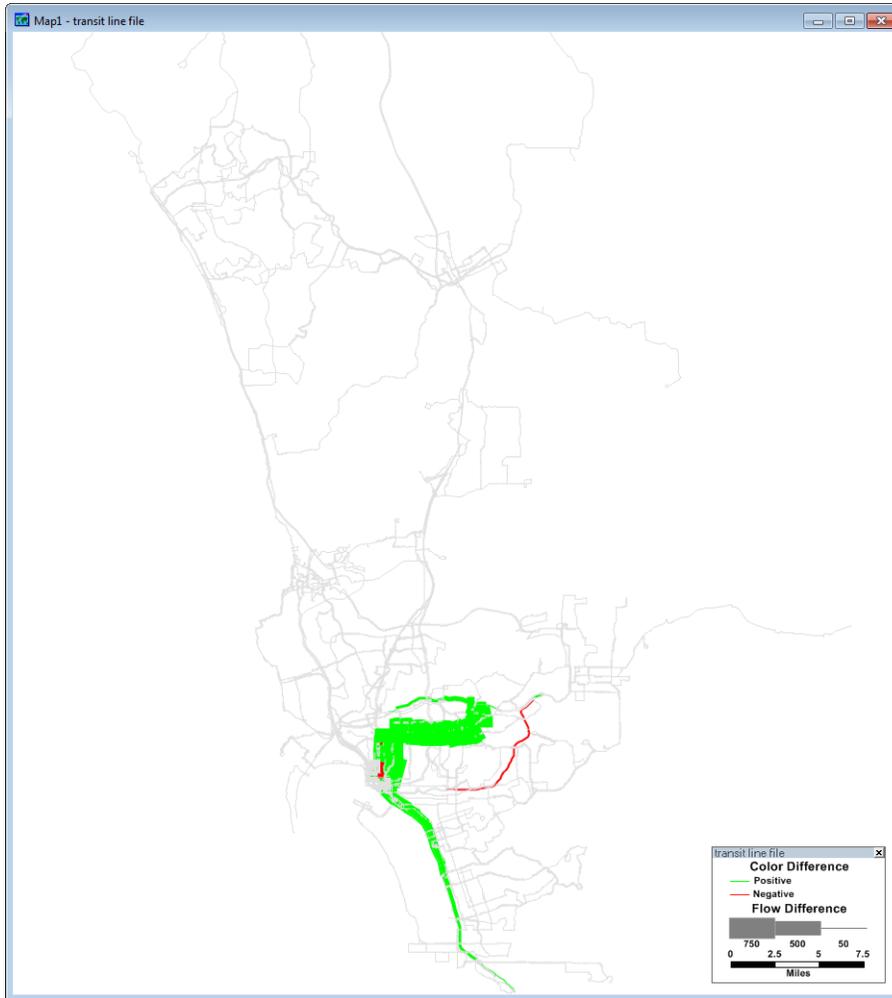


	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	377.05	22.76
Outside the vicinity of project	282.29	17.47

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,933,101	490,462	1,803,372
After project added	16,914,145	490,413	1,802,236
$\Delta$ (Project-base)	-18,956	-43	-1,136

At a relative gap of 1.E-6 in the highway assignment, AM ridership on new route is projected to be 2,047 with a net gain of 1,357 riders.

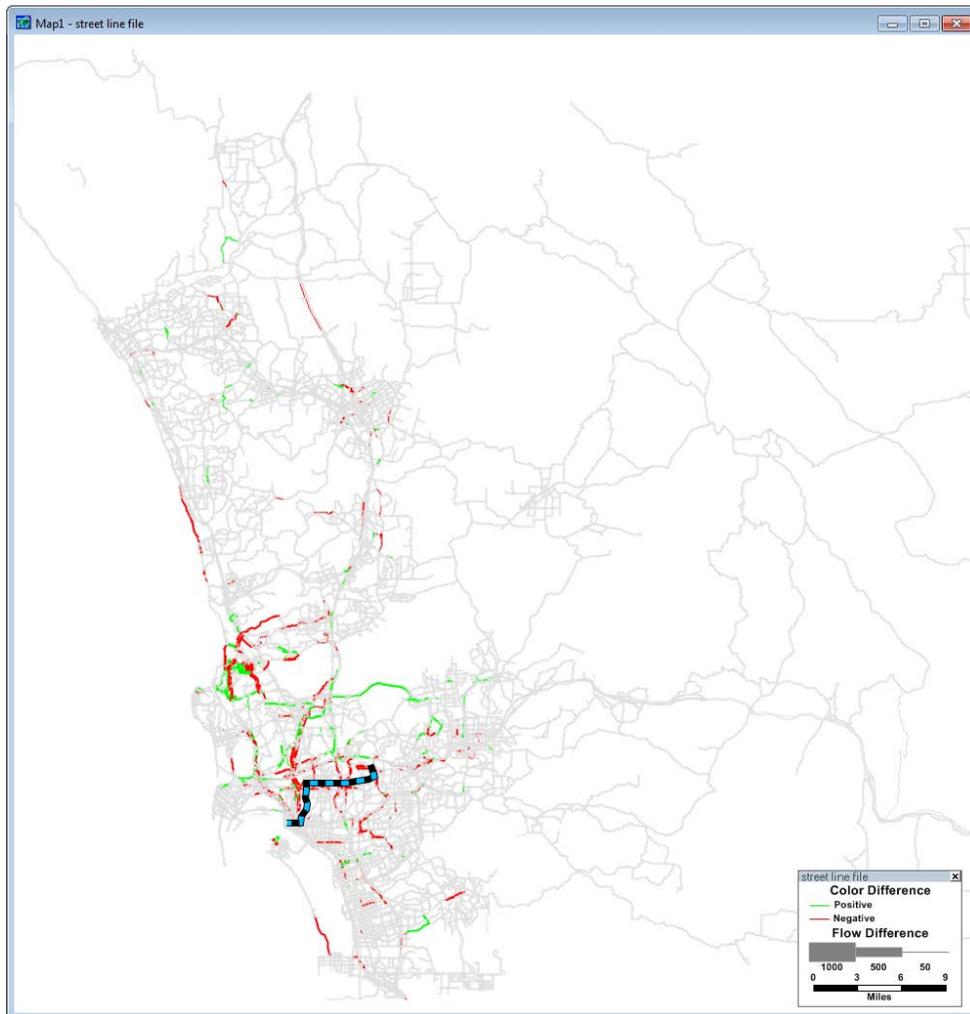
**Figure 7-75 Transit Flow Differences in the Network at 1.E-6 Convergence**



	Assigned AM transit demand	AM PHT
Before project added	19,087	4,161
After project added	20,444	4,702
Δ (Project-base)	+1,357	+541

At the higher traffic assignment convergence level, the VMT savings are slightly lower than assessed previously and there is a negligible gain in VHT (~0.01%) as indicated below. Some of the link volume changes are once again rather far away from the project.

**Figure 7-76 SANDAG Network Highway Flow Differences at 1.E-6 RG as a Result of the Transit Project**



	Maximum AM highway flow difference	Average AM highway flow difference
In the vicinity of project	391.39	20.94
Outside the vicinity of project	317.33	13.73

	AM VMT	AM VHT	Assigned AM highway demand
Before project added	16,934,563	490,529	1,803,829
After project added	16,919,902	490,588	1,802,441
$\Delta$ (Project-base)	-14,661	+59	-1,388

The following table summarizes the transit project impacts for all the cases analyzed.

**Table 7-10 SANDAG Transit Project Impact Model Run Summary**

Highway assignment convergence	Type of model run	Δ AM VMT (Project-base)	Δ AM VHT (Project-base)	Δ AM Highway trips (Project-base)	Δ AM Transit trips (Project-base)	Δ AM PHT
5.E-4	Single loop with 100% sampling	-15,771	-3	-1,133	+1,483	+613
1.E-6	Single loop with 100% sampling	-13,751	+122	-1,281	+1,356	+542
5.E-4	Full model with feedback	-14,868	+3	-1,039	+1,472	+609
1.E-5	Full model with feedback	-18,956	-43	-1,136	+1,572	+559
1.E-6	Full model with feedback	-14,661	+59	-1,388	+1,357	+541

Interestingly, the results are quite similar in terms of impact irrespective of the analysis mode chosen for this project. Even the VHT changes remain roughly of the order of 0.01% of the network VHT while varying between positive and negative savings. One reason is that we start the single loop run with essentially the same times as the last loop of the full model with feedback.

## Conclusions

Despite some outliers, most of the project impact calculations performed give some encouragement that travel demand models can potentially resolve the impacts of both highway and transit improvements. Generally, when traffic assignments are sufficiently converged, the models are able to produce plausible estimates of project impacts. Importantly for transit planners and FTA, the models and the analysis protocols demonstrated an ability to resolve the highway benefits of transit improvements. This is evidenced by the reduction in highway travel in the travel corridors that received transit improvements. Of course, in the real world, these impacts might not be observed directly due to the effects of elastic demand, which is not explicitly taken into account in any of the MPO models.

In this chapter, we have somewhat laboriously documented the effects of project evaluations with different analysis protocols and different traffic assignment convergence levels. In nearly all cases, we established that plausible project impacts are associated with higher levels of convergence. This finding was very consistent across models and projects.

We found direct evidence that traffic assignments converged to relative gaps used by different MPOs (1.E-4 or 5.E-4 as the case may be) are not necessarily reliable enough in terms of reducing errors in project evaluation. In fact, in some instances, the estimated project impacts went in the wrong direction, a problem that was remedied with tighter convergence.

Assessments with assignment-only calculations for roadway projects and with mode choice and assignment only-calculations for transit projects are conservative and seem generally well-behaved. This suggests that these limited assessments be part of project evaluation even when fuller modeling approaches are utilized.

The level of convergence in the highway assignment required to eliminate noise is tighter than previously thought and much tighter than employed in most, if not all, models. Our test cases suggest that correlated errors do not cancel out in project evaluation as some might previously have speculated. The requisite level of convergence is also variable suggesting that testing be employed to establish the appropriate levels for specific models and project studies rather than specifying a single overall guideline for all models and applications.

The fact that curious and seemingly strange impacts are sometimes calculated with different modeling protocols is a fact of life apparently, and one that warrants investigation when models are developed. Modelers need to be attentive to the type and quality of results that are generated by their models. Testing with specific project evaluations is one way to judge modeling approaches. We also found it to be an excellent means of finding data and programming errors in models.

The different analysis protocols do yield different estimates of impacts, but that is to be expected and should be considered when models are used for project evaluation. Mechanical application of models for impact assessment can easily lead to inappropriate results, and professional judgment is, in our opinion, an important component of the model application process.

The fact that the project impacts were often small is an encouraging sign that the models are not overly sensitive. Of course, real world validation is required in order to know if the models give results that are useful for prediction. But we are encouraged that the models cannot be rejected outright given the empirical tests that we performed.

We restricted our tests in this chapter to varying tight levels of relative gaps. We found that more often than not the level of convergence matters as it affects the answers obtained. We did not encounter a single case in which the highest levels of convergence gave obviously worse results. This suggests to us that it is better to err on the side of very high convergence when evaluating an important project.

Testing can be used to ascertain what level of traffic assignment convergence and which analysis protocols seem most appropriate. As we have shown, these tests are relatively straightforward to perform and could be part of any model development and validation effort.

It is important to keep in mind that plausible results are not necessarily valid or correct results. Without appropriate model validation, model outputs cannot be taken as meaningful estimates of project impacts. At a minimum, this requires validation of base cases against counts and possibly speeds. Ideally, models are tested for the ability to predict project impacts as supported by data from before-and-after studies.

It would be interesting and appropriate to perform further research on the effects of feedback convergence on project impact assessment. While we have every reason to believe that there will be significant variation in estimated project impacts as a function of feedback convergence level, we believe that this research would be most profitable conducted in conjunction with the afore-mentioned validation exercises performed with considerable before and after data on actual project impacts.

# Chapter 8

## Congested Travel Time Analysis

The ability of regional planning models to provide reasonable forecasts of transportation projects is fundamentally dependent on their ability to generate accurate congested highway travel times. Congested travel times are used in most if not all of the key model components and are crucial inputs to model estimation as well as application.

Historically, use of speed data was limited in modeling, and only a handful of MPOs collected travel time data for use in calibrating or validating their models. The data collected were often quite limited in terms of origin-destination pairs, and typically the sample sizes were too small to provide statistically significant results. Model outputs were commonly post-processed prior to projection of emissions.

Gathering travel time data through floating cars using GPS is very expensive, and it is hard to generate sufficient sample sizes for statistically significant results that cover all of the time periods of interest for different seasons. While there are some places where sensor data are available, these data are often limited to major highways.

The availability of new sources of data on travel times provides an opportunity to make more detailed assessments of congested travel speeds produced by models than have been previously possible. Congested travel times vary by time of day, day of the week, and seasons of the year, and are directly influenced by incidents of various types, weather, and the presence and operation of work zones, among other factors. This variability greatly complicates the assessment of model data, but also opens the door to addressing many unanswered questions about the performance and reliability of regional transportation systems. In this chapter, we report on some exploratory comparisons between model output and commercially available travel time data.

Some MPOs are already using commercial sources of speed data for analytical purposes, and this should be more widespread in the future due to MAP-21 regulations. In this study, we mainly used HERE Traffic data that we collected for the participating MPO regions. We also used INRIX data that were provided for the MAG region, and we performed a supplementary analysis of travel time skims using data licensed from Google.

The HERE Traffic travel speeds are provided by Traffic Message Channel (TMC) code. A TMC code typically spans several model links. We also chose to sample the travel speeds at 5 minute intervals or epochs as HERE refers to them. The 5-minute data were aggregated to longer time periods to estimate an overall AM peak average speed. Unlike the National Performance Management Research Data Set (NPMRDS), which is the HERE Traffic data purchased by FHWA and made available to State DOTs and MPOs, the data that we used included a much broader set of roads including arterials. This made it more suitable for our research purposes.

We chose to perform much of the analysis at the TMC segment level rather than at the link level. While the TMC segments are more aggregate, they were the reporting units for the HERE Traffic data available to us when we were doing the study. Estimating HERE Traffic speeds for the links would have introduced an unknown amount of error.

There is not a simple correspondence between TMC segments and MPO model network links. The TMCs are mapped to a reference layer, which for HERE Traffic is a nationwide HERE network encompassing all streets. In general, TMCs span multiple modeling links. Therefore, a means of mapping the TMCs to the model networks and identifying the model links that are fully or only parts of TMCs was an essential part of our work. This was done largely by an automated conflation process, but is a method that is only workable for model networks that are reasonably accurate in terms of geography.

It is well-known that irrespective of functional class, link speeds vary tremendously due to specific detailed road characteristics, road and weather conditions, and due to the time-varying nature of traffic as well as heterogeneity in driver behavior. For this reason, one would not expect planning models to have a great ability to match observed speeds, but one might hope that there would be some substantial correspondence between the models and average travel speeds. In our research, we went in search of this correspondence.

In our original tests, we used a single June weekday of reported speeds from HERE to prototype the analysis. Subsequently, we decided to use an average of 3 weekdays in September 2014 for the research. While we found that there was a high correlation between the speeds in June and those in September as well as a high correlation from one weekday to another, and between the same day on consecutive weeks, we felt that a weekday average would be the basis for a more appropriate comparison.

To give the models a fair test, we stratified the speed comparisons by functional class and by free flow speeds, and by other characteristics of relevance such as VDF functions and their parameters. We filtered the set of TMCs used for the more detailed, stratified comparisons by removing TMCs that had travel model speeds that differed widely from the ideal calculated VDF speeds for reasons we attributed to possible errors of various types.

**All of the TMC analysis was performed with data harvested for the AM peak period. While we provide some calculations of VHT and VMT calculated for TMCs, the reader is cautioned that the TMCs do not include all of the links present in urban road networks or MPO planning networks. Consequently, the estimates of AM VHT and VMT are for a varying subset of road segments in each MPO region and therefore cannot be interpreted directly as measuring overall travel or even a known fraction thereof.** In addition to calculations of the Root Mean Square Errors (RMSEs) between modeled and measured TMC speeds, the comparisons were further explored by preparing graphic plots of modeled and reported speeds by model V/C ratios. We omitted TMCs from the analysis if there had been an incident or a work zone noted in a corresponding data file available from HERE Traffic. Also, some TMCs were dropped if they were not reasonably homogeneous in terms of the characteristics of their constituent links.

The visual evidence in the graphs is fairly easy to evaluate. It should be noted that discrepancies between modeled and reported speeds arise not simply because the VDFs are not well-fitted to speeds, but also because the volumes themselves are likely to be error-prone for all of the usual reasons associated with errors in trip tables as well as in mode choice and traffic assignment outputs. There is also evidence that there are often cars that exceed the speed limits, and that should be reflected in the estimates of free flow speeds that are used in VDFs.

Although the TMCs comprise only a subset of all of the modeled roads, the implications of travel speed differences for VHT measurement are straightforward and revealing. For each MPO, we calculated the differences in estimated VHT between the model and the HERE traffic measurements.

The results for each MPO model follow. In inspecting the graphs it should be kept in mind that the variations between measured and modeled speeds are greatly reduced by isolating TMCs and the associated model links by functional class and free flow speed categories. In spite of this, there is substantial variation between the two sets of speed estimates.

## ARC Model Speed Analysis

For ARC, we used the congested travel speeds produced by their new activity-based model for the travel time analysis. As we understand it, these speeds came from running the model with feedback. However, ARC has subsequently revised its volume-delay functions using the NPMRDS, so these comparisons are out of date.

Below are scatterplots for highways, arterials, and lesser road classes. The model speeds are plotted on the x-axis and the TMC average speeds are plotted on the y-axis. A perfect correspondence would be the straight black line displayed in each graph.

**Figure 8-1 Comparison of ARC and HERE Speeds for Highways**

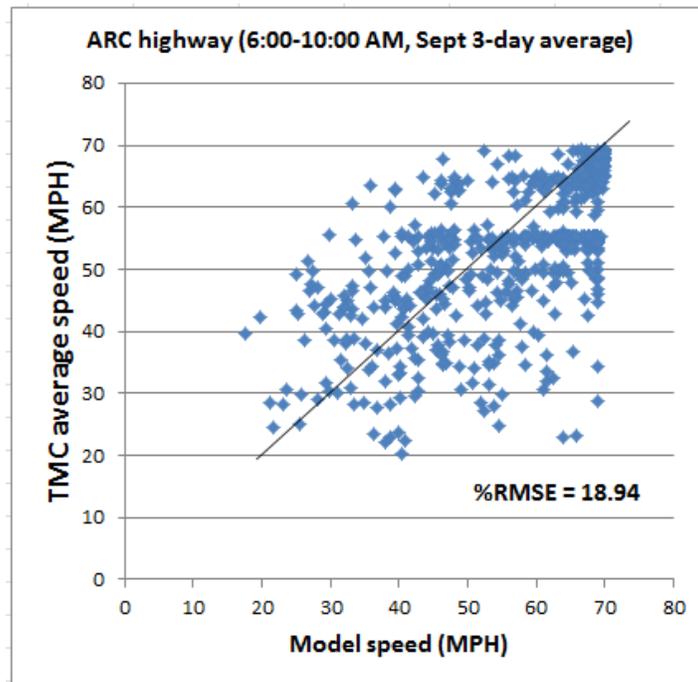


Figure 8-2 Comparison of ARC and HERE Speeds for Arterials

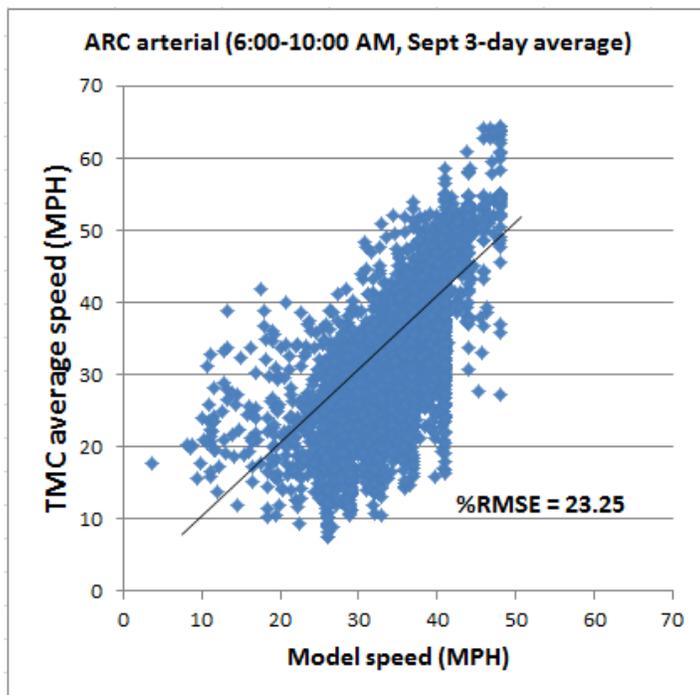
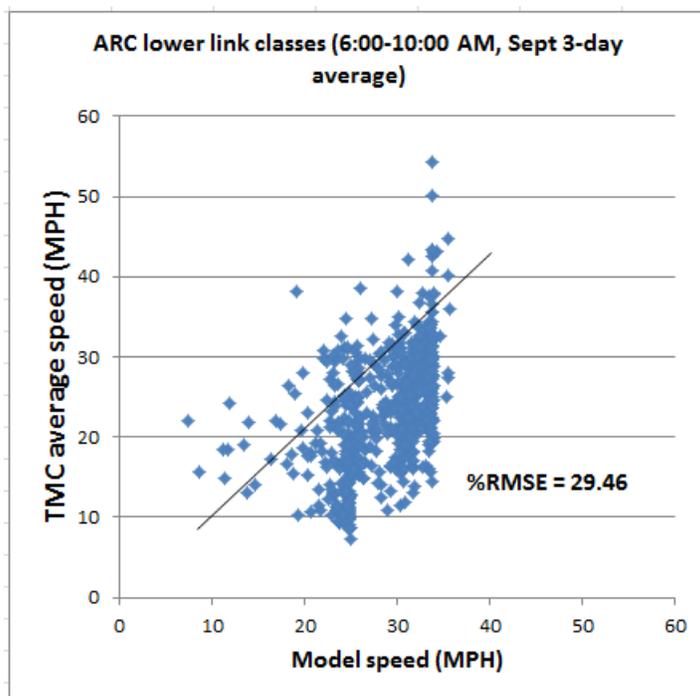


Figure 8-3 Comparison of ARC and HERE Speeds for Lower Functional Classes



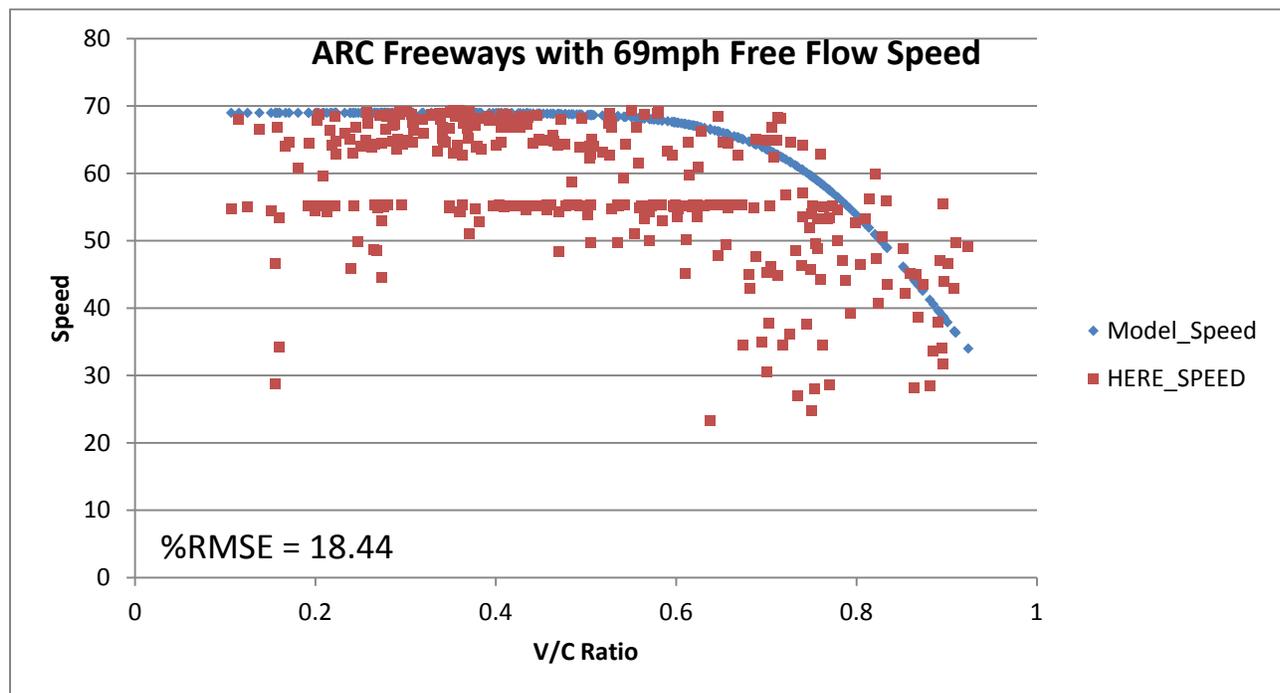
The most obvious observation is that while there is a correlation between the TMC and modeled speeds, there is very wide dispersion of measured speeds at every level of model speed. This means that most link speeds in the model differ from those that were measured. We next further stratify the comparisons by functional class and by free flow speeds. In the charts we plot the model VDF to highlight the relationships or lack of such between measured and modeled speeds.

As indicated in the charts that follow, measured speeds in the Atlanta region are generally much lower than those generated by the new regional model. This characterization applies to all functional classes except for the small number of expressways with 50 mph free flow speeds. Also, it is clear that there are widely varying speeds by functional class.

The first chart is for freeways that have a 69 mph model free flow speed. One can observe that most of the measured speeds fall below the blue VDF curve points. There is also an apparent horizontal band of measured speeds at 55 mph. This is likely to reflect a 55 mph speed limit on those links.

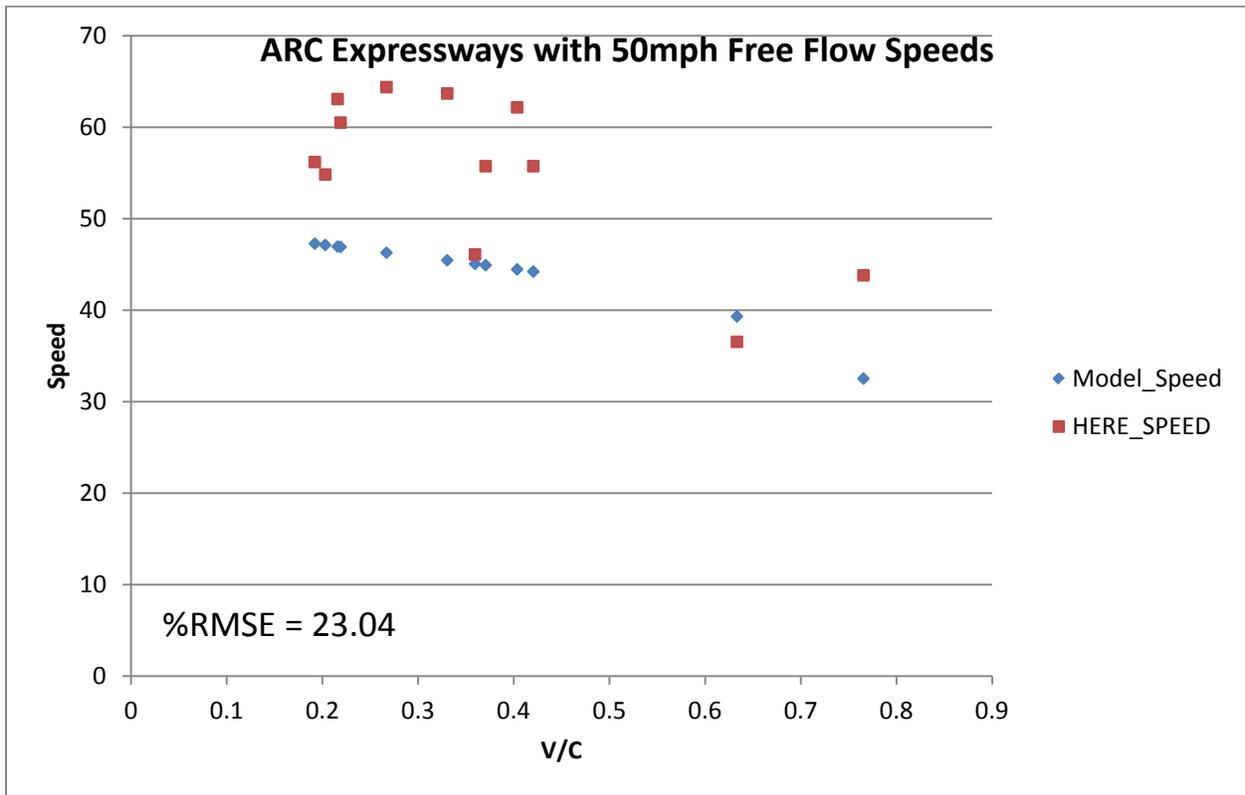
There are clear bands of free flow speeds for HERE. Even though the model free flow speed was set to 69, actual speed limits for these links were probably 55, 65, and 70mph. The model continues to be optimistic with respect to speed at higher V/C ratios. There are obvious pockets of congestion with rather low measured speeds.

**Figure 8-4 Comparison of AM ARC and HERE Speeds for Freeways**



As noted, the pattern for the very few expressways is rather different. For them, the measured speeds considerably exceed the free flow speeds assumed in the VDF. In the filtered data set, there was only one expressway considered so this result may be anomalous.

Figure 8-5 Comparison of AM ARC and HERE Speeds for Expressways



The next two charts show collector speeds that are considerably faster for the model than measured speeds, but with high variance and nearly no relationship between the two sets of data points. This may be due to considerable heterogeneity in the roads included or the presence of traffic signals which would unquestionably introduce considerable variance in measured travel speeds.

Figure 8-6 Comparison of ARC and HERE Speeds for Collectors with 34MPH Free Flow Speeds

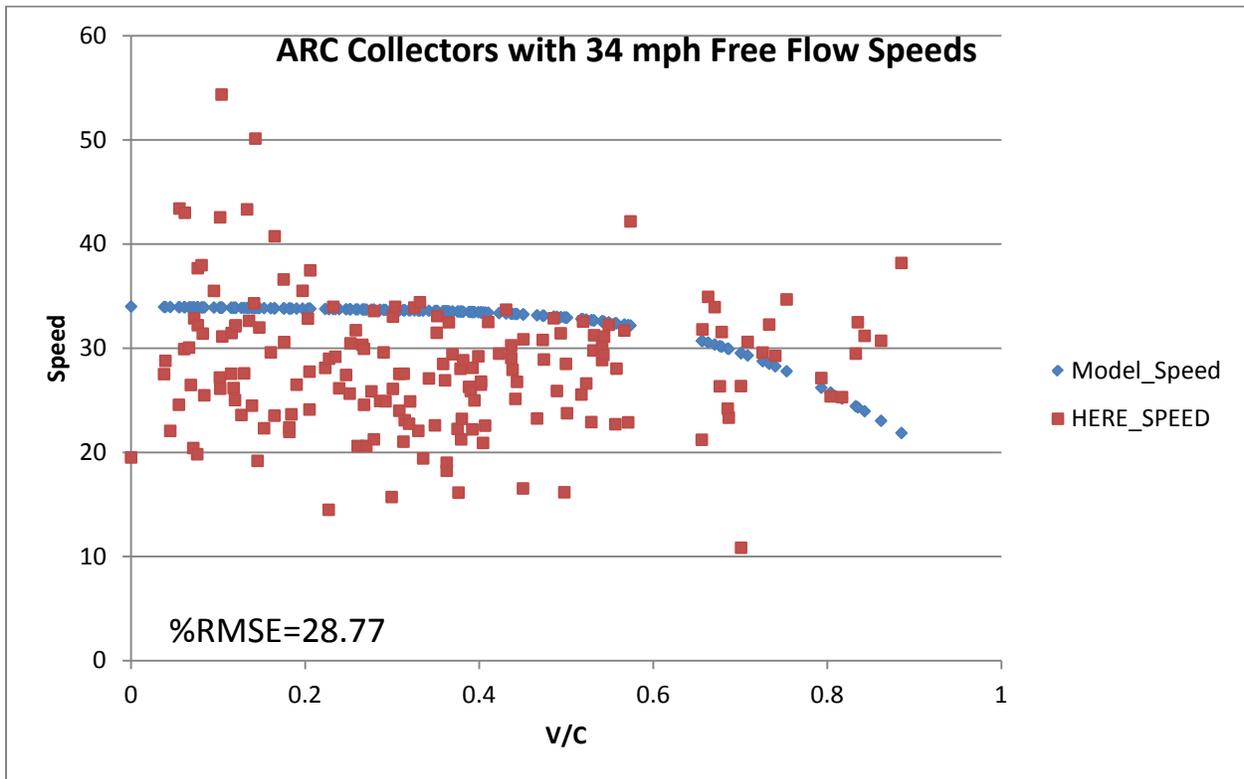
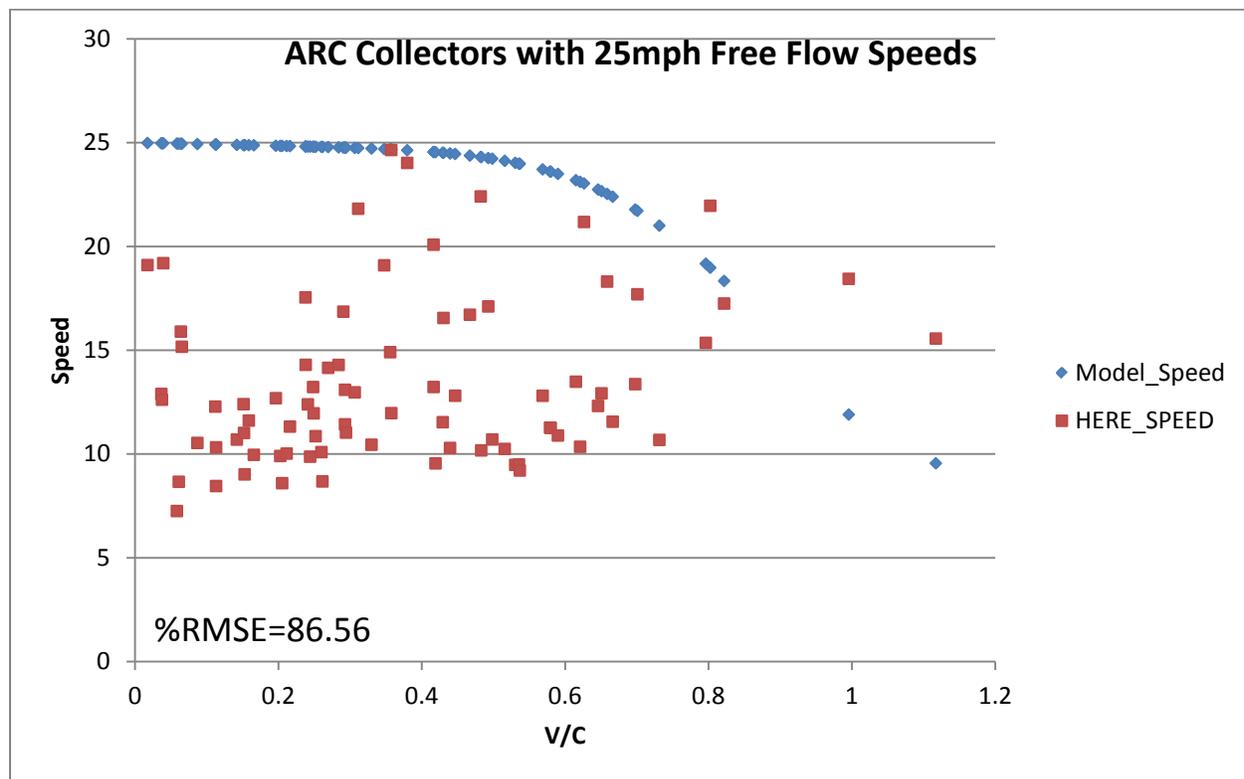


Figure 8-7 Comparison of ARC and HERE Speeds for Collectors with 25MPH Free Flow Speeds



Separating the collectors by free flow speed is of no particular consequence, it seems. No stronger relationship is in evidence.

Discrepancies in speeds lead to discrepancies between modeled and measured VHT. We calculated these quantities and their differences for the TMCs (which of course cover only a subset of regional network links). In the table below, we provide these for all TMCs and by category. VMT and average HERE speeds were calculated using a 3-day average speed collection period (Tuesday, Wednesday, and Thursday). The “All Filtered TMCs are those that are in one of the explicit functional class/speed categories listed in the tables.

**Table 8-1 Comparison of ARC AM Modeled and HERE TMC VHT and Speeds**

Category	Observations	HERE VHT	Model VHT	VHT %RMSE	VHT %Difference	HERE AVG SPEED	MODEL AVG SPEED
ARC All TMC	3769	430,544	392,765	37.98	-8.77	38.99	44.90
Freeway 70mph	333	136,287	120,668	27.67	-11.46	53.71	62.32
Expressway 60mph	12	2,534	3,180	32.62	25.51	52.41	42.95
Arterial 37mph	458	25,756	26,201	35.95	1.73	31.13	32.82
Collector 34mph	174	5,337	5,238	73.81	-1.85	28.15	31.63
Collector 25mph	81	1,775	1,145	55.46	-35.49	13.97	22.77
ARC All Filtered	1056	171,689	156,433	40.78	-8.89	47.76	54.86

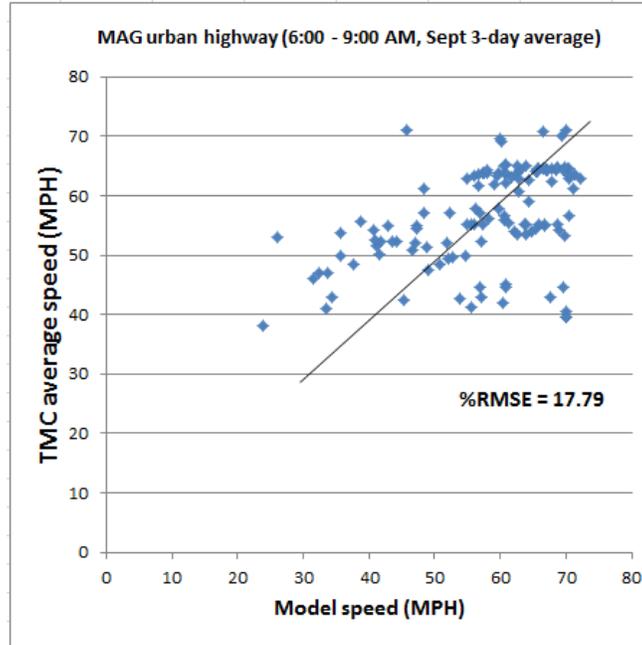
On an overall network basis, it appears that ARC AM model speeds are generally higher than measured ones. Also, based upon these tabulations and without considering sampling issues, it would seem that the ARC model underestimates VHT as it would be measured using the HERE data.

# MAG Model Speed Analysis

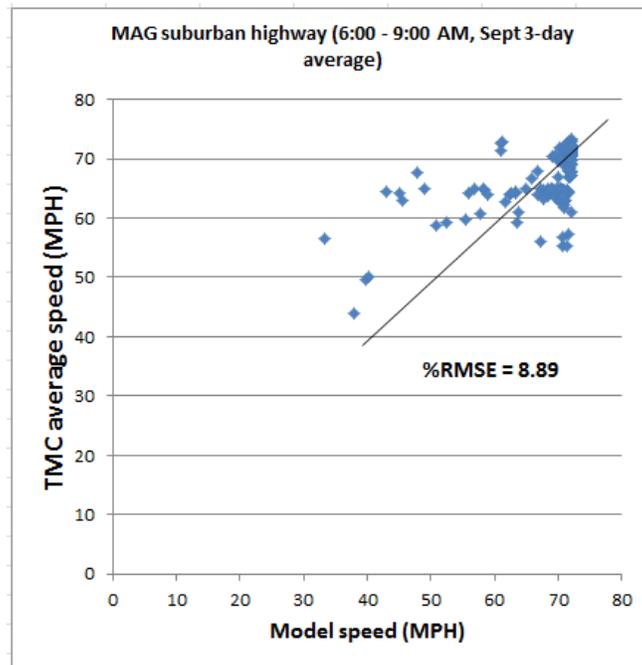
We next compare modeled speeds with the HERE TMC data for the MAG region. MAG has had a longer history of acquiring and using speed data from multiple sources than most other MPOs.

The first two figures show the comparisons for urban and suburban highways.

**Figure 8-8 Comparison of MAG and HERE Speeds for Urban Highways**

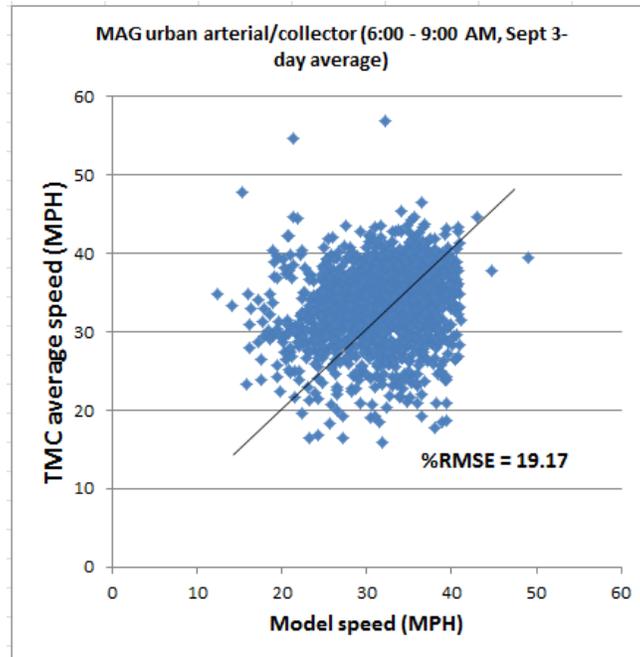


**Figure 8-9 Comparison of MAG and HERE Speeds for Suburban Highways**

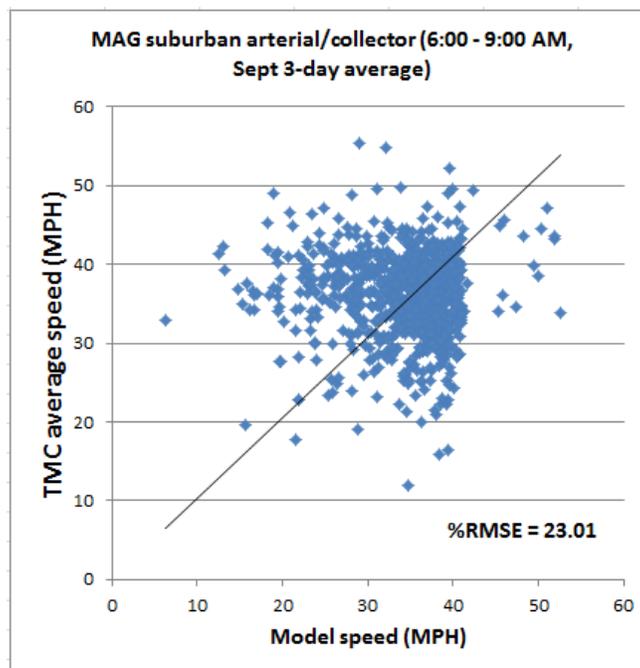


The comparisons above illustrate that the MAG model has a reasonable fit to AM measured speeds for highways. For arterials, there is a somewhat higher RMSE in both urban and suburban areas as shown in Figures 8-10 and 8-11.

**Figure 8-10 Comparison of MAG and HERE Speeds for Urban Arterials/Collectors**

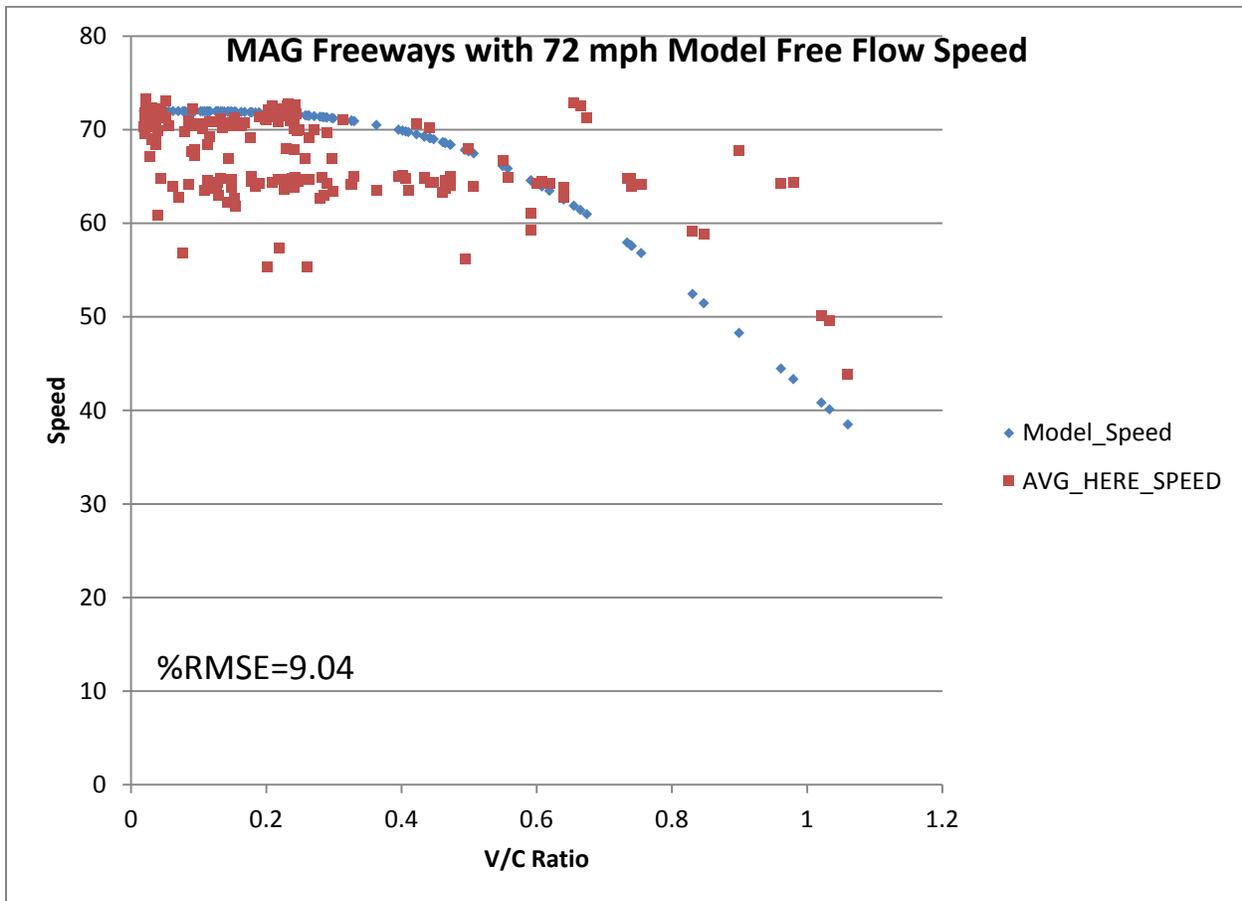


**Figure 8-11 Comparison of MAG and HERE Speeds for Suburban Arterials/Collectors**



For MAG, modeled vs. HERE speeds are shown for different functional class and free flow speed categories in the charts that follow. The first plot is for all freeways and the next two plots are for freeways in rural and urban areas in the Phoenix region.

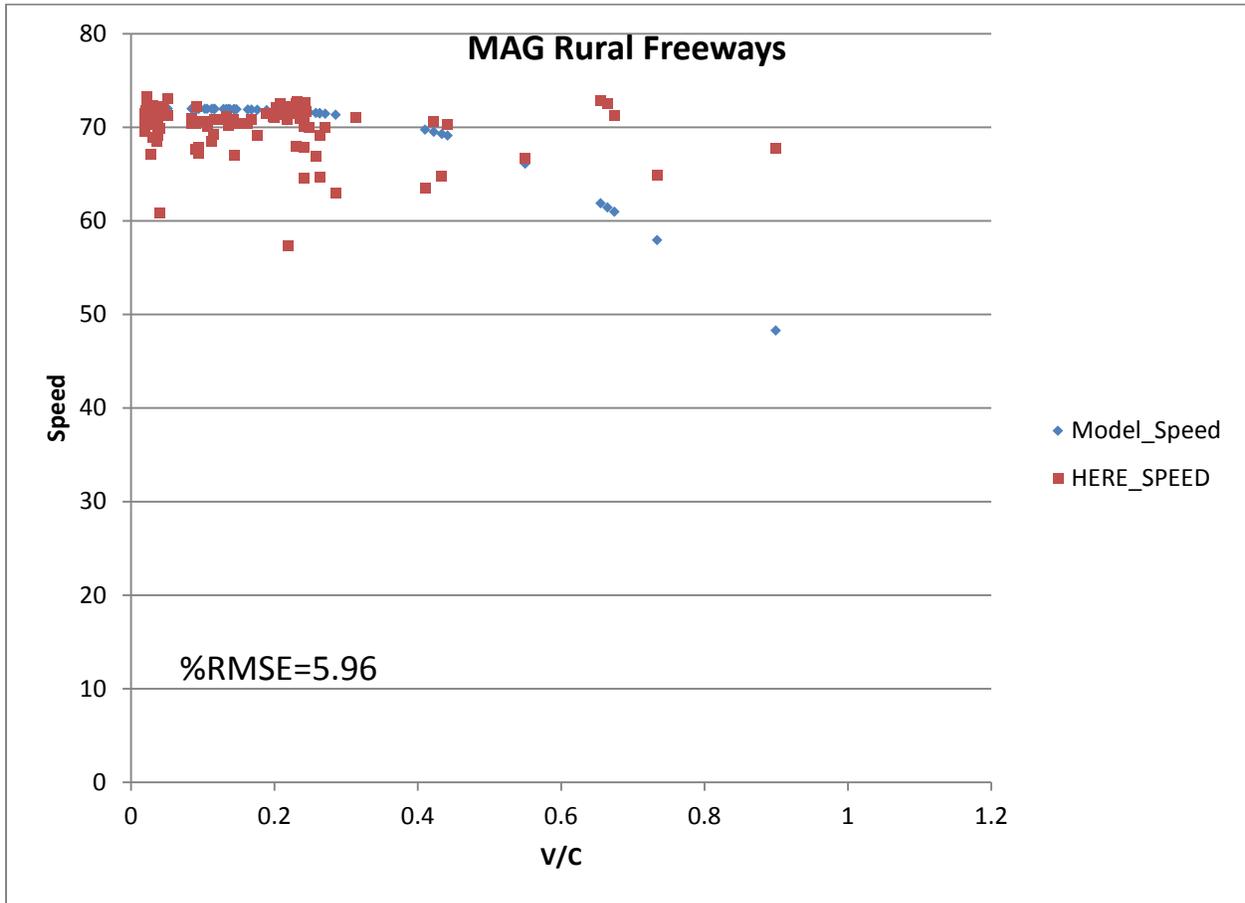
**Figure 8-12 Comparison of MAG and HERE Speeds for Freeways with 72MPH Free Flow Speeds**



The measured speeds were in general lower for low V/C ratio TMCs and higher for higher V/C TMCs. This may suggest more aggressive driving on the links in the greatest demand. It may also be due to the fact that in reality driving speeds are less sensitive to congestion than the model predicts, and only heavy congestion levels will cause reduced speeds. The presence of measured speeds along the 65 mph horizontal ordinate is likely reflective of a 65 mph speed limit that is respected by a subset of drivers.

A similar pattern was in evidence for the rural freeways. For freeways in rural areas, there was less dispersion among speeds in the measured data.

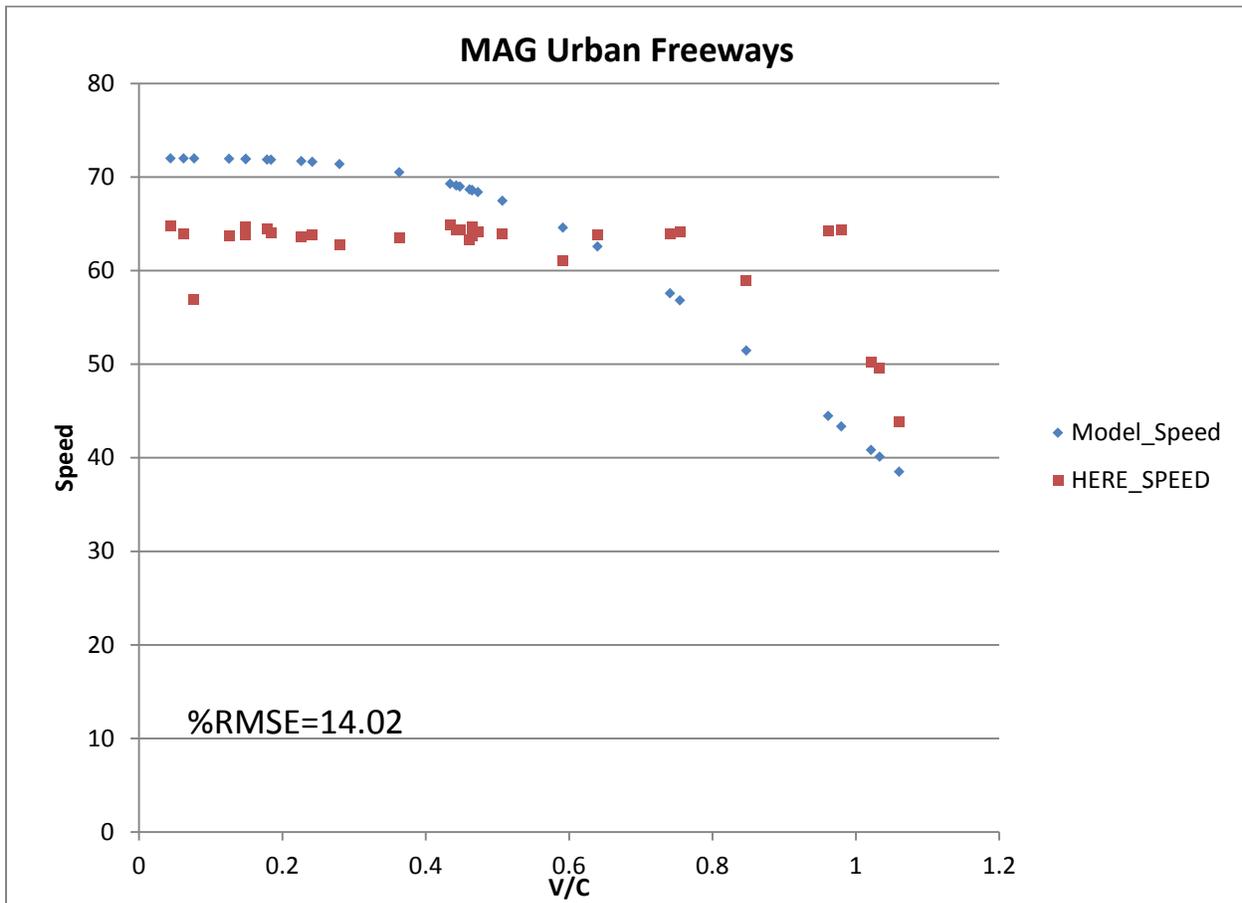
Figure 8-13 Comparison of MAG and HERE Speeds for Rural Freeways



Also, there is very little degradation of speed observed for the TMCs with the higher V/C ratios.

For urban freeways in Phoenix, there is greater dispersion in measured speeds. For both area types, the modeled speeds appear to overestimate speeds at low congestion level locations and underestimate them at higher congestion locations.

Figure 8-14 Comparison of MAG and HERE Speeds for Urban Freeways



It may be that the volumes for the high V/C locations are overstated for one reason or another leading to higher speeds in the real world than in the model. Overstatement of volumes may reflect static assignment bias. In a static assignment, the flow that uses a popular link is not distinguished by time slot within the peak period despite the fact that it obviously does not take place all at once.

The freeway graphs indicate that the model free flow speed is relatively high compared with actual HERE free flow speeds, especially for the urban area type freeway links. Also, it would appear that an adjusted VDF curve could be made to fit the data more closely.

When compared with the results for other MPOs, there is more of a relationship between modeled and measured speeds for the MAG model, which is no doubt due at least in part to the fact that MAG used speed data in its model development process.

HERE vs. model speed comparisons were also performed for arterials and collectors. These are shown for all area types first and then separately for urban and then suburban area TMCs. The BPR parameters for these arterials and collectors are relatively gentle, with a relatively low beta parameter of 2.1.

Figure 8-15 Comparison of MAG and HERE Speeds for Arterials and Collectors with 41MPH Free Flow Speeds

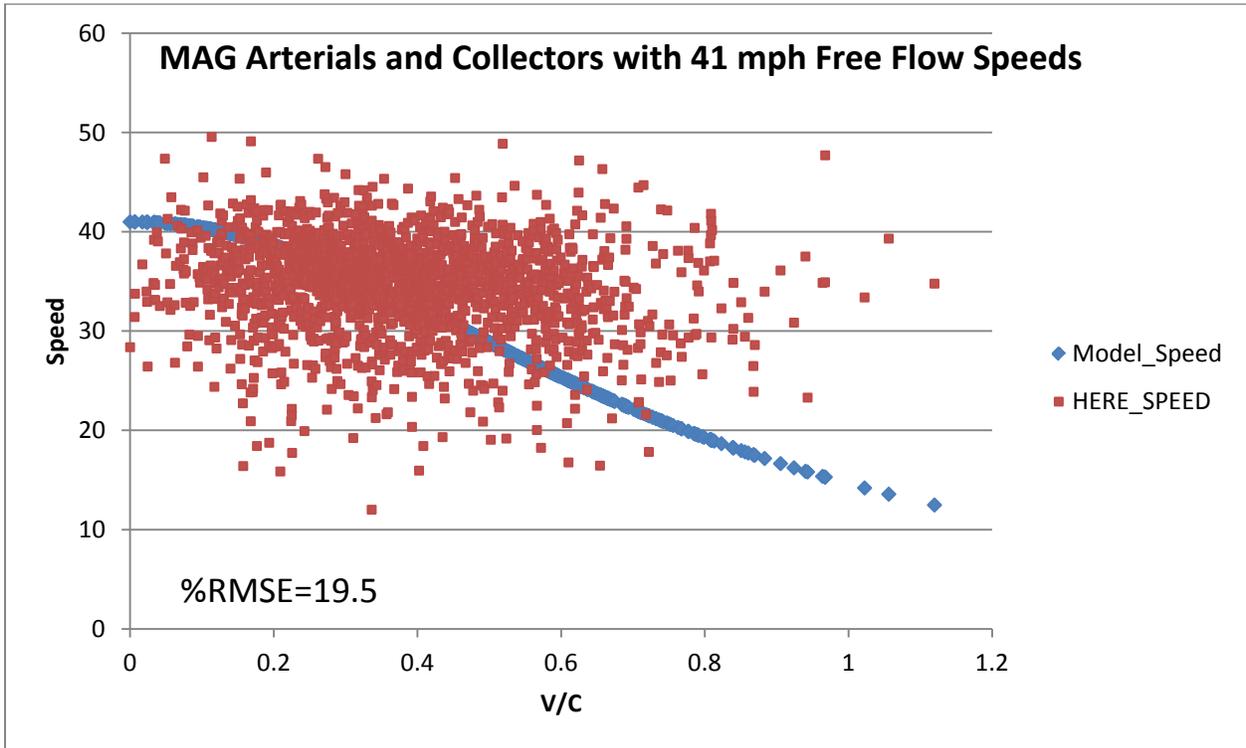
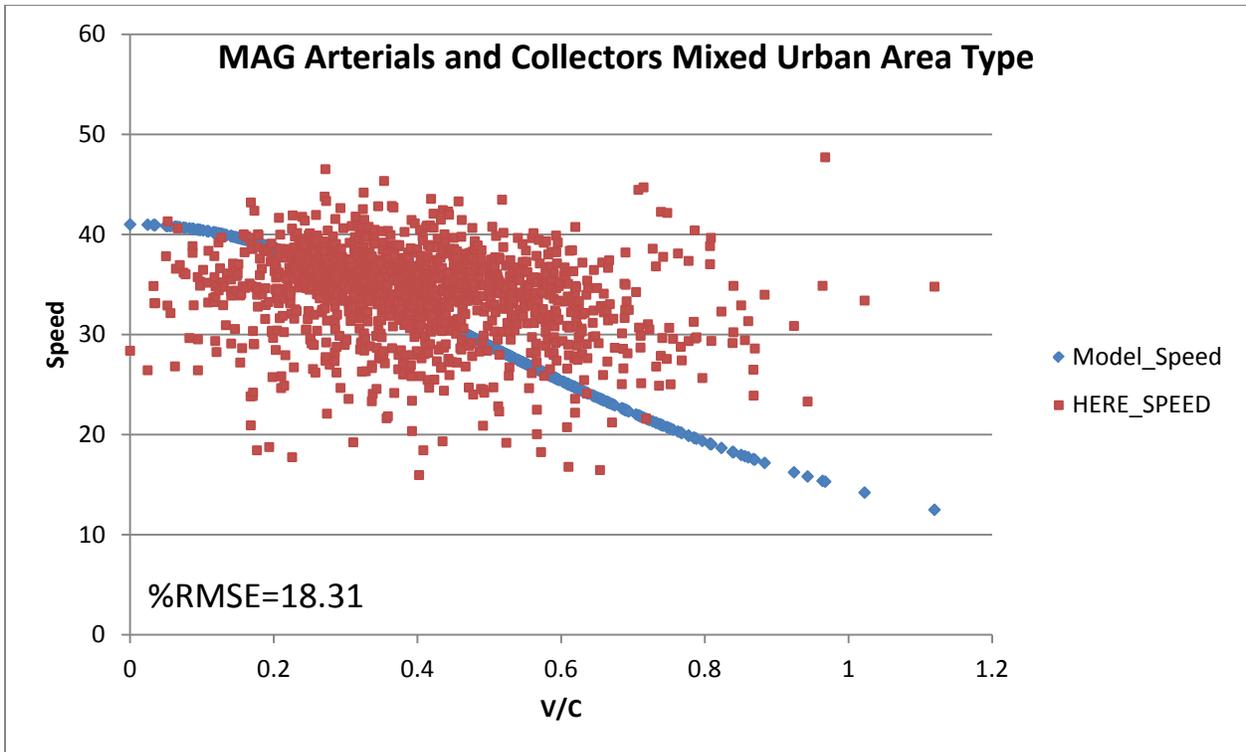
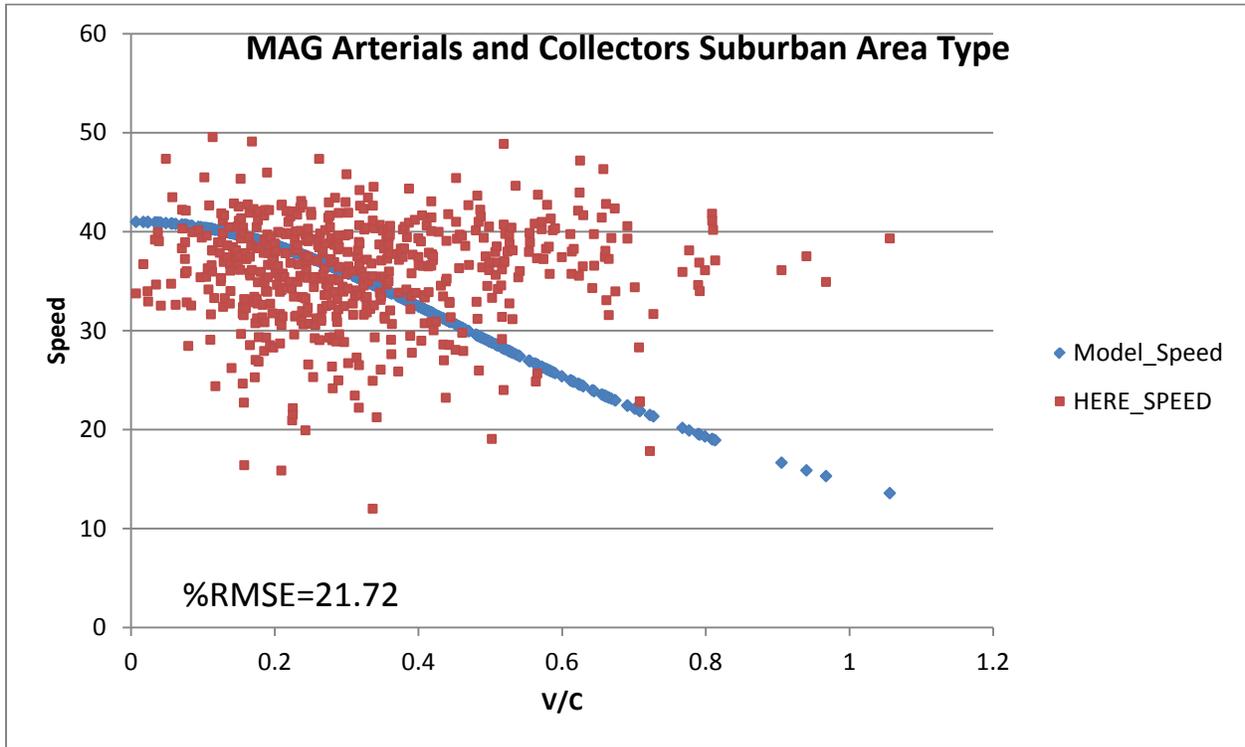


Figure 8-16 Comparison of MAG and HERE Speeds for Urban Arterials and Collectors



**Figure 8-17 Comparison of MAG and HERE Speeds for Suburban Arterials and Collectors**



In the plots above, the HERE speeds are higher than the modeled speeds for TMCs with higher travel volumes.

For MAG, the HERE Traffic vs. Model VHT and average speeds were also tabulated for each road category and are presented in the Table below.

**Table 8-2 Comparison of MAG AM Modeled and HERE TMC VHT and Speeds**

Category	Observations	HERE VHT	Model VHT	VHT %RMSE	VHT %Difference	HERE AVG SPEED	MODEL AVG SPEED
MAG ALL TMC	3777	188,819	215,373	54.60	14.06%	36.52	35.96
Freeway 72mph	174	20,433	21,021	26.03	2.88%	62.33	63.60
Arterial 40mph	794	47,094	50,826	30.72	7.92%	29.60	28.76
Collector 28mph	47	618	785	68.84	27.14%	26.11	21.99
ALL Filtered	1015	68,144	72,632	30.66	6.59%	38.48	38.02

Overall, the MAG TMC model speeds are only slightly lower than measured, and modeled VHT is somewhat higher than that based upon the HERE traffic measurements. Except for the collector class, however, model speeds match average HERE speeds and VHT rather well.

## Comparison of MAG Planning Model Travel Times with INRIX and Microsimulation-based DTA Travel Times

---

As a further analysis, we compared the MAG planning model travel speeds with those from a microsimulation-based dynamic traffic assignment (DTA) for Central Phoenix and with measurements from INRIX, whose travel speed data were used in calibration of the microsimulation model. The microsimulation model was previously developed by Caliper and covers 500 square miles encompassing the Inner Loop in Phoenix, AZ (Caliper, 2013). The model was run in TransModeler for the 3-hour AM peak period. Loaded travel time skims for 15 minute intervals were output from the model. It should be noted that the skim matrix from the simulation model for a particular interval includes only the trips that depart in that interval. The reported travel time is the average of experienced travel times for all the trips made between a given O-D pair during that time interval and excludes time on centroid connectors.

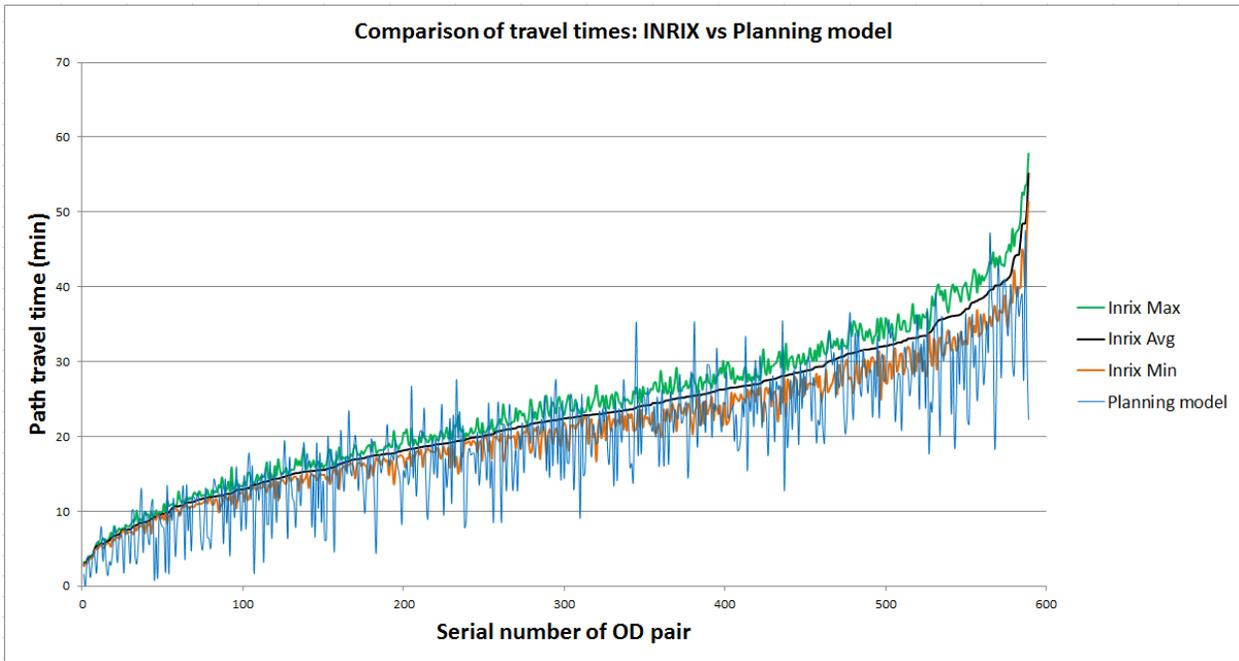
We compared the travel times derived from the simulation run with those from the planning model run in TransCAD to a relative gap of 1.E-4. Since the planning model covers a larger area, we restricted the comparison to the O-D pairs treated in the microsimulation model. Here it is worth noting that the planning model congested skims report the shortest path travel time for each O-D pair and that centroid connector travel times were excluded to facilitate direct comparison with the simulated times.

The comparison between the skims is challenging due to multiple geographic and temporal dimensions and the volume of O-D pairs. Also, the simulated times for an O-D pair can vary considerably within the AM period. Consequently, we decided to compare the planning model travel times with the average, minimum, and maximum travel times from INRIX data and from the microsimulation based upon the travel times for the 15-minute intervals.

To enable better visualization of the travel time comparisons and reduce the number of O-D pairs for graphing, we randomly sampled 1% of the O-D pairs that had one or more trips during the simulated time period. Since O-D pairs with only a single trip during the simulated period have coincident values for the average, maximum, and minimum travel times from the microsimulation, these were plotted in a separate graph.

The results are shown below with the INRIX average travel times following the darker blue line. As indicated in the prior comparison, the planning model times are often lower than the minimum travel time from INRIX. This is further demonstrated by the RMSE values shown in the Table below the graph.

**Figure 8-18 Comparison of INRIX and MAG Planning Model Travel Times for Central Phoenix**



**Table 8-3 Comparison of INRIX (I) and MAG Planning Model Travel Times (T) for Central Phoenix**

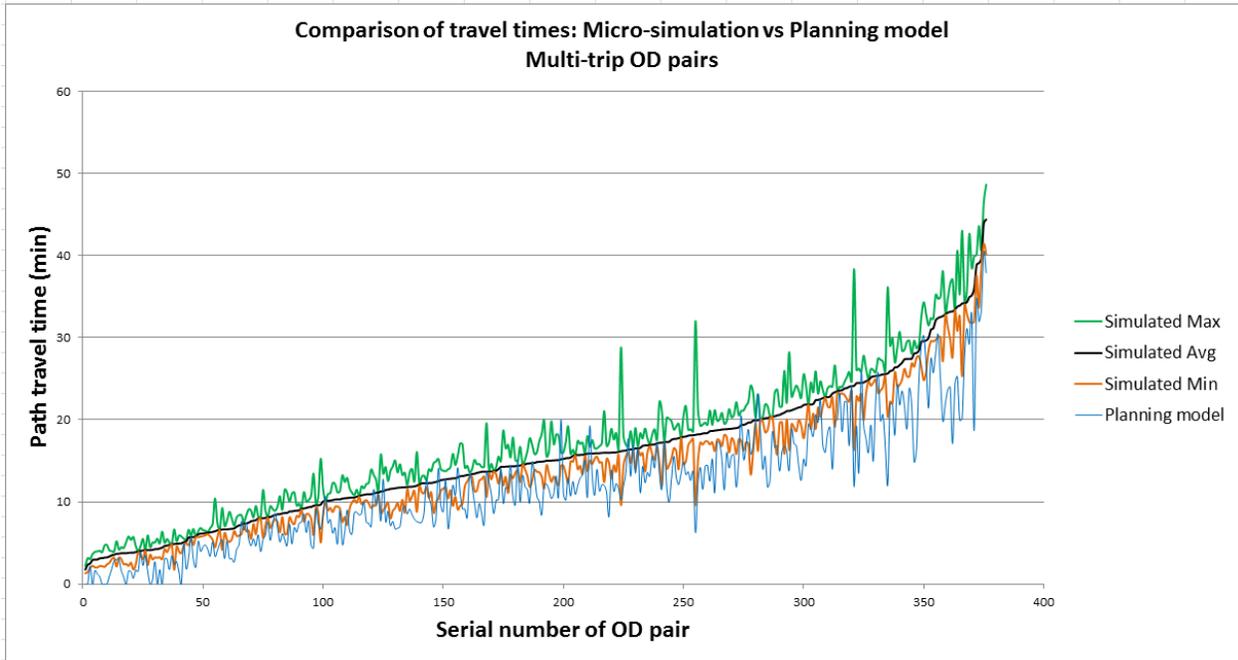
% RMSE		% difference	
$I_{MAX}$ VS T:	33.25	$(I_{MAX}-T)/T$ :	22.02
$I_{AVG}$ VS T:	27.9	$(I_{AVG}-T)/T$ :	14.12
$I_{MIN}$ VS T:	25.48	$(I_{MIN}-T)/T$ :	4.88

On average the planning model times are 14% lower than those from INRIX. This is not entirely inconsistent with the results presented previously with the HERE data as the simulation area contains a great many arterials and collectors.

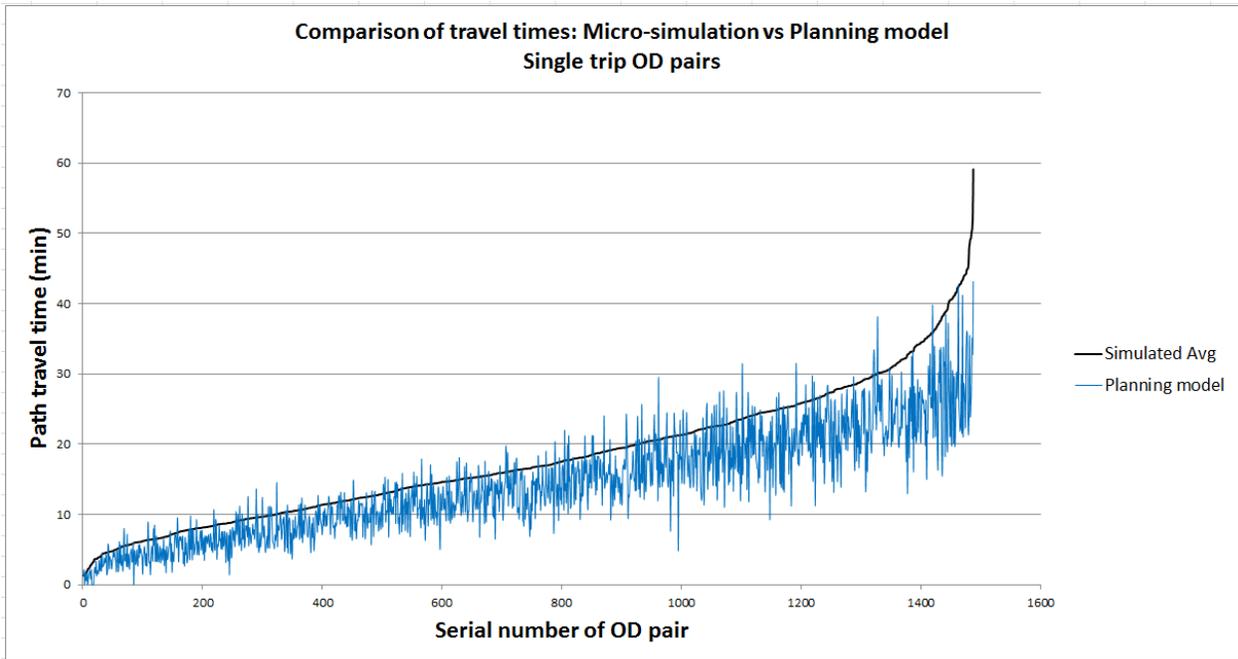
There is obviously quite a range of measured travel times within the AM peak period as reflected in the band between the minimum and maximum INRIX travel times. This range increases for longer trips as would be expected.

A similar pattern is in evidence when comparing the static AM planning model times versus the minimum, average, and maximum travel times experienced within the AM peak period from the microsimulation DTA model for each O-D pair sampled. Along the x-axis, the O-D pairs are serially arranged based on the simulated average travel time. From the graph, it is obvious that the planning model congested travel times are consistently lower than even the minimum travel times from the simulation model. The same pattern of results holds for most of the O-D pairs, for which there was only one trip in the AM simulation.

**Figure 8-19 Comparison of Micro-Simulated DTA and Planning Model Travel Times for Central Phoenix for Multi-trip OD Pairs**



**Figure 8-20 Comparison of Micro-Simulated DTA and Planning Model Travel Times for Central Phoenix for Single-trip OD Pairs**

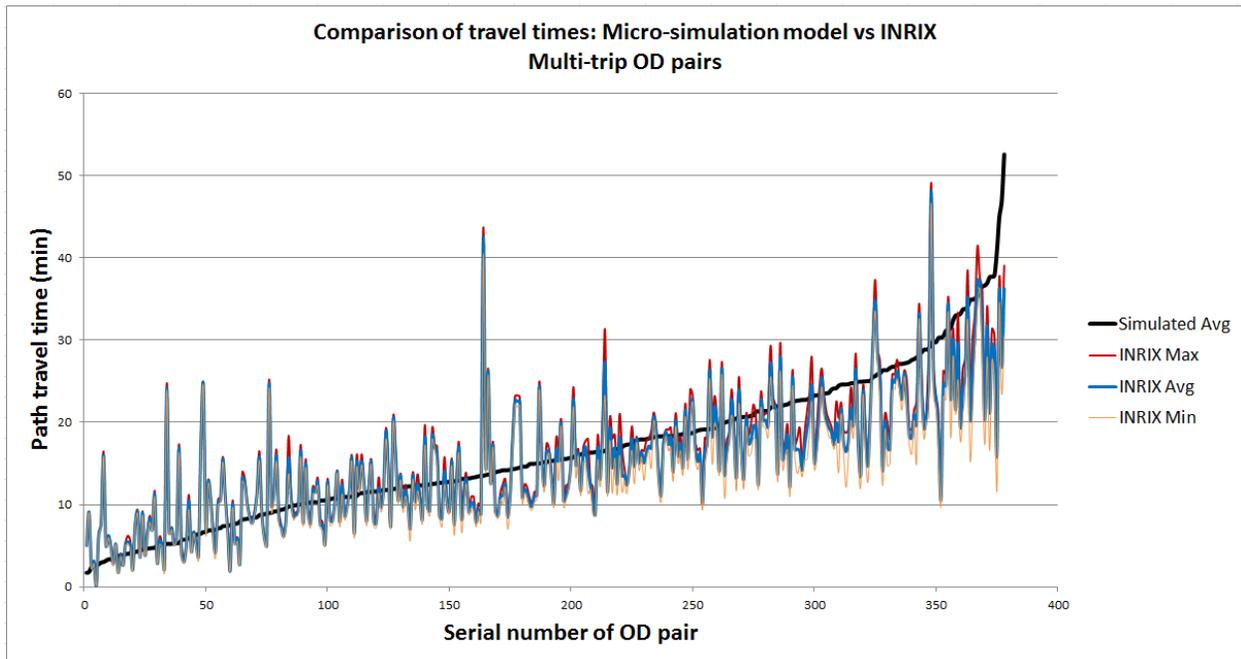


Once again the differences are larger for longer trips.

To complete the analysis we examined the relationship between the travel times from the micro-simulation model and those derived from INRIX for the same sample of O-D pairs. The data from INRIX were aggregated to indicate link speeds every 15 minutes during the AM peak period. The link speeds were converted to link travel times and used to calculate INRIX-derived skims at 15-minute intervals

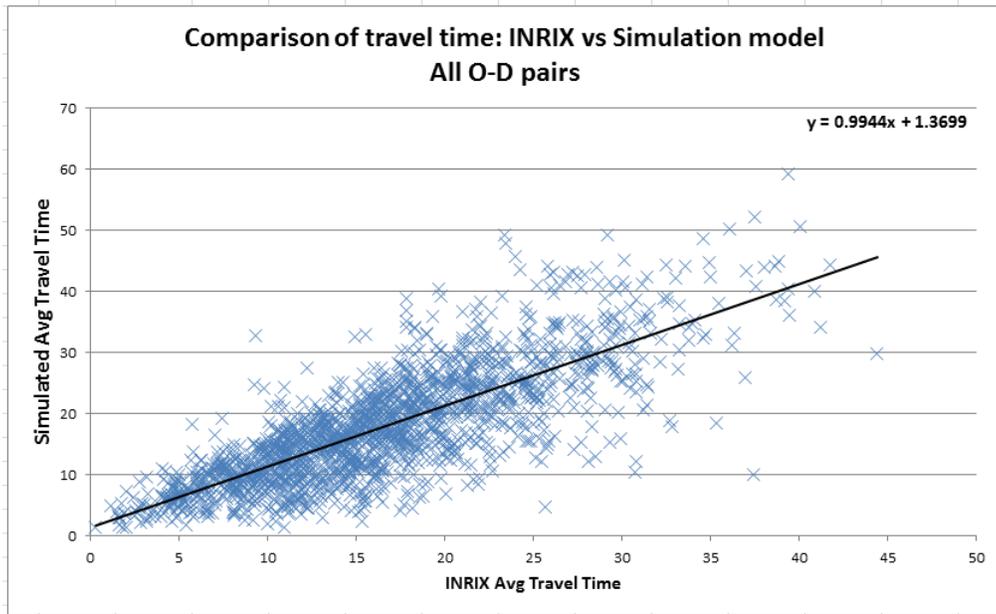
In Figure 8-21, we plot the micro-simulated average DTA travel times and compare them with the INRIX data. As one can see there, the simulated times fall within the minimum and maximum INRIX times and are fairly close to the average times for a great many, but certainly not all O-D pairs.

**Figure 8-21 Comparison of Micro-Simulated DTA and INRIX Travel Times for Multi-trip OD Pairs for Central Phoenix**



In addition, we also produced a scatterplot combining all O-D pairs. As can be seen from the equation of the trendline, there is a good degree of correspondence between micro-simulated DTA travel times and those derived from INRIX. This is not necessarily surprising since the calibration of the simulation model attempted to match the INRIX speeds.

**Figure 8-22 Scatterplot of Micro-Simulated DTA and INRIX Travel Times for ALL OD Pairs in Central Phoenix**



The simulated times are only a bit more than 1 MPH faster than the measured ones on average, as indicated by the regression line. It is encouraging that the microsimulation-based DTA model produces travel times that can match the travel time measurements fairly closely.

# NCTCOG Model Speed Analysis

For NCTCOG, we performed the comparison of travel speeds and TMC measurements with the scatterplots that follow illustrating the relationship between modeled and reported travel speeds for the different road classes.

Figure 8-23 Comparison of NCTCOG and HERE Speeds for Highways

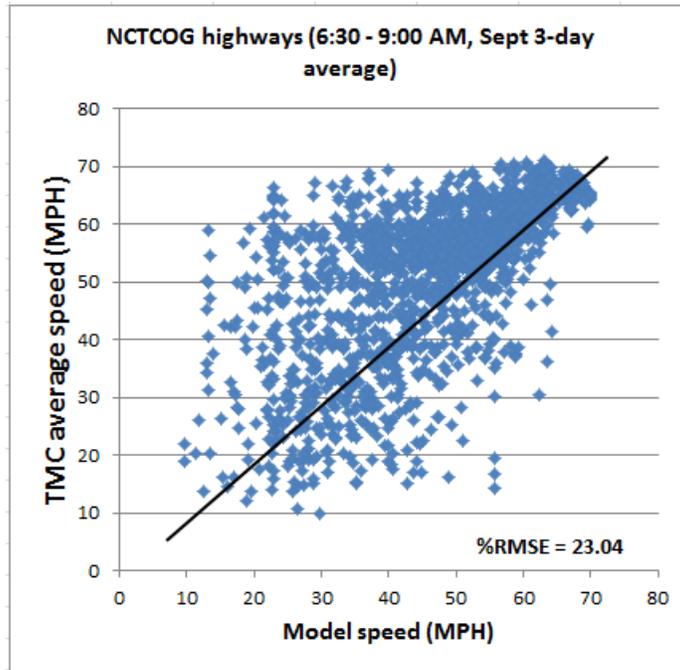
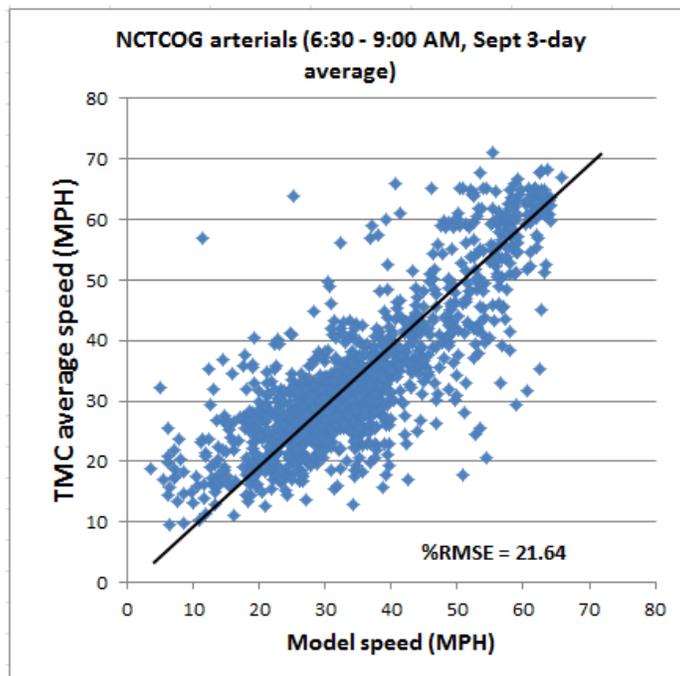
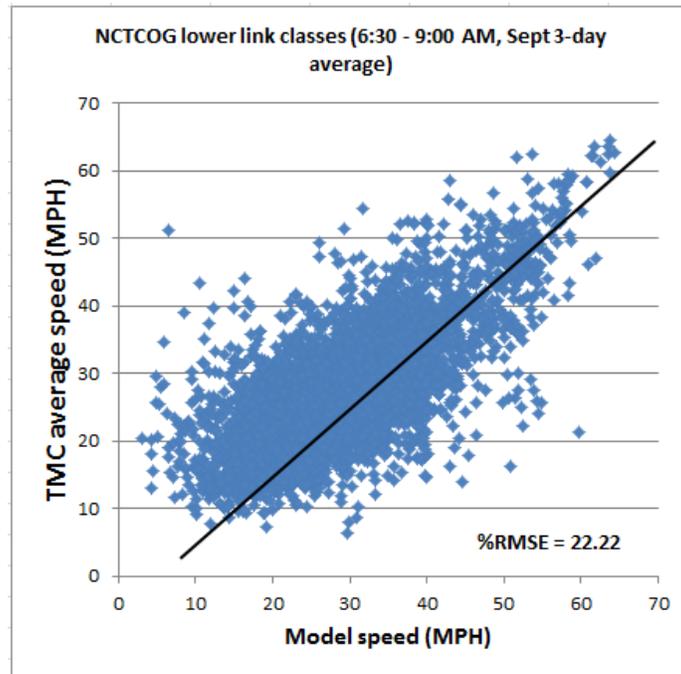


Figure 8-24 Comparison of NCTCOG and HERE Speeds for Arterials



**Figure 8-25 Comparison of NCTCOG and HERE Speeds for Lower Link Classes**



The scatterplots show a reasonable correlation between modeled and measured speeds but also significant dispersion.

The VDF speed comparisons for NCTCOG follow and are stratified by functional class and free flow speed categories. The NCTCOG VDF includes node (i.e., intersection) delay on many links. The graphs in the figures that follow show HERE vs. model speeds for freeways and expressway TMCs that have no node delay.

Figure 8-26 Comparison of NCTCOG and HERE Speeds for Freeways with 65MPH Free Flow Speeds

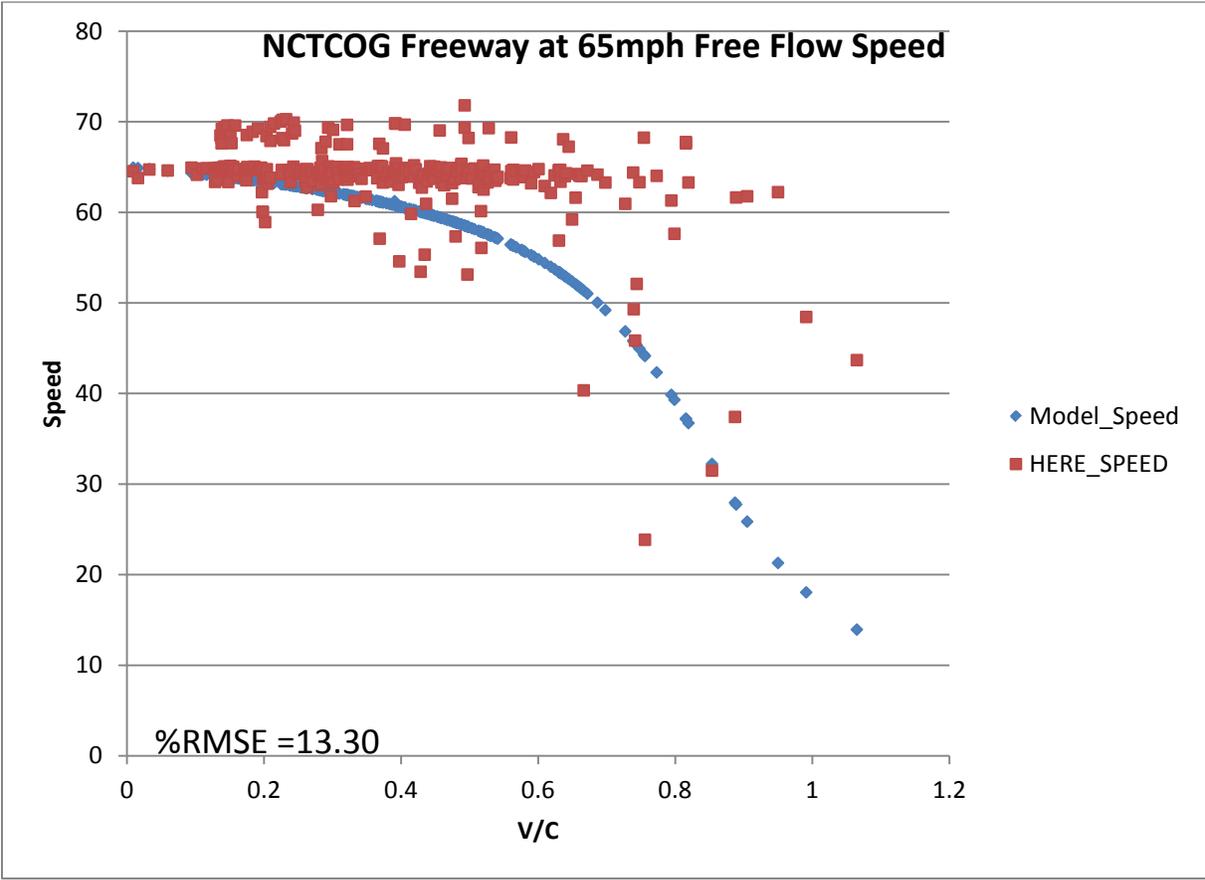
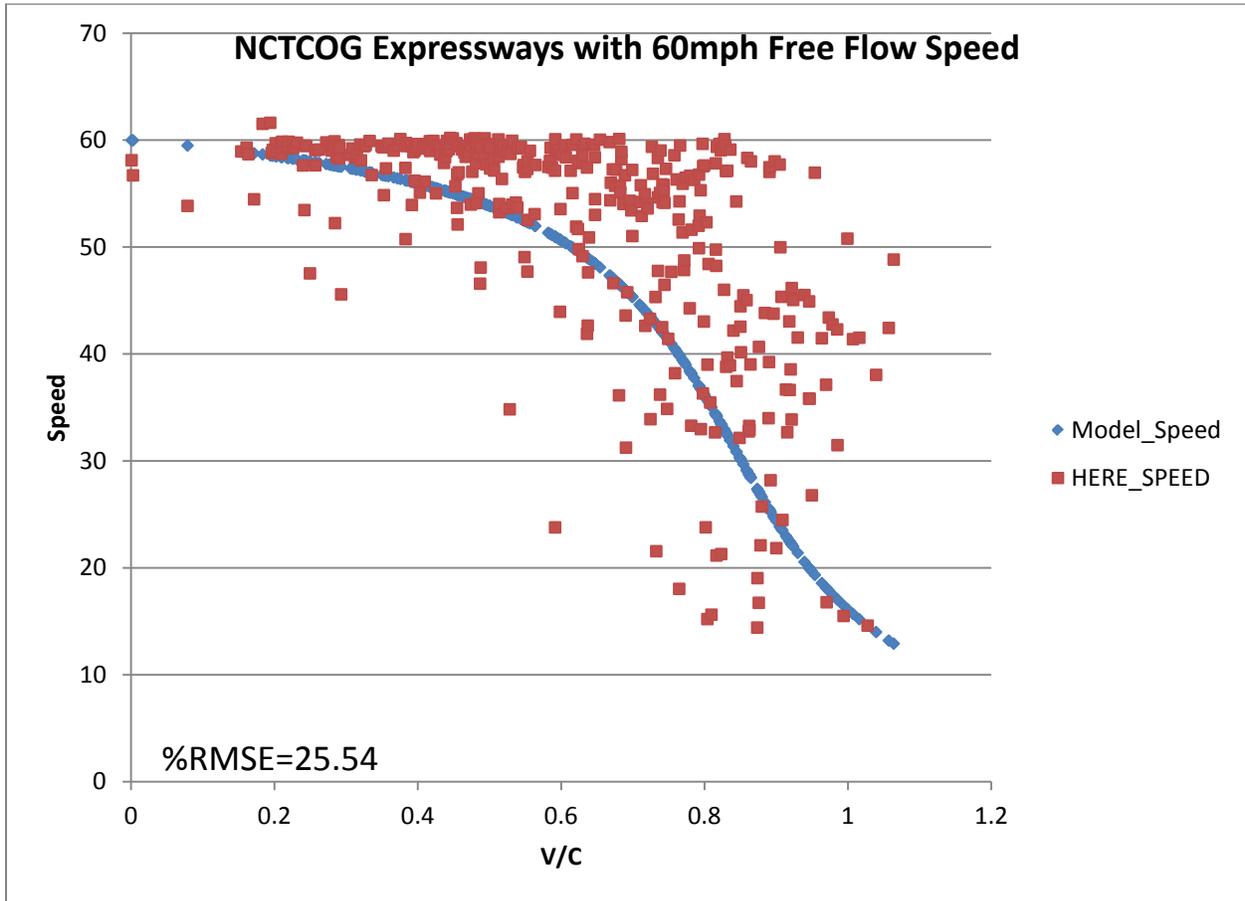


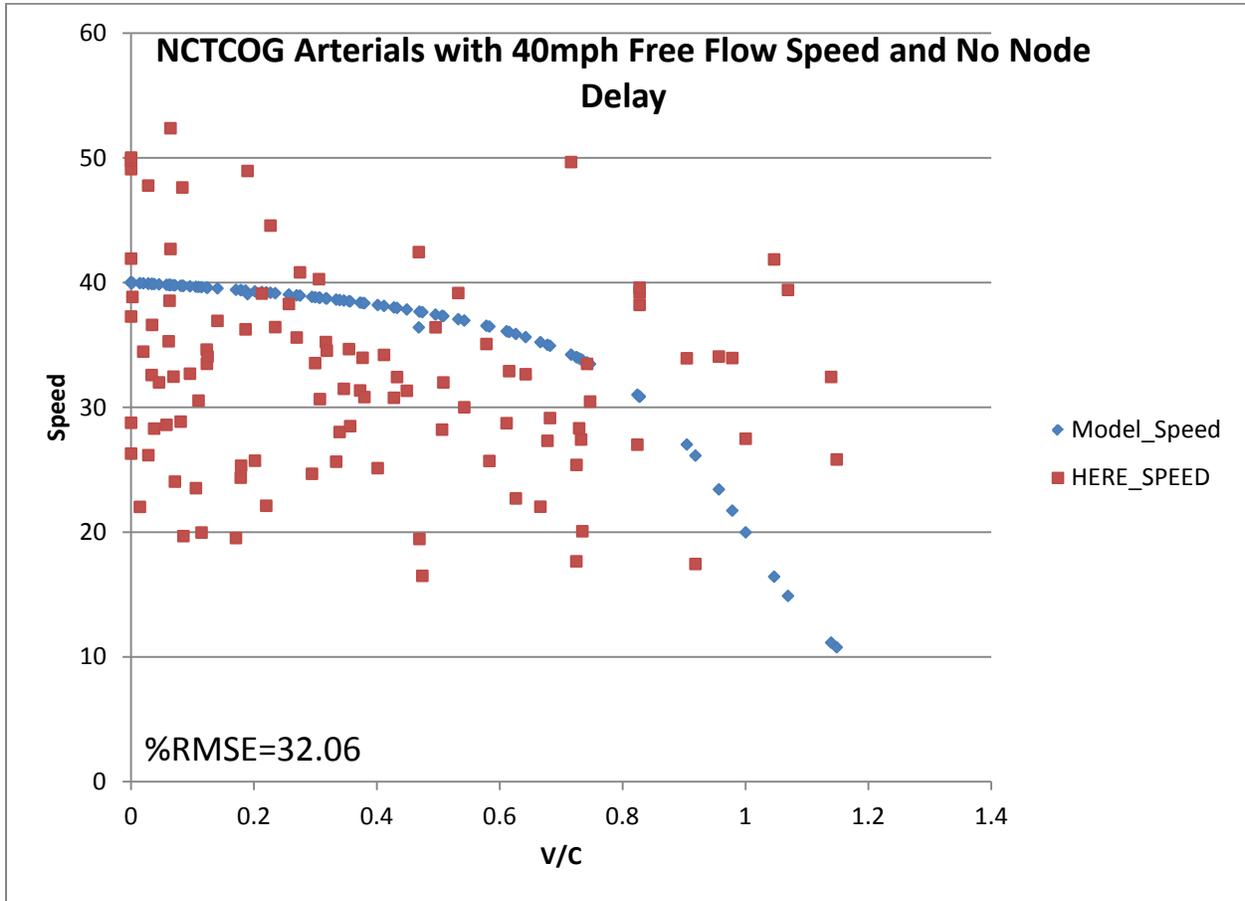
Figure 8-27 Comparison of NCTCOG and HERE Speeds for Freeways with 60 MPH Free Flow Speeds



The graphs above indicate that HERE traffic speeds are generally higher than modeled speeds. There are facilities on which the reported speeds are greater than the speed limit. Also, clusters of speeds appear close to the speed limit in each graph. In addition, both these graphs show that model speeds degrade faster than measured speeds at higher V/C ratios.

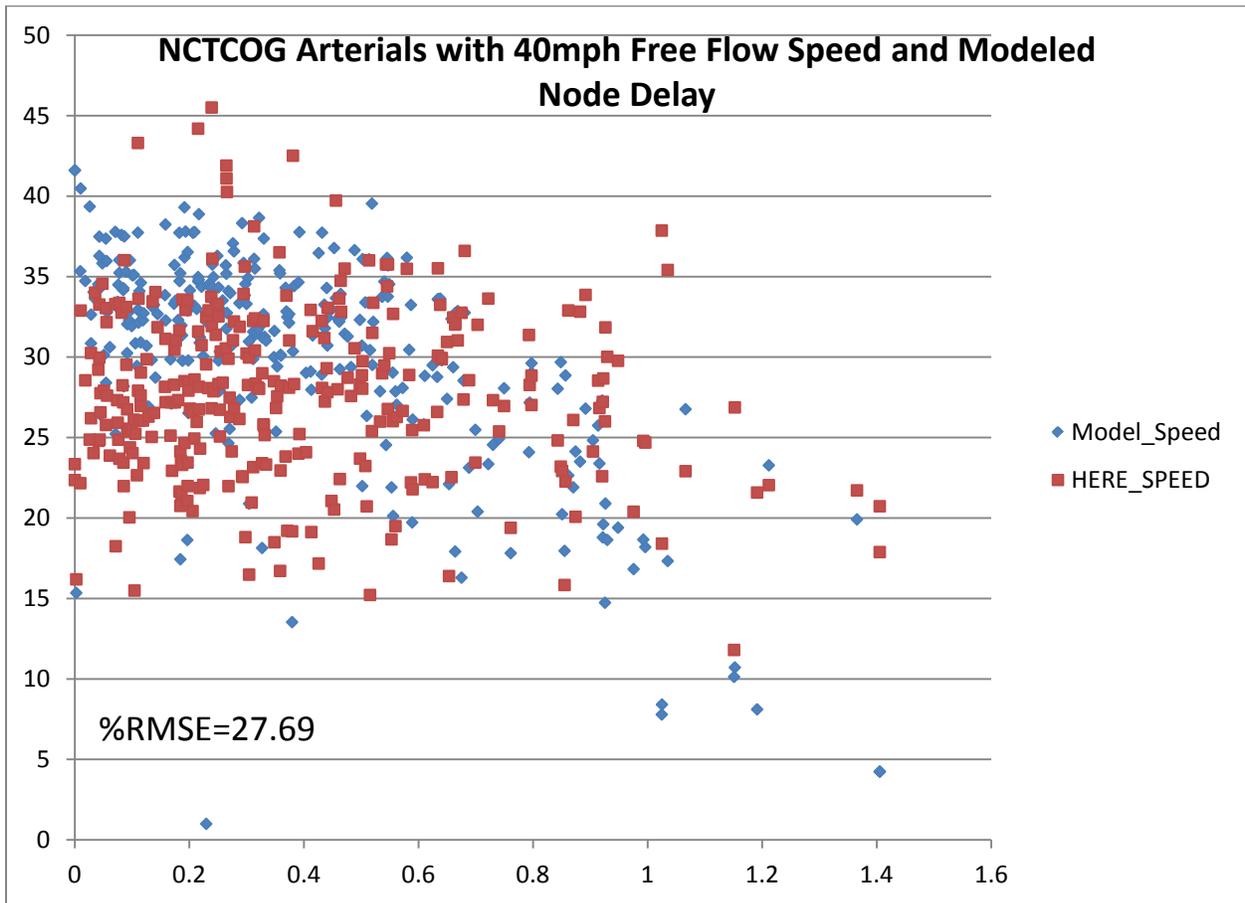
The next graph displays the comparison for arterials that have no additional modeled intersection delay.

**Figure 8-28 Comparison of NCTCOG and HERE Speeds for Arterials with 40MPH Free Flows Speeds and No Modeled Intersection Delay**



The graph shows the weak relationship between HERE and model speeds. In general the TMC speeds tend to be lower than the model VDF speeds. The next graph displays arterials that have modeled intersection delay.

Figure 8-29 Comparison of NCTCOG and HERE Speeds for Arterials with 40MPH Free Flows Speeds and Modeled Intersection Delay



The additional intersection delay lowers the overall model speeds and while the modeled speeds are more in line with measured speeds, there is still rather wide dispersion between them. Also, since the intersection delay values are unique for every link, the model speeds no longer follow a distinct delay curve.

The HERE Traffic and modeled VHT and average speeds were calculated for each functional class and are presented below.

**Table 8-4 Comparison of NCTCOG AM Modeled and HERE TMC VHT and Speeds**

Category	Observations	HERE VHT	Model VHT	VHT %RMSE	VHT %Difference	HERE AVG SPEED	MODEL AVG SPEED
NCTCOG All TMC	9739	567,576	620,774	74.83	9.37	41.28	37.92
Freeway 65mph	329	31,599	36,697	63.47	16.13	62.74	55.77
Expressway 60mph	391	50,319	62,713	71.44	24.63	49.20	41.43
Arterial 40mph no Int Delay	104	1,549	1,635	66.18	5.53	31.04	33.43
Arterial 40mph with Delay	304	9,702	11,423	154.48	17.74	27.16	27.00
NCTCOG All Filtered	1128	93,168	112,468	82.81	20.71	51.17	44.29

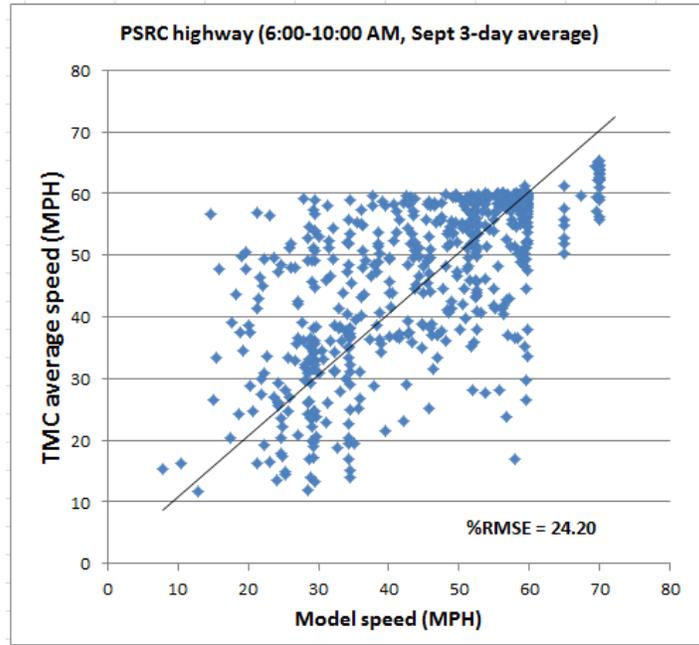
In general, average NCTCOG speeds are lower than average HERE speeds and the subsequent VHTs are higher. Looking at the “arterial no Int. delay” versus the “arterial with delay” categories, the model speeds with delay are closer to the HERE speeds (27 mph vs. 27.16 mph) than the model speeds without delay (33.43 mph for the model vs. 31.04 mph from the HERE data). The HERE speeds on the TMCs whose links include intersection delay are marginally slower than on the TMC whose links do not have intersection delay (27.16 mph vs. 31.04 mph).

While we did not study it, NCTCOG performed an alternative travel time analysis using HERE data for corridor segments rather than TMCs or links. Generally, they found RMSEs of less than 20 percent for freeways and major arterials.

# PSRC Model Speed Analysis

The results for the travel speed comparisons for the PSRC trip-based model are shown in the Figures that follow for different functional classes and free flow speed categories.

**Figure 8-30 Comparison of PSRC and HERE Speeds for Highways**



**Figure 8-31 Comparison of PSRC and HERE Speeds for Urban Arterials**

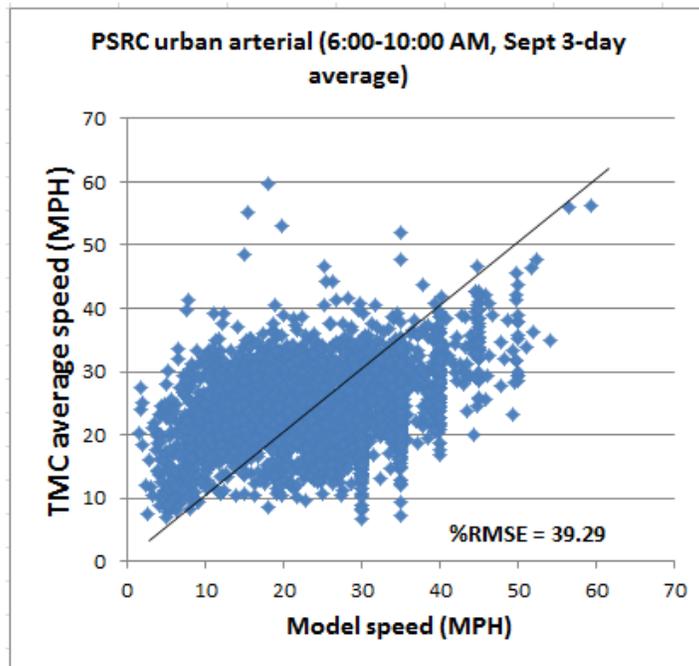
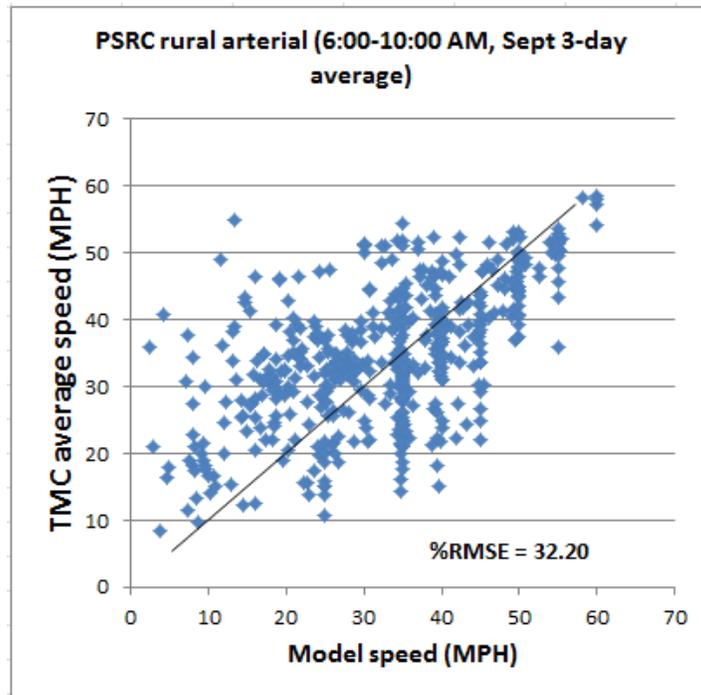


Figure 8-32 Comparison of PSRC and HERE Speeds for Rural Arterials

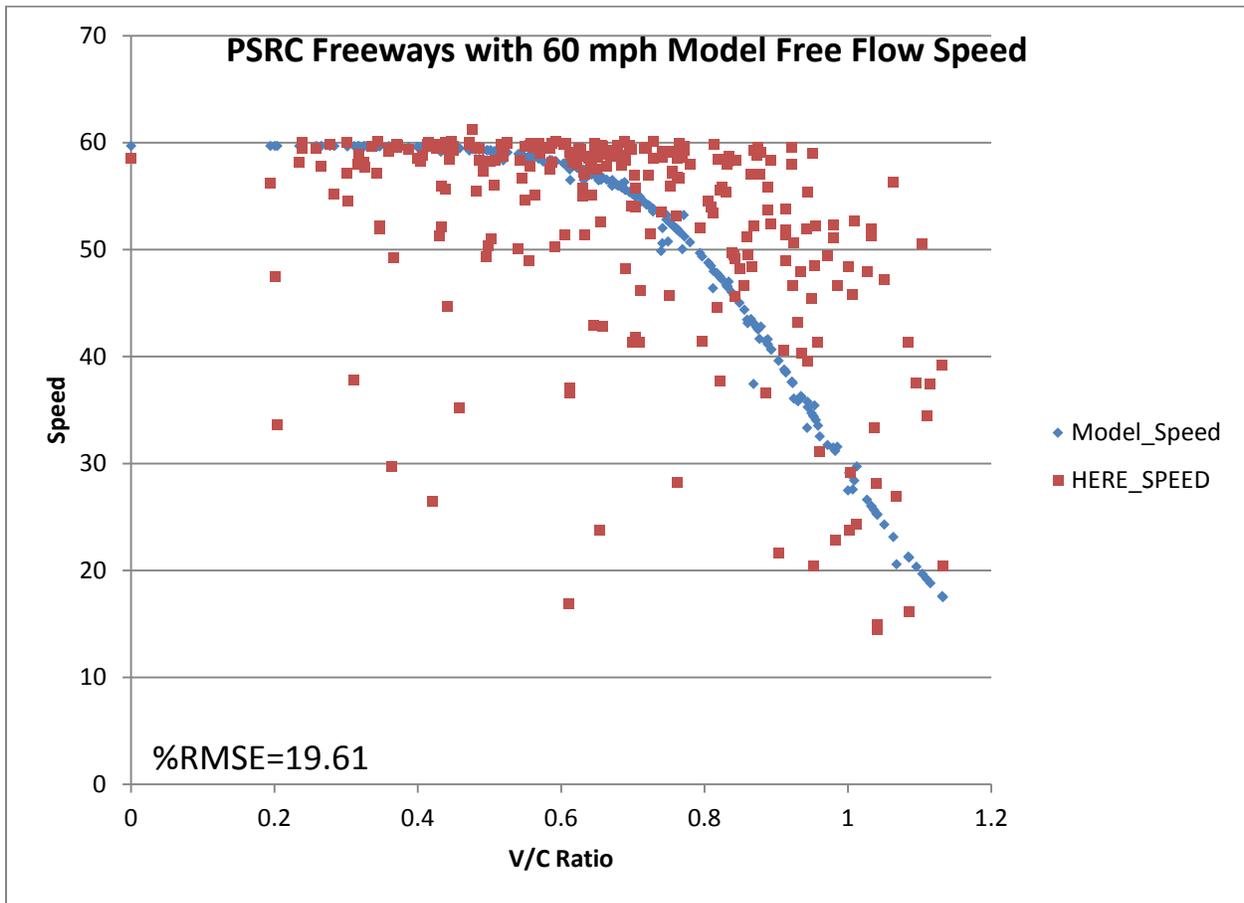


None of the above scatterplots show a very tight relationship between modeled and HERE reported speeds.

Next we present the more detailed comparisons of HERE speeds with the VDF plots by functional class and free flow speeds.

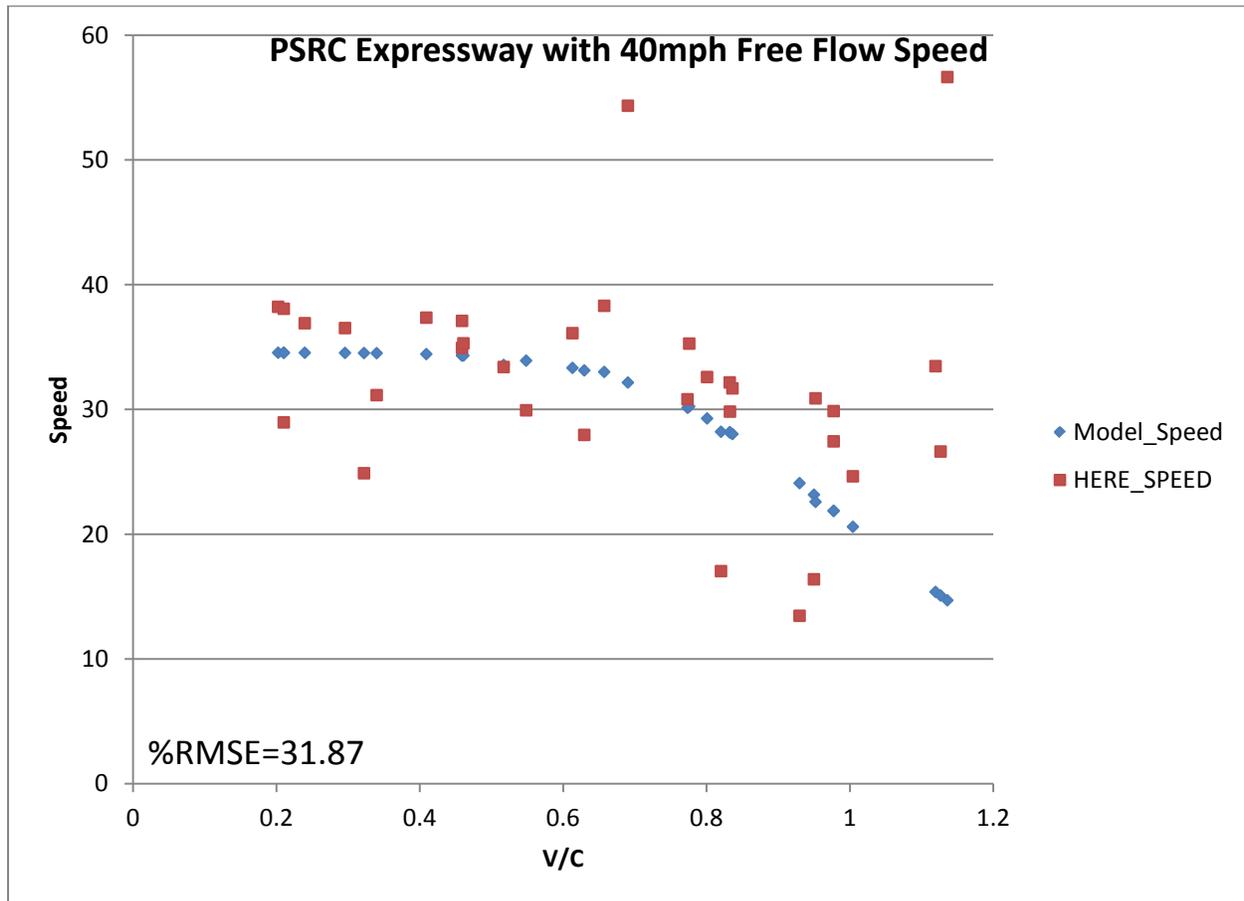
The PSRC VDF adds an extra term to the regular BPR function, which for freeways is intended to be a penalty for “unreliability” (in PSRC’s exact words), and for arterials is intended to account for intersection delay. The extra term has a different form for each of the two functional classes. The graphs that follow show HERE vs. model speeds for freeway and expressway TMCs.

Figure 8-33 Comparison of PSRC and HERE Speeds for Freeways with 60 MPH Free Flow Speeds



There is a cluster of measured speeds at the 60 mph line and in general, faster measured versus modeled speeds at higher model V/C locations. For low V/C locations, measured speeds are typically slower than the model.

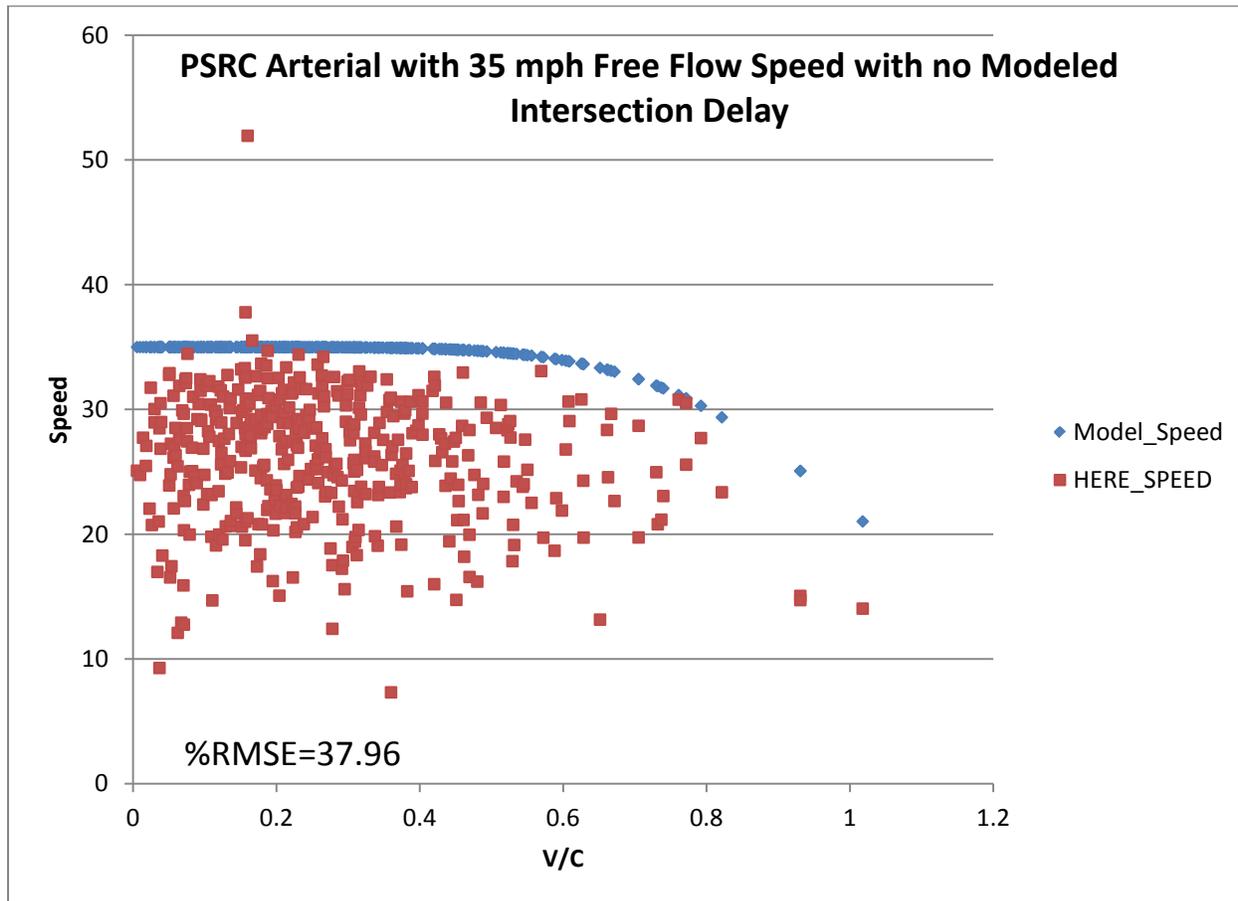
Figure 8-34 Comparison of PSRC and HERE Speeds for Expressways with 40 MPH Free Flow Speeds



In general, the HERE speeds vary somewhat from the model speeds. For the expressways, the relationship is very weak with a high %RMSE value, albeit with a small sample size. There are some very high reported speeds in the plot, suggesting a misclassification of the functional class of some links.

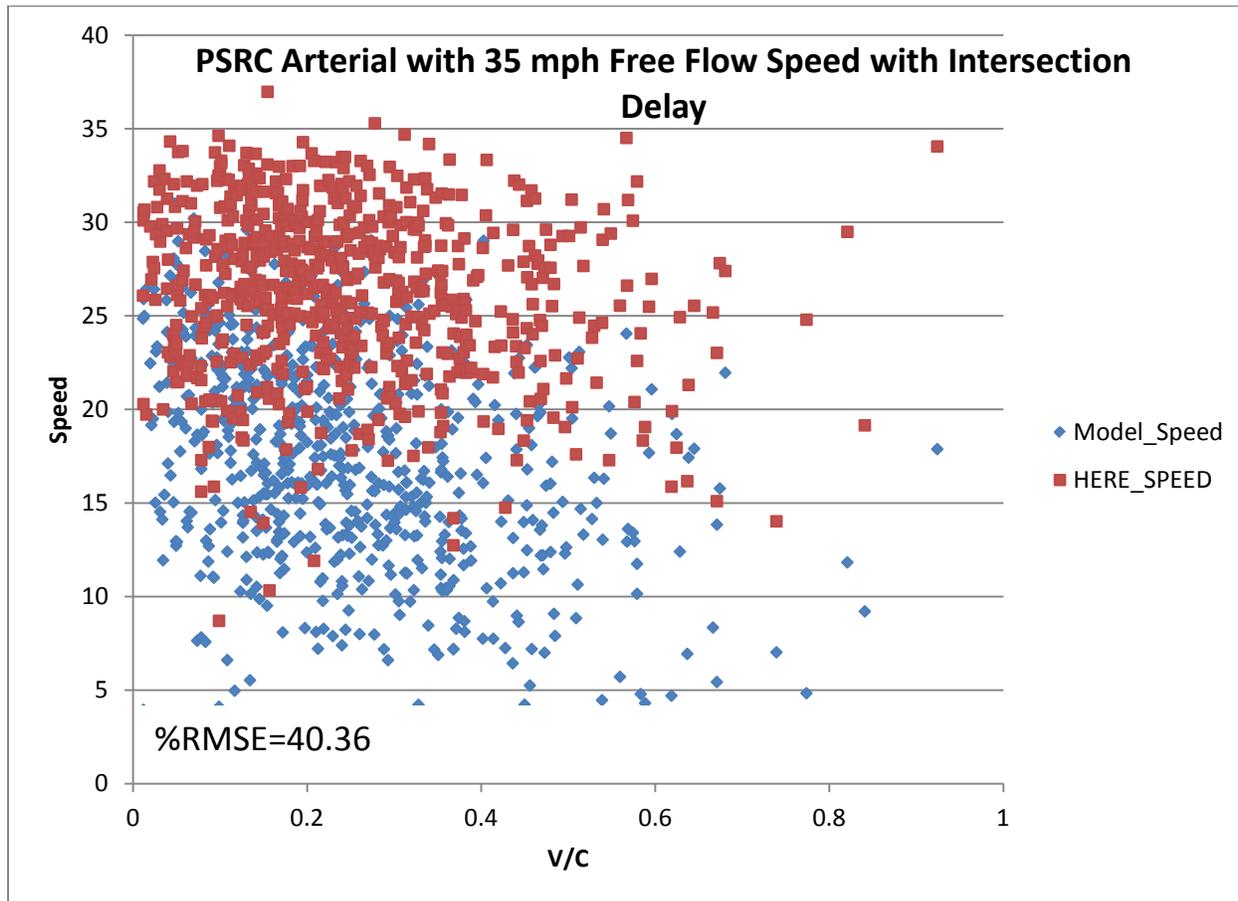
Speed comparisons were also compared for arterial links. The next graph displays the comparison for arterials that have no additional intersection delay.

Figure 8-35 Comparison of PSRC and HERE Speeds for Arterials with 35 MPH Free Flow Speeds and No Modeled Intersection Delay



In general, the model speeds are almost universally higher than the reported TMC speeds. This pattern suggests that real world speeds may be dominated by signal delay. The next graphs display arterials that are modeled with intersection delay.

Figure 8-36 Comparison of PSRC and HERE Speeds for Arterials with 35 MPH Free Flow Speeds and Modeled Intersection Delay



In the graph above, the opposite relationship is present. The use of intersection delay appears to reduce the modeled speeds considerably in relation to measured speeds.

Figure 8-37 Comparison of PSRC and HERE Speeds for Arterials with 25 MPH Free Flow Speeds

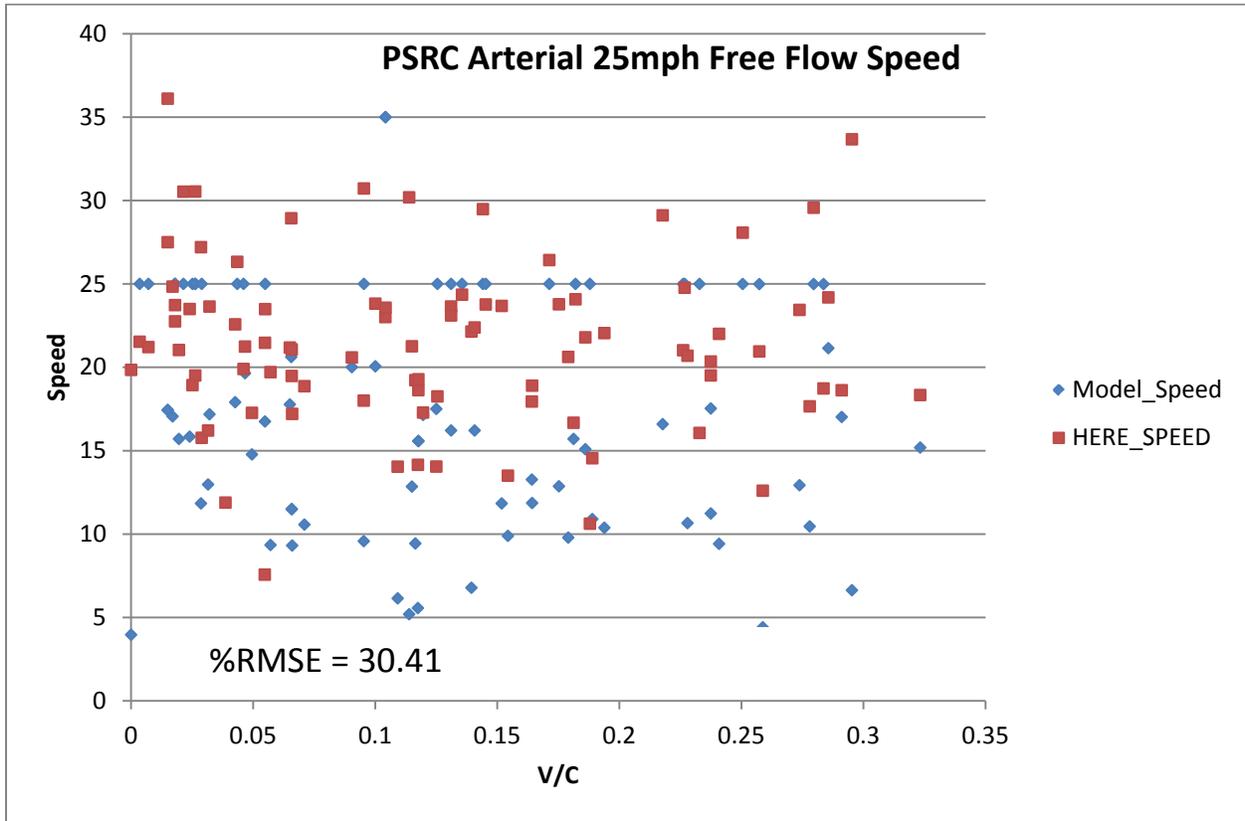


Figure 8-37 above shows comparisons for a set of TMCs that are comprised of some links that had no modeled intersection delay as well as links that do. The additional intersection delay lowers the model speeds as would be expected. Also, since the intersection delay values are unique by link, the model speeds no longer follow a distinct volume-delay curve.

HERE vs. PSRC Model VHT and average speeds were also calculated for each category of facility and are presented below.

Table 8-5 Comparison of PSRC AM Modeled and HERE TMC VHT and Speeds

Category	Observations	HERE VHT	Model VHT	VHT %RMSE	VHT %Difference	HERE AVG SPEED	MODEL AVG SPEED
PSRC All TMC	4013	230,057	293,012	129.72	27.36	38.39	34.90
Freeway 60mph	280	64,915	72,102	53.19	11.07	51.47	47.28
Expressway 40mph	33	2,314	3,298	155.44	42.54	31.65	27.43
Arterial 35mph without Int Delay	428	9,207	7,007	51.04	-23.89	25.21	34.30
Arterial 35mph with Int Delay	676	23,757	39,887	137.30	67.90	25.38	15.85
Arterial 35mph Total	1104	32,964	46,895	128.51	42.26	25.32	22.88
Arterial 25mph Total	114	968	1,326	106.48	36.98	21.12	17.72
PSRC Filtered Overall	1531	101,161	123,621	96.97	22.20	42.42	38.75

In general, the model speeds for the link types we isolated are lower than the HERE speeds, resulting in higher VHTs with the exception of the “arterial without intersection delay” category. The model speeds on arterial links without intersection delay are high compared with the HERE speeds. However, on the arterial links that have intersection delay, the model speeds are much lower than the HERE speeds. Thus, the link component of the VDF function probably under-predicts delay, and when the intersection delay is added, the overall delay is over-estimated.

## SANDAG Model Speed Analysis

Scatterplots comparing modeled and HERE speeds for SANDAG’s activity-based model are presented next. We thought it would be more interesting to examine the results from the ABM than the trip-based model it will ultimately replace.

Figure 8-38 Comparison of SANDAG and HERE Speeds for Highways

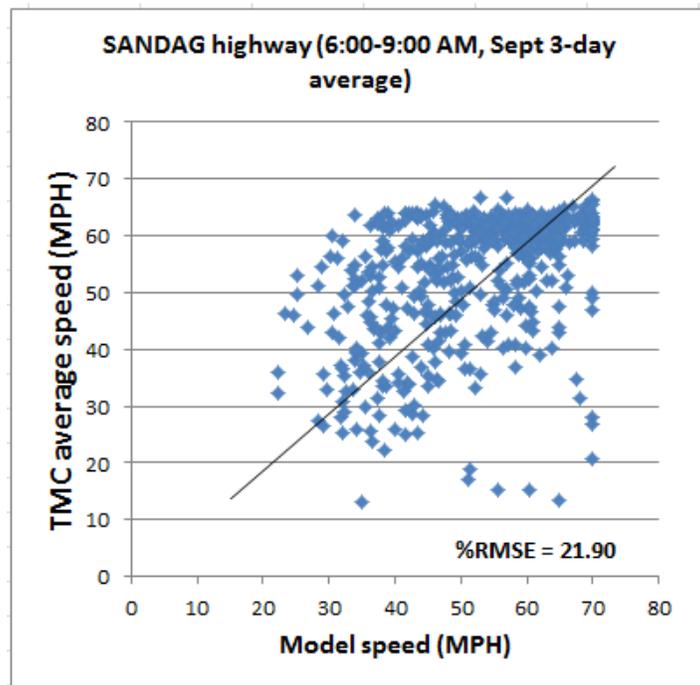


Figure 8-39 Comparison of SANDAG and HERE Speeds for Arterials

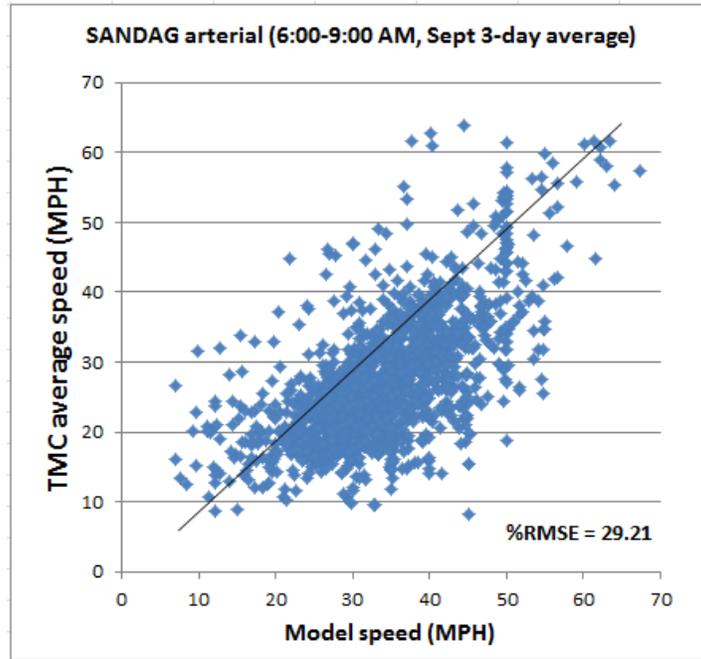
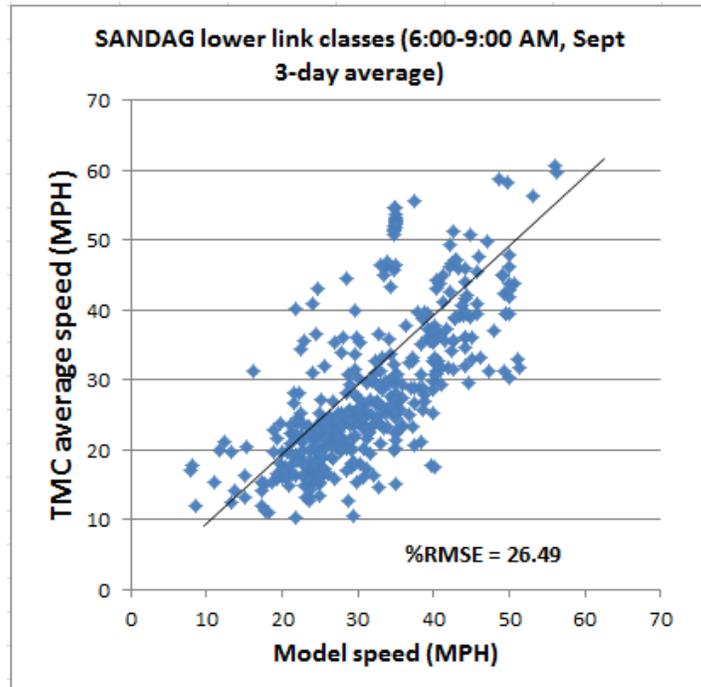


Figure 8-40 Comparison of SANDAG and HERE Speeds for Lower Link Classes



The SANDAG scatterplots are similar to those for the other MPO models reflecting fairly wide dispersion between measured and modeled TMC speeds.

The SANDAG VDF includes intersection delay on many lower class links. The first three figures that follow below show HERE vs. model speeds for freeway, ramp, and arterial TMCs that do not have intersection delay.

Figure 8-41 Comparison of SANDAG and HERE Speeds for Freeways with 65 MPH Free Flow Speeds

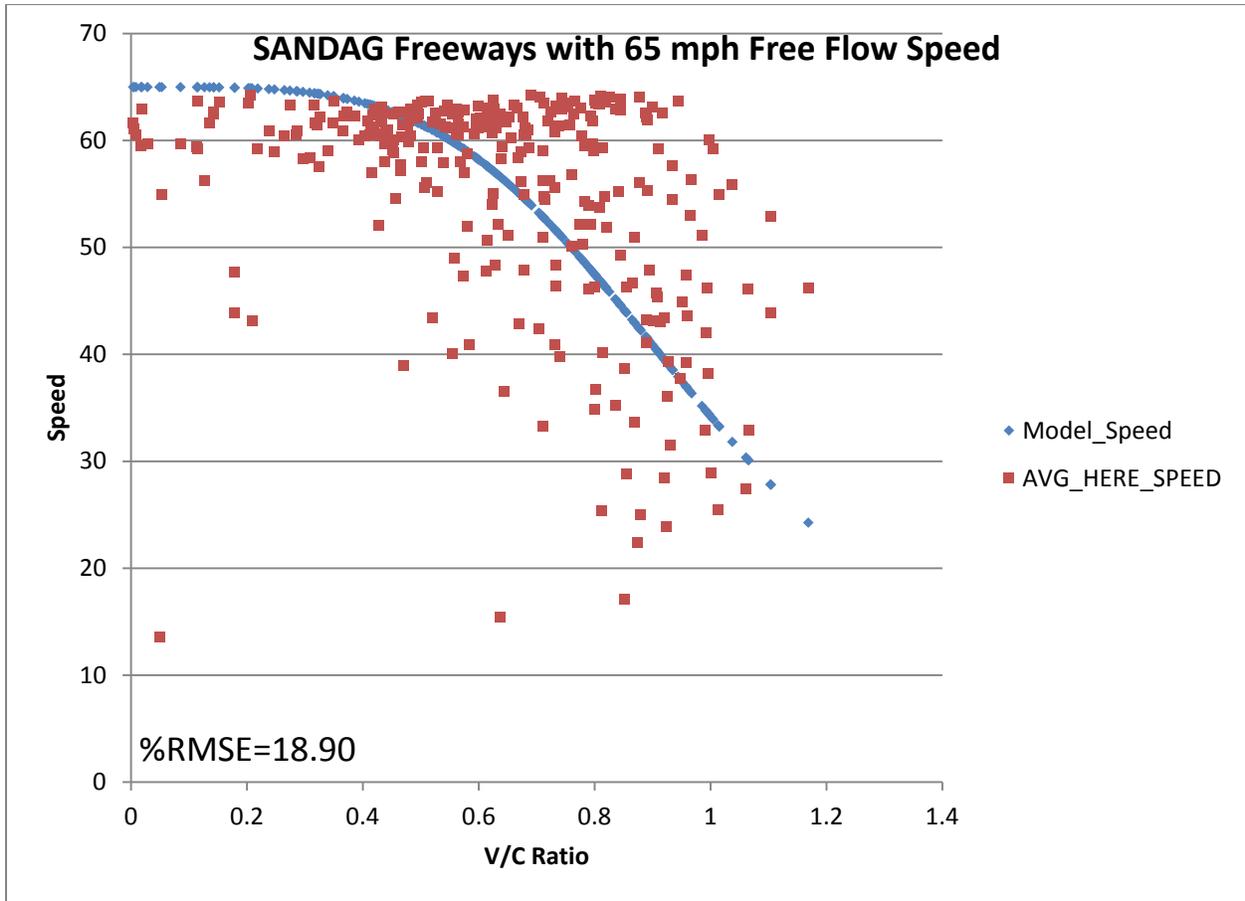
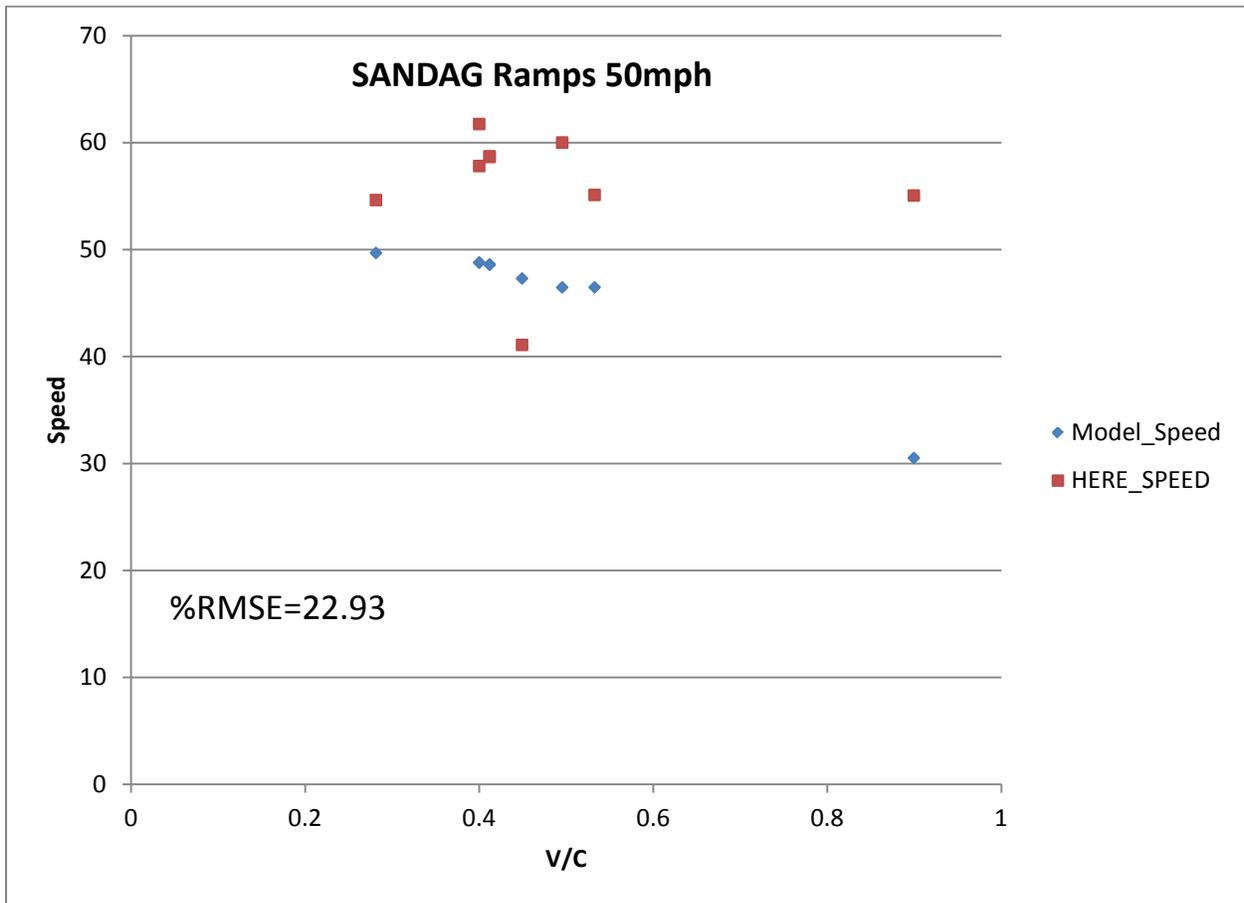


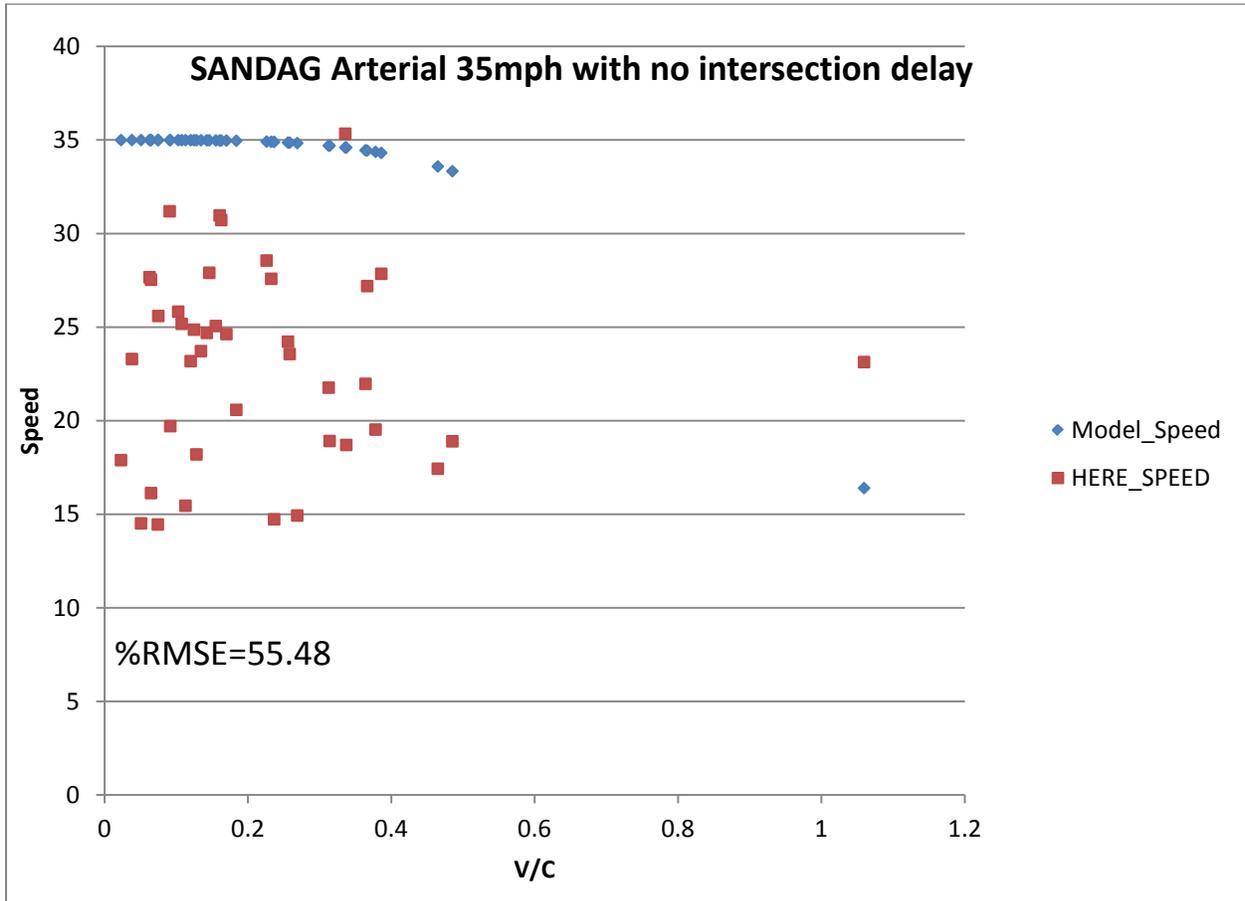
Figure 8-42 Comparison of SANDAG and HERE Speeds for Ramps with 50 MPH Free Flow Speeds



For freeways, the HERE speeds vary widely from the model speeds. For ramps, the HERE speeds are higher than the model speed, albeit with a very small sample size.

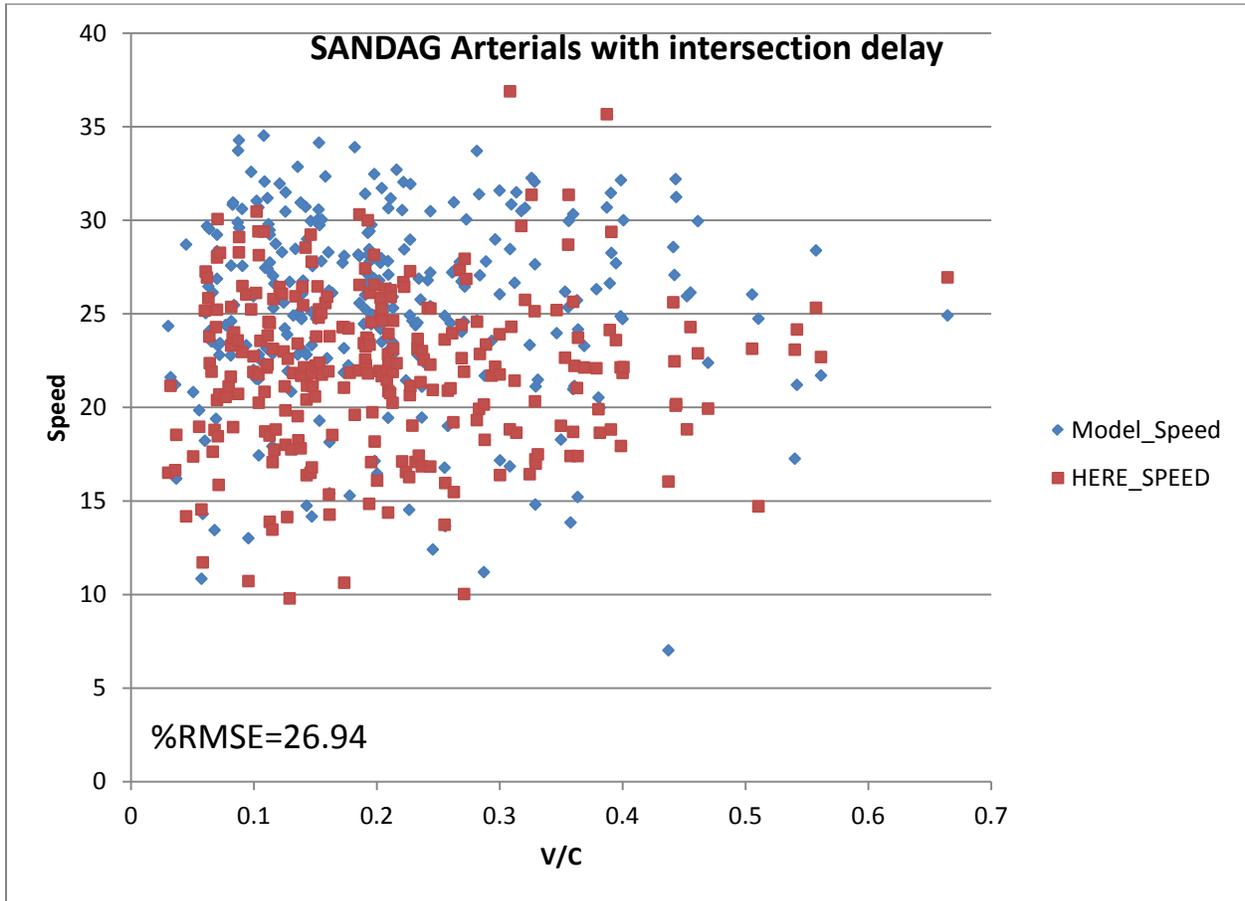
Speed comparisons were also compared for arterial links. The next graph displays the comparison for arterials whose VDFs do not include intersection delay.

Figure 8-43 Comparison of SANDAG and HERE Speeds for Arterials with 35 MPH Free Flow Speeds Modeled without Intersection Delay

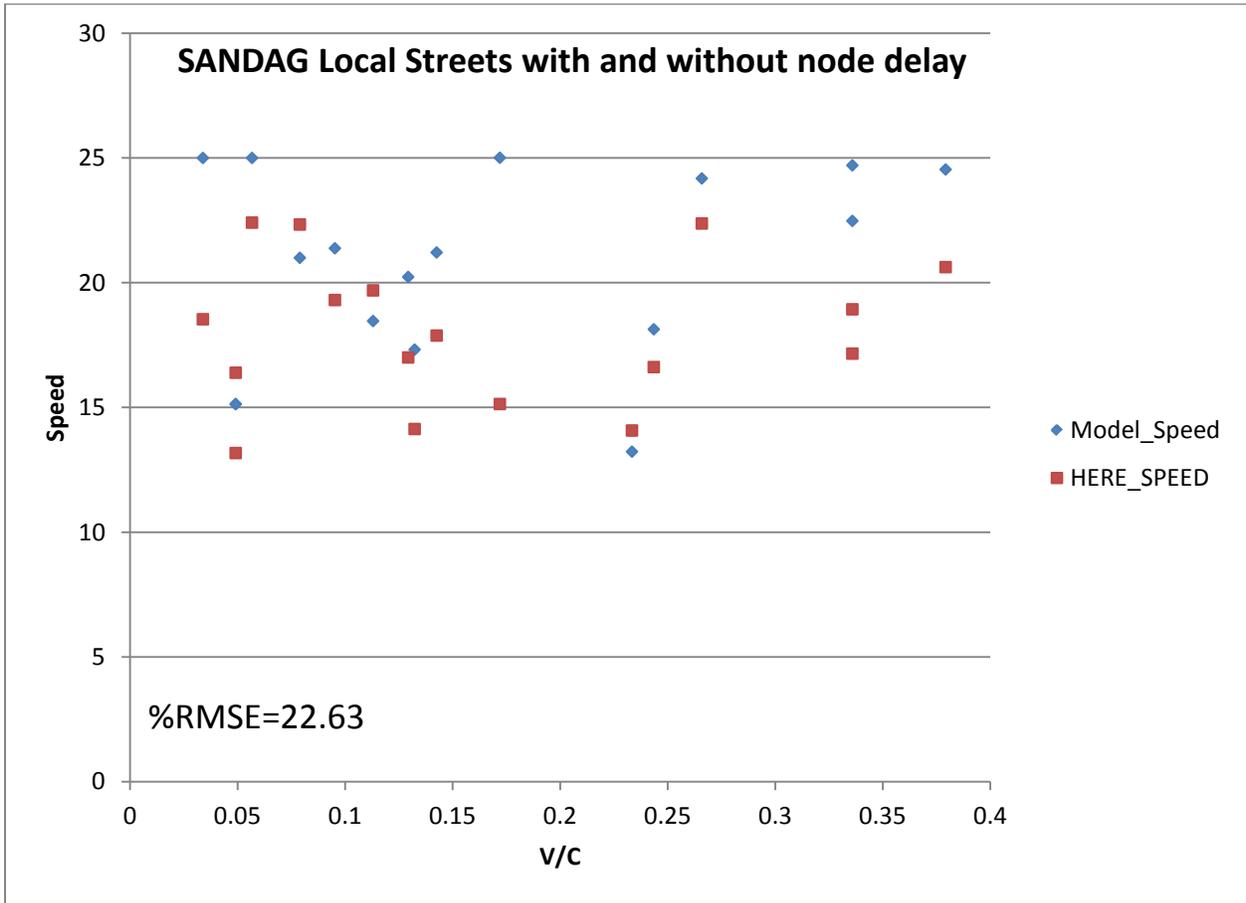


In general, the model speeds seem to be quite a bit higher than the reported TMC speeds. The next graphs display arterial and collector TMCs that are modeled with node delay.

Figure 8-44 Comparison of SANDAG and HERE Speeds for Arterials with 35 MPH Free Flow Speeds Modeled with Intersection Delay



**Figure 8-45 Comparison of SANDAG and HERE Speeds for Local Streets with 25 MPH Free Flow Speeds**



The additional intersection delay lowers the overall model speeds. Also, since the intersection delay values are unique for every link, the model speeds no longer follow a distinct delay curve. The model speeds for TMCs with node delay do tend to be more in line with HERE speeds than TMCs without node delay.

HERE vs. model VHT and average speeds were also calculated for each category and are presented in the Table that follows.

**Table 8-6 Comparison of SANDAG AM Modeled and HERE TMC VHT and Speeds**

Category	Observations	RMSE	HERE VHT	Model VHT	%Difference	HERE SPEED	MODEL SPEED
SANDAG ALL TMC	2563	55.23	282,012	289,885	2.79	43.77	42.48
Freeway 65mph	300	46.81	71,000	78,554	10.64	53.96	49.64
Arterial 35mph	315	26.77	11,789	10,424	-11.58	22.06	26.26
Arterial No Int	41	90.05	445	393	-11.77	22.68	33.68
Arterial Int	274	24.28	11,344	10,031	-11.58	21.97	25.19
Local 25mph All	17	15.30	96	89	-7.10	18.01	21.22
Ramp 50mph	9	33.86	530	623	17.48	55.77	44.11
SANDAG Filtered	641	58.52	83,415	89,690	7.52	49.92	46.62

For SANDAG, arterials and local roads have higher modeled than measured speeds while the freeways have higher measured than modeled speeds. Like NCTCOG and PSRC, model speeds on links modeled without intersection delay are high compared to HERE Traffic measurements. When intersection delay is added, model speeds are much closer to the HERE reported speeds.

## MPO Model VHT Summary Comparison

In general, modeled VHT is overestimated and model travel speeds are lower than those observed for 4 of the 5 MPO models. A table summarizing the measured and modeled TMC VHT follows below.

**Table 8-7 Summary Comparisons of HERE Measured and MPO Modeled AM TMC VHT**

MPO	TMC VHT	Modeled VHT	%Difference	VHT %RMSE
ARC	430,544	392,954	-8.77	37.98
MAG	188,819	217,595	14.06	54.60
NCTCOG	567,576	620,774	9.37	74.83
PSRC	230,057	293,029	27.36	129.72
SANDAG	282,012	289,885	2.79	55.23

With the exception of the new ARC model, the modeled TMC VHT overestimates range from just over 2.5% to more than 27%. Since the TMCs come from varying and not necessarily representative samples of road networks, these results do not necessarily reflect overall estimates of regional travel. Nevertheless, some of these discrepancies are large and perhaps indicative of a serious potential problem with model-based estimates of VHT.

## Comparison of Modeled Travel Times with Google Travel Times

---

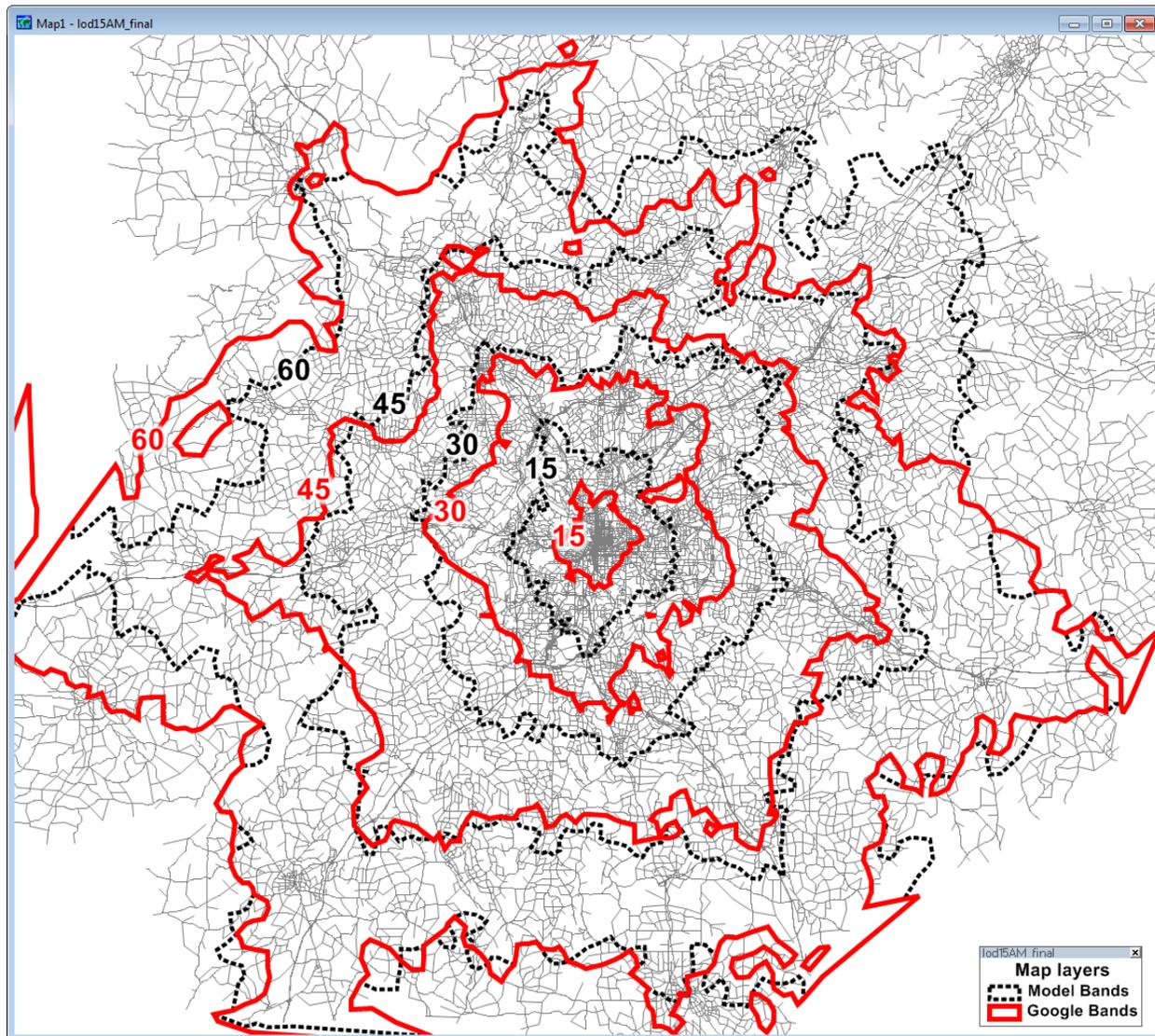
As a further investigation of the match between modeled and reported travel times, we turned to data that we accessed under a license from Google. These data correspond to the estimated point-to-point travel times that are used in navigation and they are time-specific. For consistency with the TMC analysis, we restricted the analysis to the AM period and averaged travel times over the AM peak period. The data were collected for weekdays in the Spring of 2015. Unlike the TMC data, travel times were gathered for complete trips from origins to destinations. We examined travel times from TAZs to the downtown for each MPO and also compared district-to-district travel times for each region.

For each MPO region, inbound Google travel times from various TAZ centroids to a central downtown location were collected for multiple weekdays in March. Travel times were captured once per hour for each hour in the model's AM time period. For a given TAZ to downtown location origin-destination pair, the hourly AM travel times from Google were averaged across the multiple days for which the data were collected.

Using TransCAD's network band procedure, we computed 4 isochrone bands of 15, 30, 45 and 60 minutes travel time for both the model-generated and Google-sourced data. The maps that follow compare the Google AM average travel time contours shown in red with same model travel time contours shown in black for each MPO.

In figure 8-46, we show the travel time contours (isochrones) computed for the ARC region.

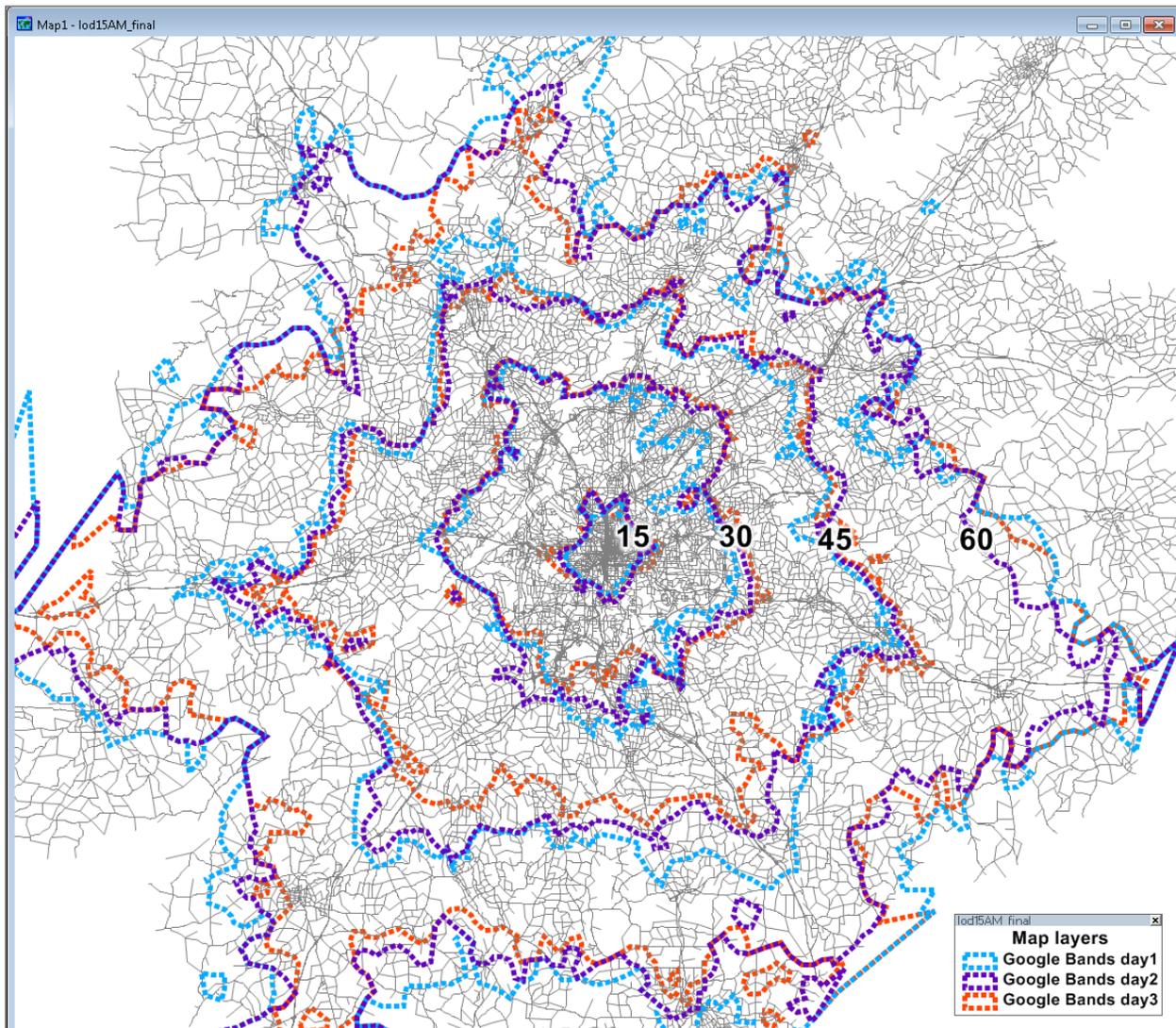
**Figure 8-46 Contour Map Comparing ARC AM Model and Google Travel Times to Downtown from all TAZs**



The ARC model times seem to agree fairly well with the Google times but, in general, the model bands are further away from the CBD, suggesting that the model speeds are higher than the Google speeds. The most dramatic difference is in the 15-minute contours, which show that the model is overly optimistic with regard to travel times for short trips. This may explain why TMC VHT is underestimated in the ARC model based upon the HERE data analysis.

We did a check to see if the Google times were very variable, but as shown below they are fairly similar over different weekdays. In Figure 8-47, we plotted the travel times for several different weekdays.

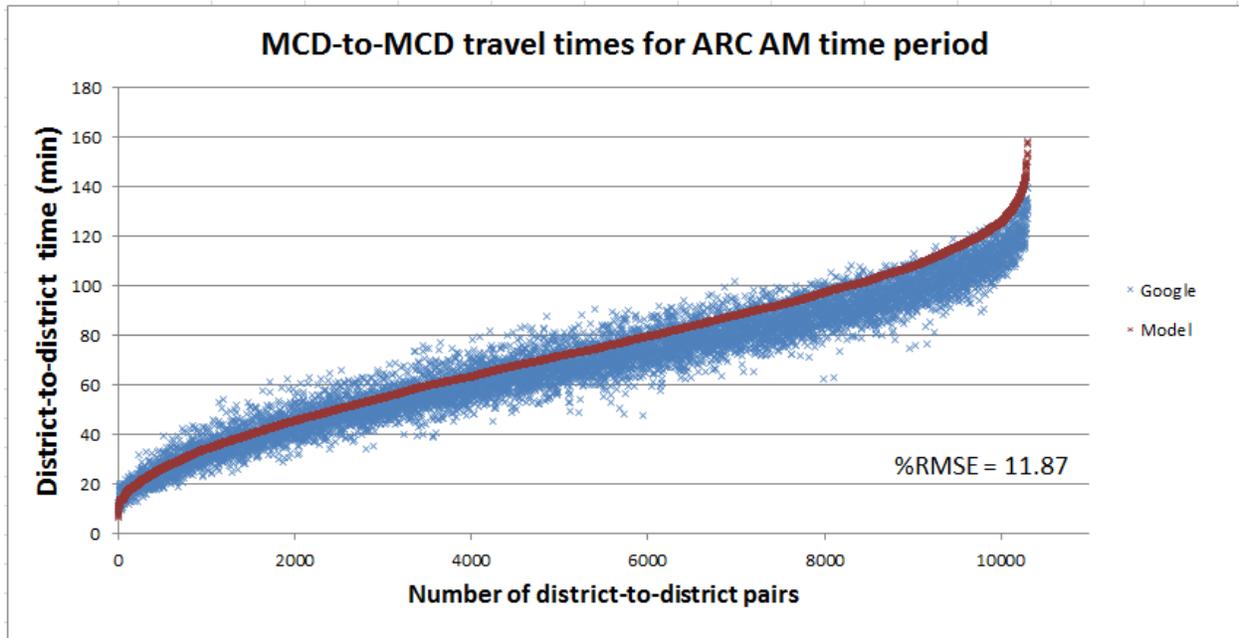
**Figure 8-47 Contour Map Comparing Google AM Travel Times to Downtown for Different Weekdays**



As one can see, the travel time contours are quite similar from day to day.

When we compare district-to-district travel times, we see that the model speeds are more often than not higher than the Google-reported speeds throughout the range of trip durations. In Figure 8-48 below, we present the comparison for trips between Minor Civil Divisions (MCDs), as ARC does not use a specified district layer for reporting model output. The comparisons are arrayed along the x-axis in order of increasing travel time duration as measured from the model.

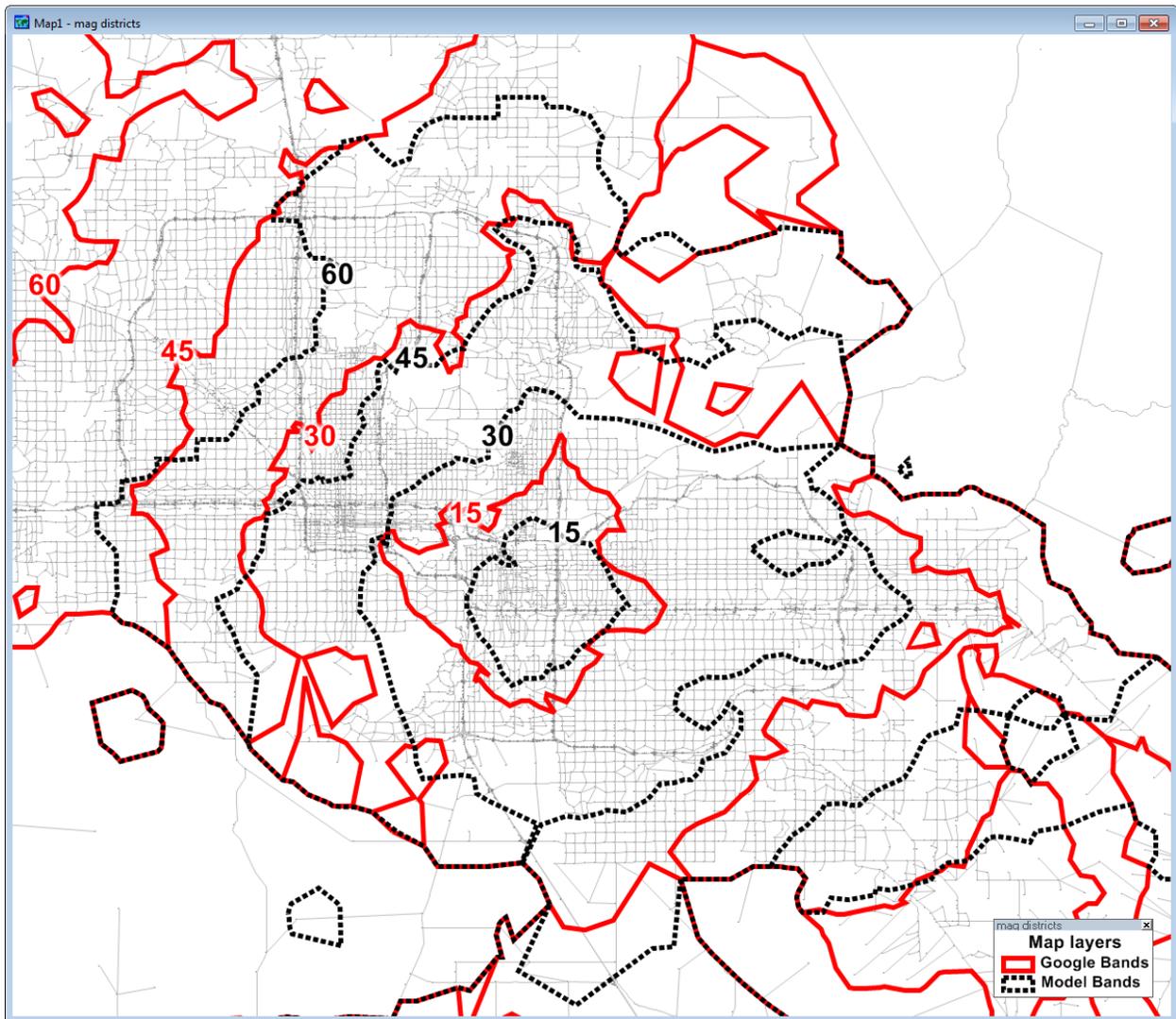
Figure 8-48 MCD-to-MCD AM Travel Time Comparison for the ARC Region



In general, this graph reveals that the Google travel times are lower for many MCD-to-MCD pairs than those from the model.

Next we examine the travel time contours and district-to-district travel times for the MAG model. The comparison of model and Google travel time contours is presented in Figure 8-49.

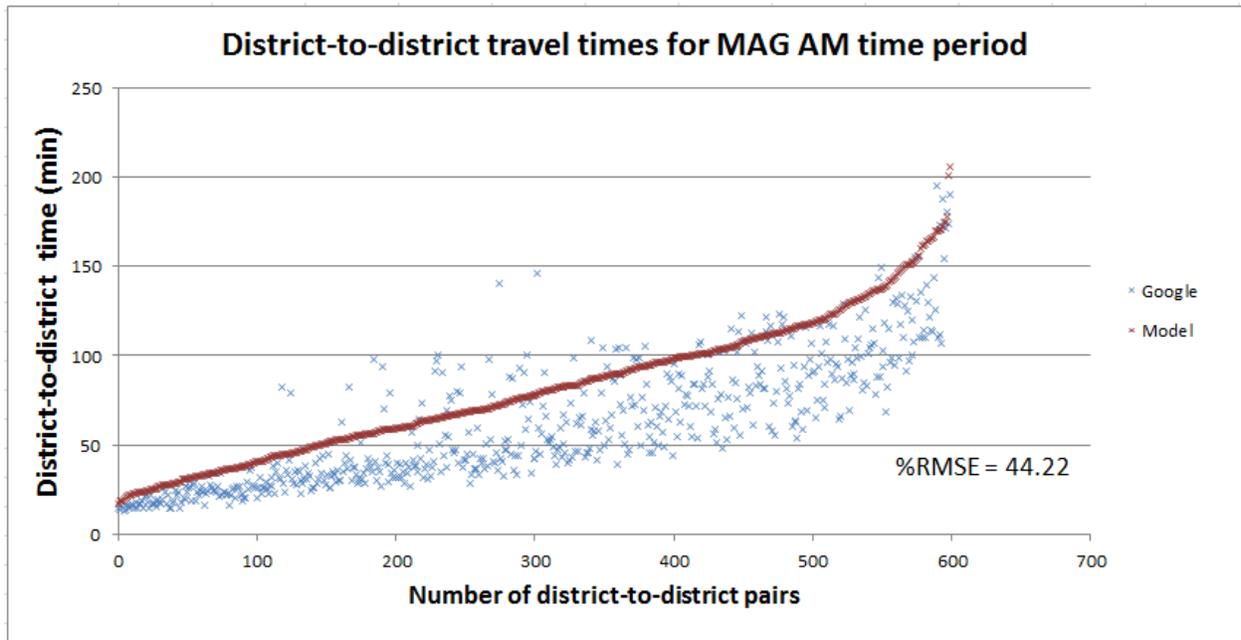
Figure 8-49 Contour Map Comparing MAG AM Model and Google Travel Times to Downtown from all TAZs



When we perform the same analysis for the MAG model, we find that each Google contour is further away from the CBD than the corresponding model contour. This reflects slower model travel speeds, which is consistent with the TMC analysis results except for freeways.

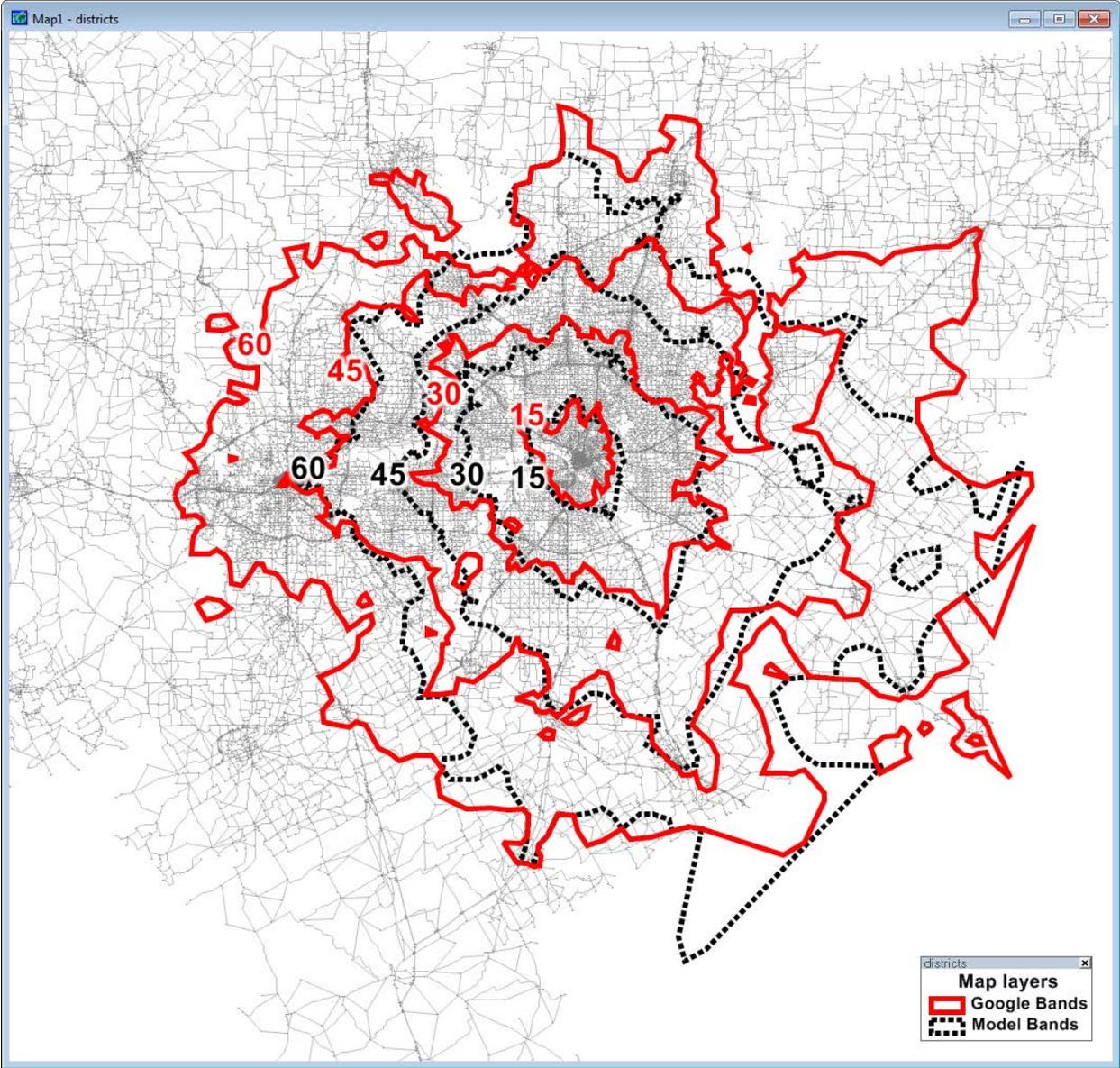
The district-to-district travel times are distinctly longer from the MAG model than those harvested from Google. This is clear from inspection of Figure 8-50, in which the model travel bands fall within the travel time bands from Google.

Figure 8-50 District-to-District Travel Time Comparison for the MAG Region



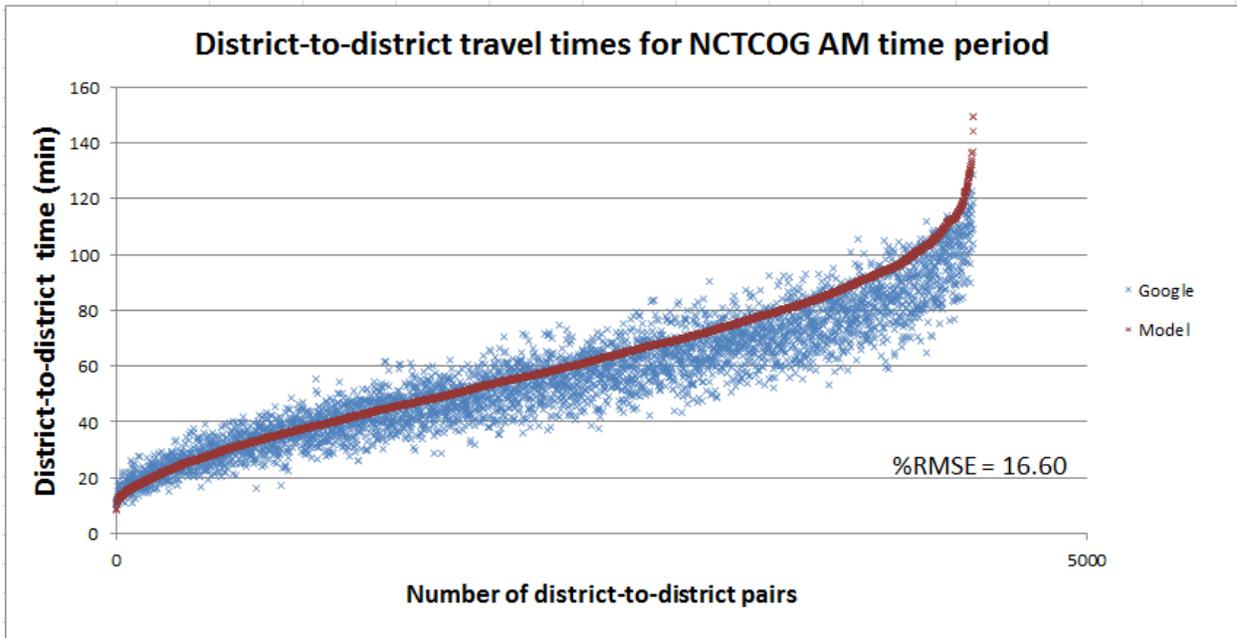
In Figure 8-51, the travel contours to a downtown location are shown for the Dallas-Ft. Worth region. The NCTCOG model travel time contours are similar to the Google travel time contours for trips of 15 minute and 30 minute duration. However, for longer trips of 45 minute and 60 minute duration the model travel times are higher, which is consistent with the higher modeled versus HERE TMC estimates.

**Figure 8-51 Contour Map Comparing NCTCOG AM Model and Google Travel Times to Downtown from all TAZs**



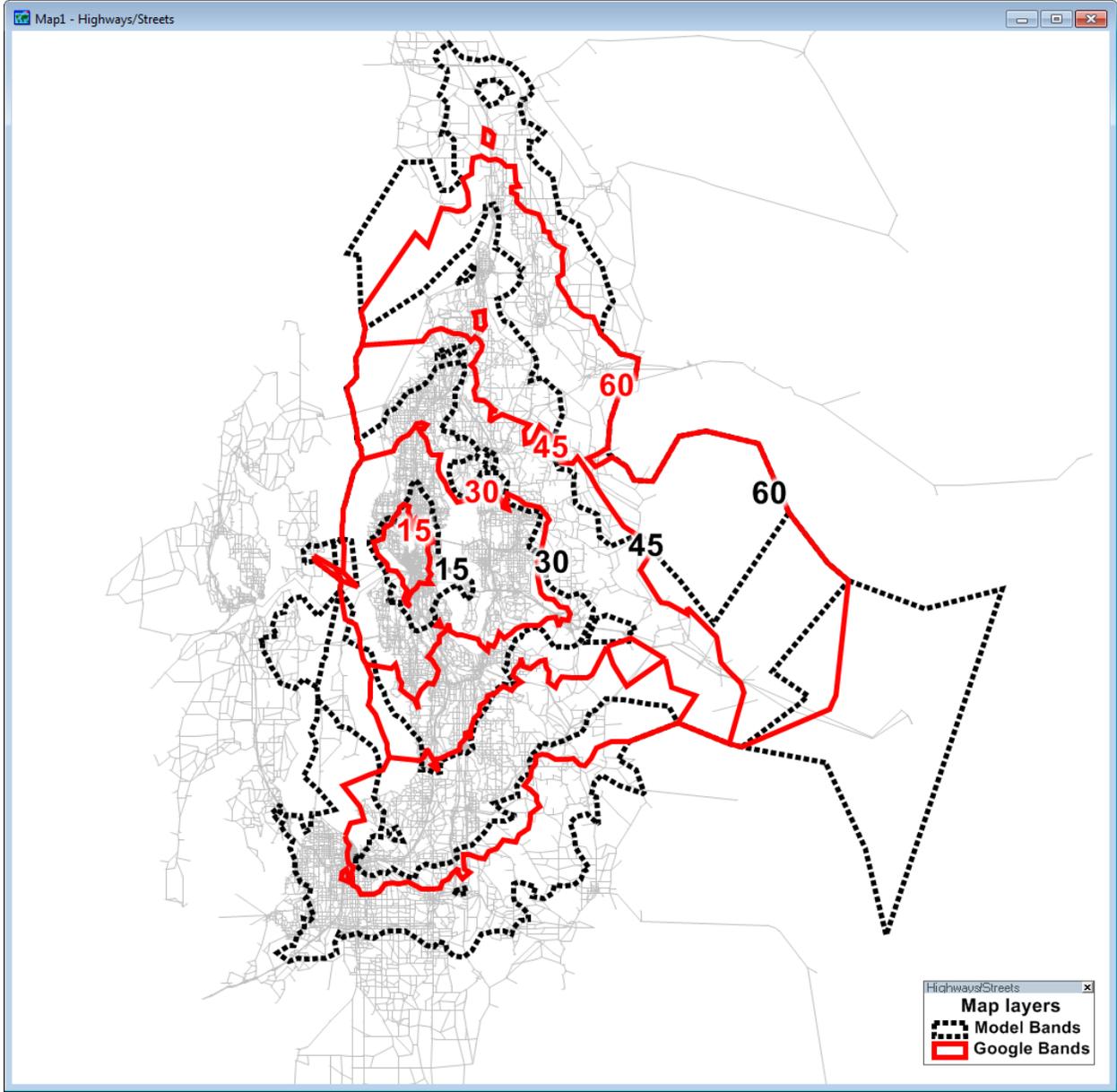
This is also reflected in the district-to-district travel time comparisons in which the model more often than not has a higher travel time. As can be seen from Figure 8-52, the model times are increasingly larger than the reported times as trip durations increase. This is consistent with the HERE TMC comparisons.

Figure 8-52 District-to-District Travel Time Comparison for the NCTCOG Region



The PSRC travel time comparisons are presented next. The PSRC travel time contours, shown in Figure 8-53, are slightly more complex than those from the other MPO models due to the presence of bridges and the inclusion of ferry services that carry cars in the highway assignment. The model contours are generally a bit more spread out than the Google contours, but not always so. The TMC analysis suggested higher congestion in the model than in the HERE data, but that is not so evident from the travel time contours.

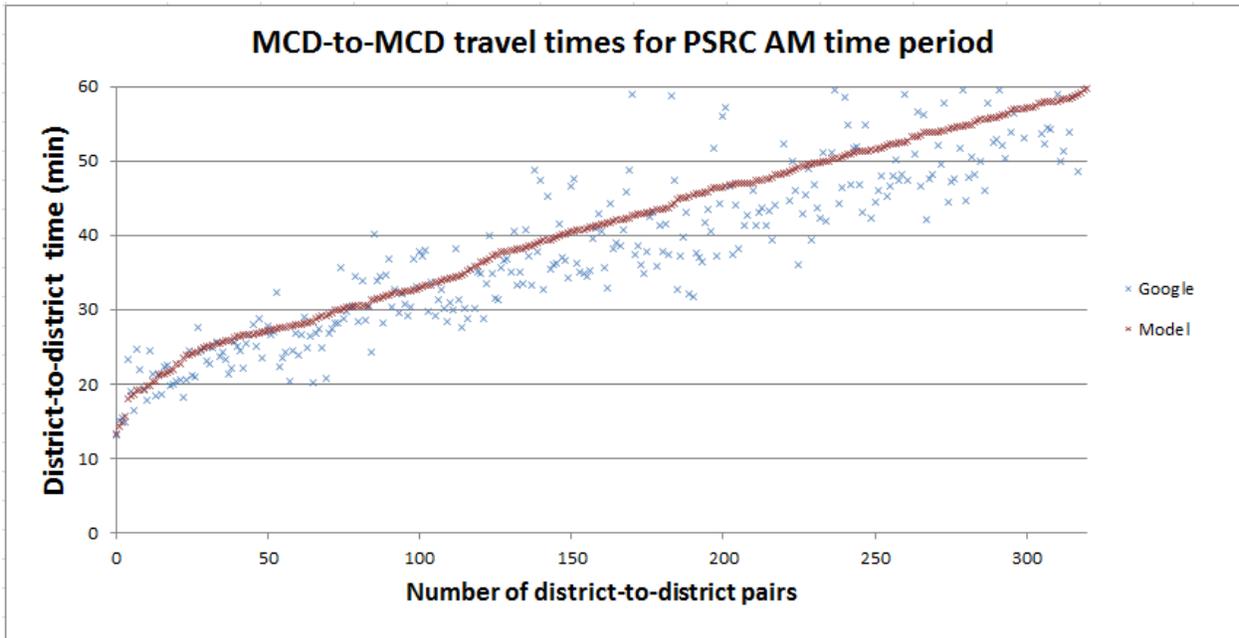
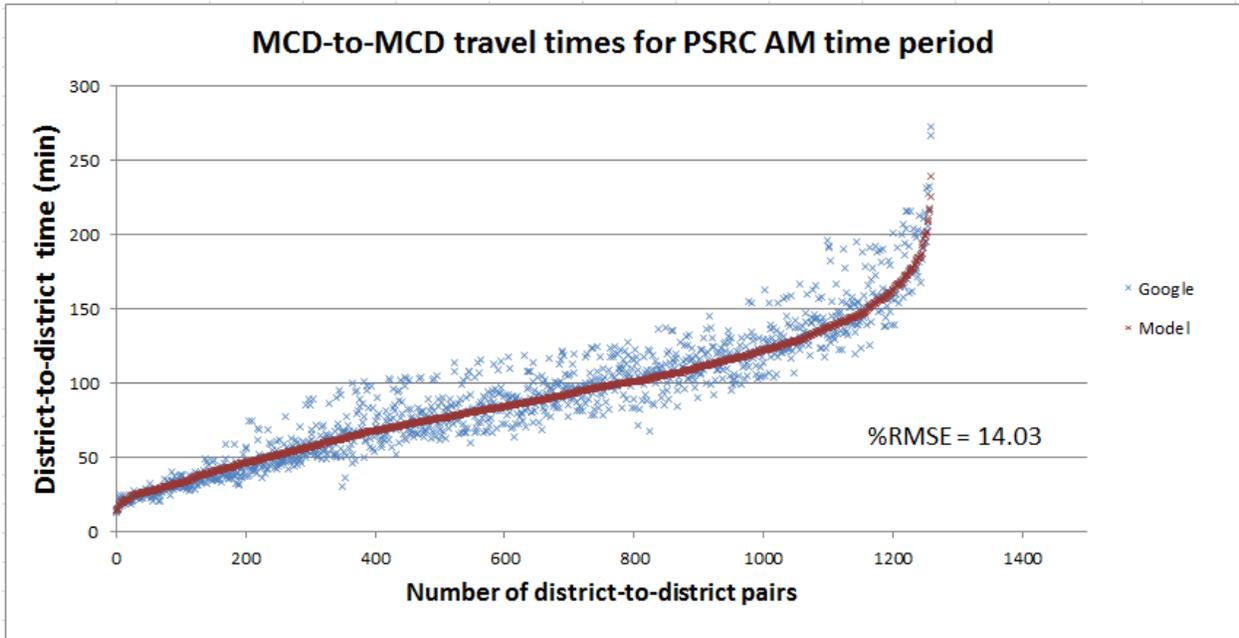
**Figure 8-53 Contour Map Comparing PSRC AM Model and Google Travel Times to Downtown from all TAZs**



On closer inspection, the 15 and 30 minute model bands are outside of the corresponding Google bands; this is not consistent with the TMC analysis, in which the computed signal delay was found to upwardly bias the model travel times.

PSRC does not define districts for summarizing results so we used the municipal civil division (MCD) geography for analysis. When we examine overall MCD-to-MCD travel times, the model travel times fall within those derived from Google. However, the model has higher travel times relative to Google for trips of up to 60 minutes duration, a finding which is evident in the second plot in Figure 8-54.

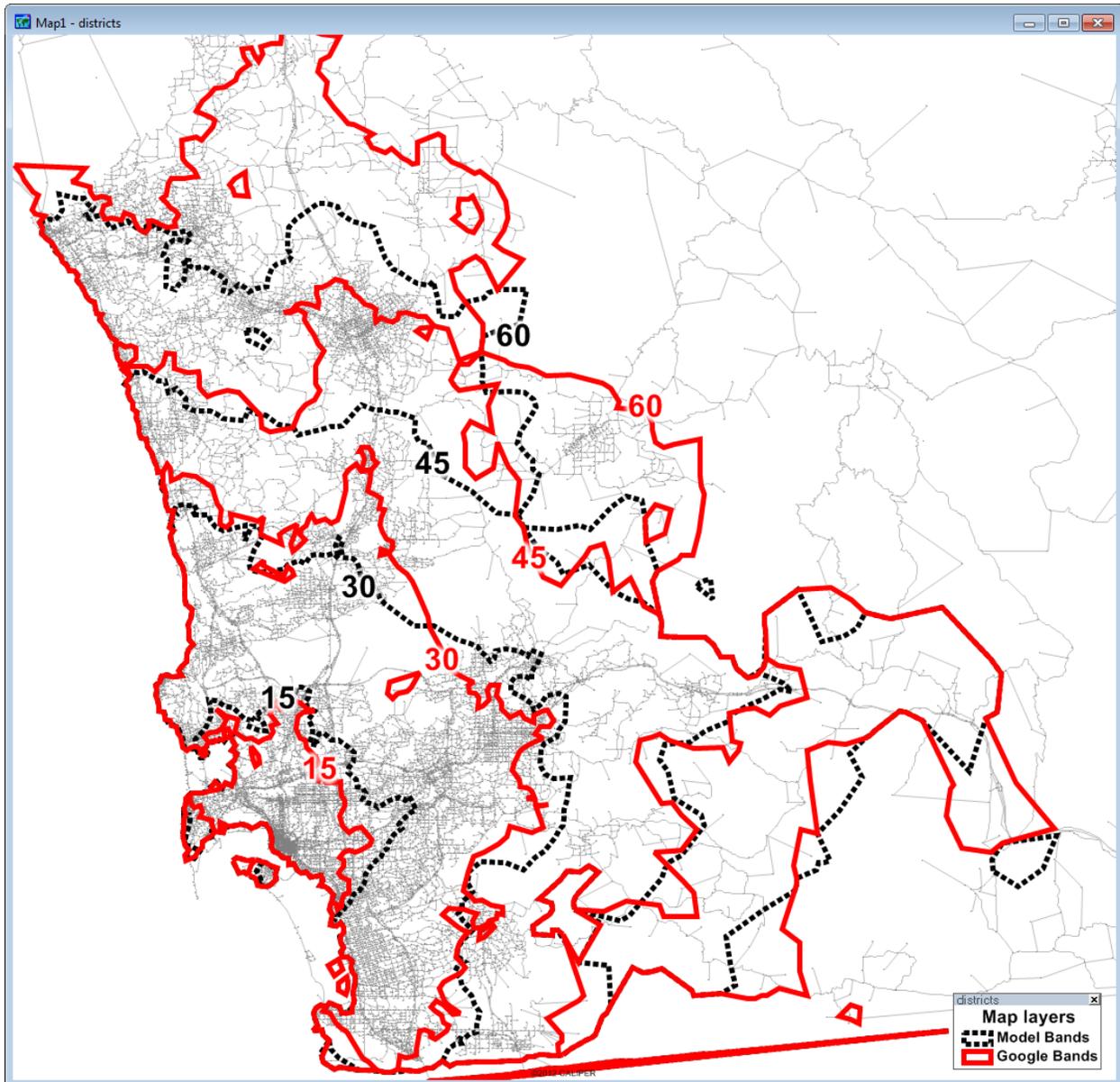
Figure 8-54 MCD-to-MCD Travel Time Comparison for the PSRC Region



Overall, while the MCD-to-MCD travel times are higher for the model than reported by Google, the differences are not as large as suggested by the TMC analysis. Of course, the TMC results, the isochrones to downtown, and any district-to-district comparisons are all different samples and would not necessarily give the same results.

Lastly, we performed the same analysis for the SANDAG ABM. In Figure 8-55 we show the model and Google travel time contours to downtown.

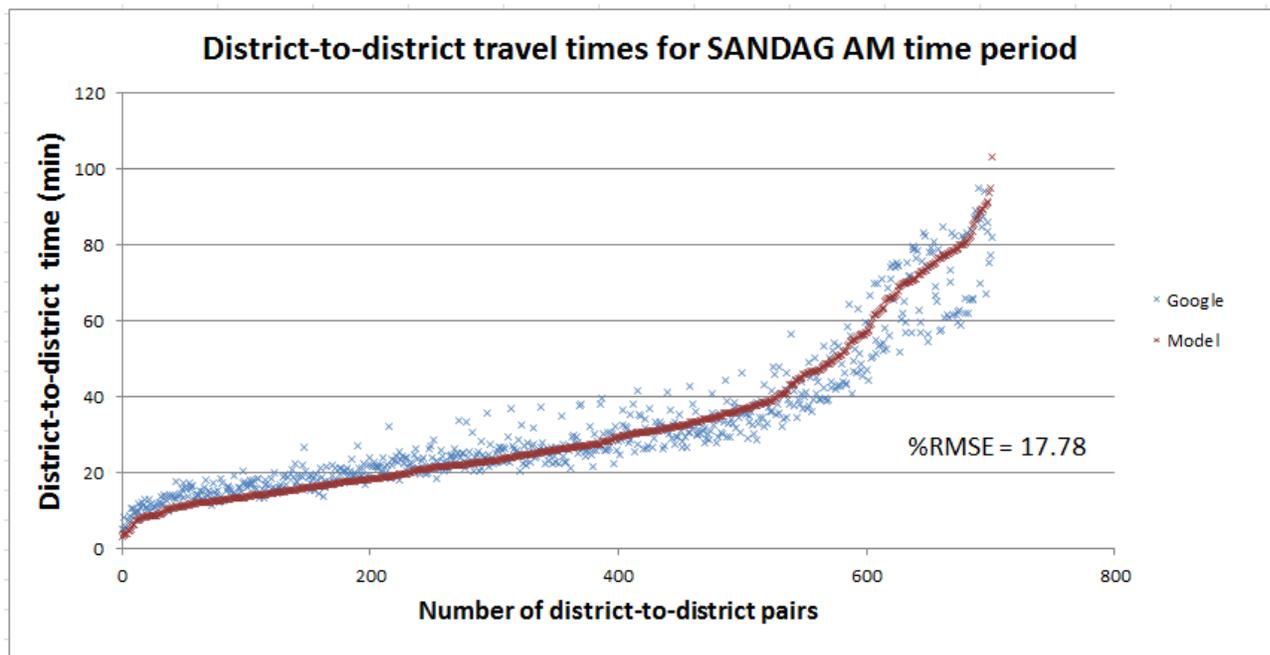
**Figure 8-55 Contour Map Comparing SANDAG AM Model and Google Travel Times to Downtown from all TAZs**



The SANDAG ABM model does not show a clear trend towards underestimation or overestimation of travel times to downtown which is apparent from the crisscrossing of the 30 minute, 45 minute and 60 minute model bands with those from Google. This is consistent with the HERE TMC analysis that found fairly close agreement between modeled and measured VHT.

However, for short trips around downtown the model travel times are slightly optimistic as the Google 15 minute band is almost entirely contained within the 15 minute model contour. This can be observed in the district-to-district comparisons plotted in Figure 8-56 that show lower travel times for shorter trips and a reversal of that for the longer duration district to district pairs.

**Figure 8-56 District-to-District Travel Time Comparison for the SANDAG ABM Model**



Overall this supplementary analysis substantially confirmed the findings from the TMC analysis in terms of the general differences between model-based and commercial sources of travel speed data. Analyzing complete trips or ideally complete TAZ to TAZ travel times and speeds would be preferable in the future and would help clarify some key modeling issues.

## Concluding Remarks

---

The conclusion that emerges from the analysis is that measured speeds, be they from HERE Traffic or Google, can be quite different from the congested speed estimates produced by the MPO models that we have examined. This is a result that warrants considerable reflection.

One might expect that congested speeds would be similar in locations of very heavy traffic or, alternatively, that speeds at low congestion levels would be similar and close to free flow speeds, but both of those suppositions are contradicted by the HERE Traffic data.

It appears that reported average speeds in the AM peak period vary tremendously even for links of the same functional class that have the same modeled volume-to-capacity ratios. This certainly poses a formidable challenge to modeling.

It is well known that travel speeds are highly variable and can be influenced by numerous factors that are outside the scope of a travel demand model. Modeling speed is a difficult problem for freeways and even more difficult for arterials. As would be expected, arterials exhibit a much larger variability of speeds when compared to freeways at given predicted volume-to-capacity ratios. However, model VDFs that incorporate node delay do not seem to explain the observed variations in travel speeds very well.

There are a variety of factors that underlie the problem of explaining observed travel speeds. Obviously, there are many omitted variables that might influence travel speeds such as driver behavior heterogeneity. The second factor is the likely error in link volumes that would be attributed to errors in trip tables and other choice models. A lesser source of error, but present nonetheless, would be the assumed peak period capacities and the assumed volume-delay functions, neither of which are likely to be sensitive to road geometry or traffic flow considerations. All of these errors contribute to the failure of the models to do a reasonable job of predicting average travel times.

Overall, modeled speeds are generally slower than measured by HERE Traffic data. For 4 of the 5 MPO models examined, measured TMC VHT was significantly lower than modeled VHT. The percentage deviations from the modeled estimates were surprisingly far off from the measured speeds.

Errors in VHT are a potentially serious problem for transportation planning and emissions modeling, and bias in VHT and travel speeds call into question plan evaluation and air quality estimates. It should be obvious that getting the heaviest volume links to have the correct speeds and volumes is critical to VHT measurement and should be a point of emphasis in model development.

In the future, modelers will have much greater access to travel speed data and will be able to use it in the model development process. Use of travel speed data in the modeling process would appear to be helpful in a variety of ways including in selecting the functional form of the volume-delay equations and in estimating their parameters. Most of the models appear to use free flow speeds that are hypothesized rather than measured or stratified by posted speed limits. It may make sense to have some free flow speeds higher than the posted limit to deal with aggressive drivers. Refitting the VDF functions or reconsidering the VDFs themselves could improve the fit of the modeled speeds to the TMC speeds. It is possible that specifying omitted variables or further stratification would reduce the apparent errors in modeled speeds as well. It

is encouraging that the one MPO that worked with speed data was able to produce a travel demand model that did a better job of matching speeds.

It is pretty clear that travel demand models should not be used for performance measurement or reporting given the obvious problems they have in reproducing measured speeds. Measured speeds should be used instead.

One could obviously do a great deal more research along these lines and conduct a more extensive analysis of travel time variability. Further research may suggest alternative means of model improvement.

Lastly, we would like to point out that the analysis as exemplified by the calculations described in this chapter is relatively straightforward and could become a standard part of model validation should modelers choose to take on the task.

# Chapter 9

## Concluding Discussion of Study Findings and Recommendations

In this chapter, we provide some perspectives on the main findings of the study, and we address FTA's questions about improved model development, validation, and project evaluation. We also identify some potential topics for further research.

### Perspectives on the Study Findings

---

This study provides cause for both concern and optimism with respect to travel forecasting models. In the inventory of current practices, we found that many MPOs had deficient traffic assignment practices that can be characterized by poor formulations, inefficient or improper solution algorithms, and insufficient convergence. Feedback mechanisms, while evidently acknowledged to be necessary, were often non-existent, incomplete, inconsistently approached, and insufficiently computed.

Working with the models from 5 MPOs that FTA selected as among the best extant, we found room for improvement in each model in terms of one or more aspects of their traffic assignment method and feedback approach. We also found that the congested travel times produced by models were typically not consistent with travel time data from measurements as provided from commercial sources. However, the one MPO that had exerted the greatest effort in utilizing travel speeds in their model development came the closest to achieving a reasonable match. In our opinion, most, if not all of the problems identified can be remedied with simple changes in models and greater attention to detail and data in model building and validation.

This study has identified the importance of achieving tighter convergence in traffic assignment and paying close attention to feedback closure in model development and application. Quite apart from theoretical considerations, tests indicated that project evaluations will be different and better with tighter assignment model convergence. With tight convergence, spurious effects on link flows for any particular model run and for before-and-after comparisons of project scenarios were greatly reduced and often eliminated.

The case for feedback computations is conceptually clear in terms of seeking consistency in model application, but raises issues about the appropriateness of the analysis protocol and the behavioral paradigm it embraces. When project impacts are assessed with models using feedback loops, changes in trip destinations and mode shares often result even when the projects are not likely to have such impacts.

Travel forecasting models have numerous moving parts, nearly any one of which can have a dramatic impact on the forecasts produced. Rather than simply offer an opinion about each aspect of the traffic assignment models or feedback mechanisms, we performed empirical tests to see if differences in modeling practices lead to differences in projected outcomes. Hundreds of empirical experiments were performed to identify the possible consequences of variations and improvements in these modeling methods. The aim in doing so was to ascertain whether or not the effects would be consequential. What we found was that in many cases a change in approach leads to a considerable difference in forecast results.

Traffic assignment models play a pivotal role in urban travel demand modeling because they determine the volumes and congested travel times on the road network. As a result, good practices in the formulation and application of traffic assignment models can have a disproportionate effect on the quality of forecasts and the evaluation of highway and transit improvement projects.

Traffic assignment models have been studied for more than 40 years, but in the last decade important new algorithms and insights have been produced. Armed with these improved methods, we are able to assess matters that were previously obscure. Also, copious amounts of new data on traffic volumes and travel speeds provide a new environment for assessing traffic and travel demand models.

While there is an extensive research literature on nearly every aspect of traffic assignment models, rather little has actually considered practical issues associated with large MPO models and the ability of models to produce realistic congested travel times and project impact assessments.

Another blind spot for practice has been the ignoring of calibration and validation technical guidance published many years ago by FHWA and FTA [31]. That guidance embodied good ideas that should be modernized and updated to reflect today's modeling problems, techniques, computational capabilities, and data.

The static user equilibrium traffic assignment model makes and exploits a great simplification in predicting traffic flows. Having said that, it appears to be capable of providing reasonable results when well implemented. At least, this research provided no definitive evidence to the contrary.

In reviewing traffic assignment modeling practices, we found an array of ad hoc procedures and poorly executed models. Even amongst the best MPO models, there were shortcomings and peculiarities in the formulation of the traffic assignment models that should be remedied. In particular, we can find no reason to believe that turn prohibitions should be ignored when they are present. Also, we think that more careful attention to appropriately fitted and validated volume-delay functions rather than simply introducing more complexity in volume-delay functions is warranted. We also believe that vehicle operating costs should not be part of the generalized cost of travel in traffic assignment models. Rather than take a purist theoretic view of these models, we used empirical experiments to judge the type and quality of results provided and how these vary with particular aspects of modeling practice.

### ***User equilibrium traffic assignment models and their convergence***

The static user equilibrium traffic assignment model represents a considerable simplification of real world behavior, but nevertheless appears to be a robust and effective tool for planning models. In our tests, the traffic assignment models appeared to produce plausible assessment of project impacts when suitably converged. Despite the undoubted ultimate emergence of simulation-based dynamic traffic assignment (DTA) models, the UE model will be used in regional modeling for some time to come.

It is important to recognize that a static traffic assignment model is not a model of traffic dynamics, and it requires well-behaved volume-delay functions to converge properly. Some, if not much, of the power of the traffic assignment model stems from its simplicity and attempting to elaborate it unduly may very well sap it of its usefulness. It is not a simulation and therefore should not necessarily attempt to reflect the actual operating performance of specific road facilities. Consequently, overzealous modelers should probably avoid elaborate volume-delay functions and focus on doing the basics properly with appropriate centroid connectors and turn prohibitions. With respect to recommendations on volume-delay functions and capacities, we find the guidance in an old study by Alan Horowitz [32] to be reasonable and more than sufficiently ambitious for regional planning models.

We now know that the link flows computed with traffic assignment models can vary quite a bit with convergence levels achieved. Unfortunately, traffic assignment models suffer from a significant amount of convergence error, and the errors do not appear to cancel out in before-and-after scenario comparisons. We found, somewhat contrary to our own expectations, that convergence to relative gaps of .0001 may not always be sufficient to gauge the correct direction of impacts from specific projects. In all our tests there was not a single case in which tighter convergence gave obviously less plausible results.

### ***Feedback procedures and guidance***

It is clear that feedback procedures deployed in MPO models need to be strengthened. Feedback, when used, should be performed for all model time periods and to the same degree in making comparisons of forecasts and base case scenarios.

More appropriate and tighter feedback convergence criteria should be used. Stopping when link flows are changing 1% or more per feedback iteration is both deceptive and insufficient in achieving a consistent and stable forecast.

Rather than suggest a “best” method for feedback, it seems to us that different averaging techniques should be explored, leading to the choice of an effective method for each model.

### ***Congested travel times produced by travel models***

The congested travel times from models are not a good approximation of measured travel times at the present time. In examining the 5 MPO models, we found that 4 of the 5 models predicted slower travel times than were measured independently.

The explanations for this are various, but certainly some are traceable to the volume-delay functions used in the models, all of which permit volumes to exceed capacities. A second reason is that while free flow speeds are typically faster than posted speed limits, the models often use lower free flow speeds. A third reason is that some centroid connectors overload network links unduly.

The approaches taken to determining link capacities in large MPO models are somewhat broad brush, and for many models are based upon gross categories of functional class and area type. This can mask important differences or may simply introduce some degree of bias.

Attempts to use more elaborate volume-delay functions have sometimes backfired with some functions that do not match travel speeds well, and, also impede proper assignment model convergence. It is particularly challenging to model arterial and freeway performance and to determine capacities that are appropriate where there are traffic signals or where there are freeway merging and weaving sections.

One of the main reasons that models do not produce congested speeds that are close to measurements is that for most MPOs, it was not an explicit goal of the model building process to do so. Given that travel speed data has only recently been broadly available that is not surprising. MAG was the one MPO that explicitly examined travel speed measurements as part of their model building and validation, and they did not overstate congestion as a result.

The broad availability of travel speed data should facilitate estimation of volume-delay functions that are applicable to local conditions and functional classes. This could easily be incorporated in the model development process.

In many modeling projects, travel model parameters for mode and destination choice are estimated early in the modeling process and utilize estimates of congested travel times that are not the same as those ultimately produced by a calibrated and validated model. This is a dangerous practice as this leads to biased parameter estimates and is not likely to be constructive in forecasting. This is another use for measured travel times.

### ***Validation of traffic assignment models***

A serious problem that we discovered was insufficient validation of models with counts. Most of the MPOs had too few directional traffic counts by time period and functional class for proper validation. This is not a technical matter but rather a problem of perception or priorities. Certainly MPO budgets for model building could accommodate collection of a sufficient number of traffic counts for model validation if that is judged to be a priority.

Of course, traffic counts are subject to both variation and error and must be carefully analyzed as part of any validation effort. Construction of data sets for model validation should be an essential part of any model development effort.

The Travel Model Validation and Reasonableness Check Manual Second Edition [33] indicates the centrality of counts to validation and has numerous aggregate checks and guidelines. It would certainly be an improvement if all MPO models followed those guidelines, but more disaggregate validation should be encouraged. Screenline validation is less stringent than validation at the link level and in our opinion much less useful in identifying problems and achieving good results. We found difference plots to be an essential tool in examining model goodness of fit with respect to counts. These are simple to produce with any planning model or GIS software.

As discussed previously, the number of counts by functional class, time period, and direction needs to be large enough for statistical significance. This point is not covered in the aforementioned manual, and it will likely require that supplementary data collection efforts be mounted and/or coordinated with multiple agencies. The vast areas associated with large MPOs would warrant far more numerous count locations than would be necessary for a small MPO. It would certainly not be unreasonable to have minimum sample sizes for counts by county.

The broad availability of travel speed data from commercial sources makes validation to both volumes and speeds by time period and direction at the link level relatively straightforward and attractive as a means of improving travel forecasting models. Because travel times are variable, it is not expected that travel speeds would necessarily match any average measurement, but rather that the model-produced speeds would fall within the range of speeds that are observed.

### ***Project evaluation and benefits estimation***

We analyzed a number of highway and transit projects varying the analysis protocol and traffic assignment convergence level utilized. Generally we found that the predicted impacts were reasonable at the highest convergence levels both in terms of magnitude and in geographic location. Even when analyzing transit projects of modest scale, the tightly converged comparisons could reveal highway benefits in reasonable locations. Of course, these observations will need to be confirmed with before-and-after studies of implemented projects for anyone to have confidence in the conclusions reached.

For years, it has been suggested that point estimates of project impacts be replaced by a range of possible impacts. Varying the analysis protocol is one way of generating a range of benefits that has some logic behind it. Of course, varying the inputs and observing the range of outputs would also be appropriate.

There is a significant literature addressing problems of project evaluation and forecasting. A recent review by David Hartgen [34] sets out many of the reasons why forecasts for transit and toll road projects indicate greater benefits than the projects actually deliver. This study suggests that in addition to many other problems outlined in Hartgen's review, there are actual substantive reasons why models might systematically give incorrect forecasts. Specifically, it is likely that rail transit forecasts are unduly optimistic because they rely on modeled auto travel times that are greatly overestimated both in the base case year and in forecast years. Moreover, insufficiently converged traffic assignments can function like random number generators with undetected consequences. It is also possible that a general lack of care in model building and calibration could account for some of the problems observed with forecasts.

### ***The value of in-depth empirical review of models***

Even simple travel demand models have complex, multi-dimensional elements that are hard to evaluate, especially using only summary statistics. Over and over again we were struck by insights that only came from working with models and varying their characteristics a bit one at a time. We could have done an even more in-depth exploration of any of the models, and we encourage modelers to do so for their own work.

### ***Computational burden***

We understand that computational burden is the most commonly cited excuse for not computing traffic assignments to tight gaps and for not attempting tight feedback closure. In spite of that it seems to us that a great deal more computation is warranted.

Also, we believe that both improvements in algorithmic techniques and in computing environments can overcome these objections. At least the argument that it doesn't matter has been shown to be invalid.

### ***Validation of travel models***

The missing piece in this study and in modeling generally is the absence of validation of model constructs, components, and forecasts with actual before and after data on changes to the transportation system. Models are widely asserted and applied without passing tests of validity causing a lack of confidence in forecasts and a lack of direction in moving forward with modeling improvements. The transportation environment is always changing, providing opportunities to assess before and after changes and the ability of travel models to predict the outcomes of projects. This strikes us as being of the highest priority for current practice and future research.

## Options for National Implementation

---

This study was motivated by prior research by FTA and others suggesting that insufficient convergence of traffic assignment models was a significant problem in regional models and a problem that had consequences for evaluation of transit projects. It was also a response to Congressional interest in quantifying the benefits to road users of transit improvements and a component of FTA initiatives to improve modeling and forecasting. Specifically, this study is part of FTA's ongoing attempts to improve the ability to evaluate major new transit projects, and it supports FTA's initiatives to address the problem through technical scrutiny of model forecasts, the development of alternative methodology for forecasting and checking other forecasts, and the pursuit of before-and-after studies to understand how well models work and how they might be improved.

FTA's review focus for New Starts has typically been on trip tables and mode choice as is appropriate. This study extends scrutiny to several other important aspects of models and has indicated that regional planning models could stand improvement in their traffic assignment and feedback procedures when they are used as the basis for transit project forecasting.

FTA initially had the idea that some type of standardization of modeling practices would be both feasible and beneficial to the modeling community and would aid FTA in evaluating transit projects more accurately and fully. Our documentation of the diversity of modeling practices and the general lack of agreement amongst modelers and consultants about best practices makes standardization of approaches using regional models unlikely and, in our opinion, the absence of demonstrated success in forecasting may make standardization unwise or premature. In other words, promotion of a nationally consistent approach might limit progress more than it would improve forecasts.

Given the widespread deficiencies in forecasting practices, however, other measures may be beneficial and appropriate. These could range from providing technical guidance about specific modeling practices to articulating specific tests that FTA would like to see accompany model-based forecasts. Our research suggests that focusing on the auto travel times from models would be very helpful in improving transit forecasts. Simply letting that be known as a point of emphasis should have a beneficial impact on model development.

Independent of this research, FTA has invested in STOPS (Simplified Trips-on-Project Software) as an approach that project sponsors can use, as an alternative to regional models, to prepare predictions of transit passenger trips for proposed New Starts transit projects. As would most transit forecasting methods, STOPS relies upon reasonable estimates of zone-to-zone travel times by auto and by transit. FTA can ask for substantiation of the travel times for highway trips when either regional models or STOPS is used for forecasting. FTA may also wish to consider the independent use of commercially available travel time data to validate the provided travel times, or even consider the direct use of zone-to-zone travel times derived from this data as a substitute for regional model-produced times.

Our approach with respect to examining alternative analysis protocols is consistent with FTA practice of using fixed trip tables to provide conservative estimates of project benefits. It also provides a range of estimates that might be useful to consider. Certainly, it is not difficult to produce forecasts using different elements of a model chain, with different levels of convergence, and with different levels of feedback computations.

While we did not discuss it, removing the noise due to convergence error from traffic assignments should have a beneficial effect in building and applying trip distribution and mode choice models. Removing the noise from the traffic model appears also to reduce geographic bias in congested travel times.

In our opinion, there should be no doubt that in highly congested areas, highway benefits can result from major transit improvement projects. While we believe that it is possible to estimate these highway benefits, that does not mean that we recommend that FTA or anyone else rely upon model-based estimates of those benefits for project justification.

The empirical analysis that we performed with several of the MPO models provides a simple approach for augmenting how FTA might review the models that are used for new starts submissions. Specifically, it supplements the detailed examination of trip tables and mode split computations that are at the heart of any transit forecast. The empirical analysis is neither complex nor is it costly. It can be performed by MPOs themselves, their consultants, or FTA's consultants. However it is accomplished, it should lead to model improvements and less flawed forecasts.

In the ongoing quest to develop good forecasting tools and good forecasts, plausible and explicable outcomes are important. By that we mean that model results need to have straightforward and verifiable explanations to be taken seriously. This has been FTA's perspective as we understand it, and we found it to be applicable to examining the project evaluations that we performed. Indeed, we found that working with models empirically was revelatory when compared to only reviewing model documentation and results. Should it be of interest, forensic scrutiny of models will lead to much greater quality control and more reliable forecasting results.

We hope that the study makes a convincing case for use of better methods, new data sources, and much greater testing and validation of models. The more disaggregate view that we have taken with respect to validation of traffic at the link level by direction and time period is consistent with the underlying perspective in FTA's Summit program, which examines ridership impacts at the origin-destination level. This has proven to be an excellent means of discovering problems with models and in some respects provided motivation for this study.

The broad availability of travel time data from point to point by time of day and for every day of the year has the potential to be transformative for modeling. Foremost, it opens the door to model validation at the link level by time of day and direction with both counts and travel speeds, which should help bring about a significant increase in model quality. It should also help in picking appropriate time periods for model calibration and validation.

The scrutiny that we placed upon the MPO models actually just scratches the surface of what a full blown model audit might look like. That would include detailed examination of demographics, trip tables, and mode split. Also, we must point out that those who have specific regional and local knowledge would be likely to spot numerous other data errors and modeling problems that might not be apparent to others.

Among the options open to FTA is sponsorship of model audits to be provided by independent third parties. There are always mistakes in models, and these can be caught by detailed examination of model scripts, modeling procedures, input data, and numerical results, none of which would typically be noticed in a peer review.

In the analysis of modeling practices, one can detect that there is a bit of a herd mentality amongst MPOs and consultants with respect to modeling practices. With respect to some issues such as traffic assignment convergence, this can be turned to advantage.

With a little encouragement from FTA or FHWA, there is a good chance that a voluntary consensus can be built for use of convergent traffic assignment procedures, assessment of the accuracy of the travel times, and minimal criteria for goodness of fit and validity. Also, it seems realistic to make a point of emphasis to validate modeled travel times with external measurements.

The MPOs whose models we studied were responsive to criticism and changed their models after we brought certain concerns to light. This suggests that FTA and FHWA could bring about modeling improvements by sponsoring studies that continue to examine modeling practices and their consequences.

As for the broader problem of improving the state of modeling practice, FHWA would have to join FTA for any initiative to have widespread impacts. This study and direct input that we received from many MPOs suggests that technical guidance for modeling would be welcomed and appreciated. Certainly some MPOs and consultants would benefit from eliminating poor practices from their models. If technical guidance were to be provided, there would need to be scope for flexibility due to the fact that methods keep improving and new models and problems raise new challenges.

## Research Suggestions

---

This study was applied and empirical in nature and limited to working with existing methods. It did not address the numerous potential research topics associated with traffic assignment models and feedback issues in multi-stage trip-based or activity models.

The most direct extension of this study would entail similar work with much more extensive and comprehensive count and speed data for validation. This would provide the opportunity to do meaningful work evaluating model formulations in terms of their ability to match real world observations.

The availability of multiple sources of travel time data opens the door to research on experienced travel times in urban regions and how this information can be profitably exploited in model development and validation. It should lead to an understanding of the variability of travel times within peak periods and between and across days and seasons and provide the basis for generating the travel time distributions used for model validation.

Obviously calibration to counts and speeds, which is often a feature of traffic simulation projects, can also be attempted with static traffic assignment models. How successful that can be is an open question. It is also an open question the degree to which static assignment models can reflect the operational characteristics of transportation facilities, and this has a bearing upon the effort and complexity warranted in matching volume-delay functions to road links.

The work on faster traffic assignment convergence and more realistic formulations of assignment models will no doubt continue as it has proven to be both worthwhile in the past and remains a subject of academic as well as practical interest. We certainly do not have all the tools we need.

Assignment methods for analyzing tolled facilities pose specific problems, only some of which are likely to be resolved with static models. In general, multi-class assignment models do not have unique class flow solutions, leading to difficulties in estimating toll revenues [35]. Also, some common methods of toll road assignment have been found to have significant deficiencies [36].

There is considerable scope for further research on fast and effective methods of achieving feedback consistency in the types of models that MPOs use and will want to use in the future. Investigation of different averaging strategies as well as alternative schemes for finding consistent model solutions will be most welcome.

Any assessment of the usefulness of planning models of whatever type should be based on their contribution to project selection and/or policy analysis. Without objective assessments of their forecasting ability, planning models will lack credibility and a reasonable basis for considering their improvement. Consequently, our strongest recommendation is that before-and-after studies of short-term and longer-term improvements be conducted to enable research on the ability of models to reproduce observed results. A greater emphasis on the predictive abilities of models strikes us as a healthy direction for future work.

We have already seen the emergence of simulation-based dynamic traffic models, which we expect will eventually replace static traffic assignments completely. Supporting research for both dynamic highway and dynamic transit models will be needed to identify the most effective approaches and hasten their implementation.



# References

- [1] Wardrop, J.G. (1952) Some theoretical aspects of road traffic research, *Proc. Inst. Civil Engineers Part 2*, 325-378
- [2] Beckman, M., McGuire, C., and Winsten, C. (1956) *Studies in the Economics of Transportation*, Yale University Press, New Haven
- [3] LeBlanc, L., Morlok, E., and Pierskalla, W. (1975) An Efficient Approach to Solving the Road Network Equilibrium Traffic Assignment Problem, *Transportation Research* Vol 9, 309-318
- [4] Nguyen, S. (1976) A unified approach to equilibrium methods for traffic assignment, in Traffic Equilibrium Methods M. Florian ed (1974 *Lecture Notes in Economics and Mathematical Systems*, Springer-Verlag, pp. 148-182
- [5] Rose, G., Daskin, M., and Koppelman, F. (1988) An examination of convergence error in equilibrium traffic assignment models, *Transportation Research B*, Vol. 22B No. 4, 261-274
- [6] Slavin, H., Brandon, J. and Rabinowicz, A. (2006) An Empirical Comparison of Alternative User Equilibrium Traffic Assignment Methods, Proceedings of the European Transport Conference 2006, Strasbourg, France.
- [7] Bar-Gera, H. (2002) Origin-based algorithm for the traffic assignment problem, *Transportation Science* 36 (4), 398-417
- [8] Bar-Gera, H. (2010) Traffic assignment by paired alternative segments, *Transportation Research B*, Vol. 44 Issue 8-9, pp. 1022-1046
- [9] Dial, R. (2006) A path-based user-equilibrium traffic assignment algorithm that obviates path storage and enumeration, *Transportation Research B*, vol 40, 917-936
- [10] Daneva, M. and Lindberg, P.O. (2003) Improved Frank-Wolfe directions through conjugation with applications to the traffic assignment problem, Linkoping University, Department of Mathematics
- [11] Mitradjieva, M. and Lindberg, P.O. (2013) The stiff is moving-conjugate direction Frank-Wolfe methods with applications to traffic assignment, *Transportation Science* 47:2 , 280-293
- [12] Bernstein, D. (1990) Programmability of continuous and discrete network equilibria, Ph.D. thesis, University of Pennsylvania
- [13] Boyce, D., Ralevic-Dekic, D., and Bar-Gera, H (2004) Convergence of traffic assignments: How much is enough? *Journal of Transportation Engineering*, ASCE, Jan./Feb. 2004
- [14] Slavin, H., Brandon, J., Rabinowicz, A., and Sundaram, S. (2009) Application of accelerated user equilibrium traffic assignments to regional planning models, paper prepared for presentation at the 12<sup>th</sup> Transportation Planning Applications Conference, Houston, TX, May 2009

- [15] Lu, S. and Nie, Y. (2010) Stability of user-equilibrium route flow solutions for the traffic assignment problem, *Transportation Research B* Vol. 44 (4), 609-617
- [16] Boyce, D., Nie, Y., Bar-Gera, H., Liu, Y., and Hu, Y. (2010) Field test of a method for finding consistent route flows and multiple-class link flows in road traffic assignments, Transportation Center, Northwestern University
- [17] Bar-Gera, H., Boyce, D. and Nie, Y. (2012) User-equilibrium route flows and the condition of proportionality, *Transportation Research B*, Vol.46, Issue 3, 440-462
- [18] Florian, M. and Morosan, C. (2014) On uniqueness and proportionality in multi-class equilibrium assignment, Presentation to TRB Conference on Innovations in Transportation Modeling, Baltimore, MD May 2014
- [19] Slavin, H., Brandon, J., Rabinowicz, A. and Sundaram, S. (2011) New findings from the application of accelerated user equilibrium traffic assignments, Presentation 13<sup>th</sup> TRB National Transportation Planning Applications Conference, Reno NV
- [20] Rich, J., Nielsen, O. and Cantarella, G. (2014) System convergence in transport modelling, paper presented at the Association for European Transport Conference, Frankfurt, Germany, September 2014
- [21] Boyce, D. (2011) Note on the calculation of feedback in the sequential procedure, personal communication, November 23, 2011
- [22] Gibb, J. (2015) Adaptive stopping criteria for traffic assignments within convergent feedback models, Paper presented at the 94<sup>th</sup> Annual Meeting of the Transportation Research Board and revised
- [23] COMSIS Corporation (1996) Incorporating feedback in travel forecasting: Methods, pitfalls, and common concerns, Report DOT-T-96-14, March 1996
- [24] Bottom, J. (2000) Consistent anticipatory route guidance, Ph.D. thesis, Massachusetts Institute of Technology
- [25] Slavin, H., Brandon, J., Rabinowicz, A., and Sundaram, S. (2007) Achieving planning model convergence, Presentation to the 11<sup>th</sup> TRB Applications Planning Conference, Daytona Beach, FL. May 2007
- [26] Boyce, D., O'Neill, C., and Scherr, W. (2007) New results on solving the sequential travel forecasting procedure with feedback, Paper prepared for presentation to the TRB Planning Application Conference, Daytona Beach
- [27] Florian, M. (2009) Comment on convergence methodology of large scale model systems, TMIP-L@LISTSERV.TAMU.EDU, February 7, 2009
- [28] Gibb, J. and Bowman, J.L. (2007) Convergence of an activity-based travel model system to equilibrium: Experimental designs and findings, Paper presented at the 11<sup>th</sup> TRB Planning Applications Conference, Daytona Beach, Florida May 2007

- [29] Florian, M. Constantin, I., and Florian, D. (2009) A new look at the projected gradient method for equilibrium assignment, Paper presented at the 2009 TRB Annual Meeting, Washington, D.C. January 2009
- [30] Caliper Corporation (2013) MAG Inner Loop Traffic Operations Model, Report prepared for the Maricopa Associations of Governments, Phoenix, Arizona
- [31] Ismart, D. (1990) Calibration and Adjustment of System Planning Models, FHWA, December 1990
- [32] Horowitz, A. (1991) Delay/Volume Relations for Travel Forecasting Based upon the 1985 Highway Capacity Manual, Report prepared for FHWA March 1, 1991
- [33] TMIP (2010) Model Validation and Reasonableness Checking Manual Second Edition, Chapter 9 Assignment Procedures, Report prepared by Cambridge Systematics, Inc. September 2010
- [34] Hartgen, D. (2013) Hubris or humility? Accuracy issues for the next 50 years of travel demand modeling, *Transportation* Vol. 40, Issue 6, 1133-1157, October 15, 2013
- [35] Engelson, L. and Lindberg, P.O. (2006) Congestion Pricing of Road Networks with Users Having Different Time Values in *Applied Optimization* vol.101, p.81104
- [36] Caliper Corporation (2014) A Brief Note on Toll Road Assignment Methods, Draft Working Paper, September 2014

