USING A SIMULATION ENVIRONMENT FOR DYNAMIC TOLL ANALYSIS

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ABSTRACT

The Capital Beltway HOT Lanes will be a 14 mile subset of the Washington, D.C. region's Capital Beltway (Interstate 495) upon completion in December 2012. Buses, carpools (HOV-3+), motorcycles and emergency vehicles will be able to access the Capital Beltway HOT lanes for free while drivers with fewer than three occupants must pay a toll to use the HOT lanes. Upon opening, they will be among the most advanced variably priced toll lanes in the world. A dynamic toll algorithm (DTA) will be responsible for making adjustments to the toll prices at regular intervals based on measured traffic density. An effective means to examine, develop and test the toll system capabilities prior to implementation was considered essential.

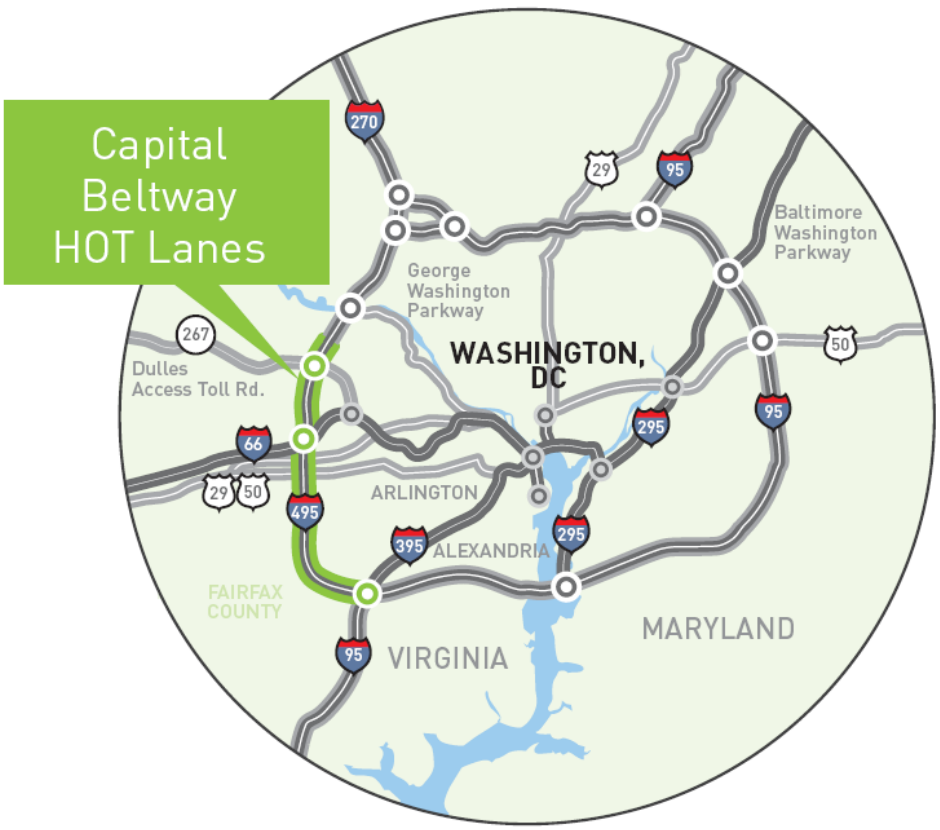
A very limited number of real-world algorithms currently exist for dynamic pricing on toll roads, and none was currently available in any existing simulation environment capable of accurately reflecting the fully dynamic nature of the Beltway's HOT Lanes toll system. After evaluating various options, the eventual selection of Caliper Corporation's *TransModeler* was made as the package of choice. A new and distinctive micro-simulation traffic environment was created based on the MnPass algorithm and used in the dynamic tolling analysis for the project. The simulation analysis was undertaken in the system procurement phase of the project to allow for integrated testing activities concurrent with the design and development process, which will yield significant positive outcomes for the project.

INTRODUCTION

This document summarizes the use of traffic micro-simulation to enhance the development and implementation of a dynamic toll algorithm (DTA) for the Capital Beltway High Occupancy Toll (HOT) Lanes in northern Virginia, U.S.A. The Virginia Department of Transportation (VDOT) and Fluor-Transurban are working together in a public-private partnership to deliver HOT Lanes to the Capital Beltway by December 2012. Fluor Virginia and Transurban DRIVe LLC (Fluor-Transurban) are making a substantial investment to fund construction of the lanes and Transurban USA will operate and provide routine maintenance for the lanes. Fluor is partnering with Lane Construction to design and build the Capital Beltway HOT Lanes.

The Beltway HOT Lanes are currently under construction, and when completed will be a 14 mile subset of Washington, D.C.'s Capital Beltway, which is a circumferential, 64 mile long freeway around the city (see Figure 1 below). Two HOT Lanes in each direction will operate adjacent to the four existing general purpose (GP) lanes in each direction. The HOT and GP lanes will be physically separated by a four-foot buffer area with flexible channelizing devices, and the northbound and southbound directions of travel are barrier separated. Buses, carpools with 3+ persons (HOV-3), and motorcycles will have free access to the Beltway HOT Lanes, while drivers with fewer than three occupants can pay a toll to access the lanes.

Figure 1 - Overview of Capital Beltway HOT Lanes



Transurban USA is under a subcontract with Fluor-Lane for the provision of the services for the design, engineering, procurement, installation, testing and related operations and maintenance start-up services for the Tolling and Traffic Management System (TTMS) for the Beltway HOT Lanes Project. Raytheon Company is the System Integrator responsible, under a subcontract to Transurban, for the provision of services for the design development, systems engineering, integration, testing and project management for the supply and installation of the tolling system roadside equipment, back office system, and integration of the traffic management system. Raytheon is supported by VESystems, LLC (part of the Federal Signal Corporation) in delivering the Back Office System (BOS) and Dynamic Pricing Subsystem (DPS) solution, and Transdyn Inc. is delivering the Automated Incident Detection (AID) Subsystem and overall integrated Traffic Management System (TMS).

The Beltway HOT Lanes are highly complex and unique in several ways:

- The network tolls are fully dynamic based on prevailing traffic, not time of day. Real-time traffic information (volume, speed and density) will be collected on the roadway network, and prices will be adjusted at regular intervals as needed to maintain free-flow travel conditions. As traffic demand increases, as a general rule the toll rates will increase, and as traffic demand decreases, the toll rates will decrease.

- Upon opening, the Beltway HOT Lanes will be among the most complex variably priced lanes in the world. There are 18 “zones” of traffic on the network (nine in each direction) that could have a distinct toll price at any given time based on prevailing traffic levels. The cost of a trip is the cumulative amount of tolls across all of the zones traversed by a vehicle. Figure 2 on the following page provides a schematic of the Beltway HOT Lanes zones.

- Toll collection is fully electronic; all vehicles require transponders (including HOV-3). Vehicles carrying three or more persons may use the HOT Lanes for free, while vehicles with one or two passengers may pay a toll to use the facility. Regardless of status, all users must have an EZ-Pass transponder. Switchable transponders will be available to the traveling public prior to opening to indicate whether the vehicle is an HOV-3 or toll paying vehicle.

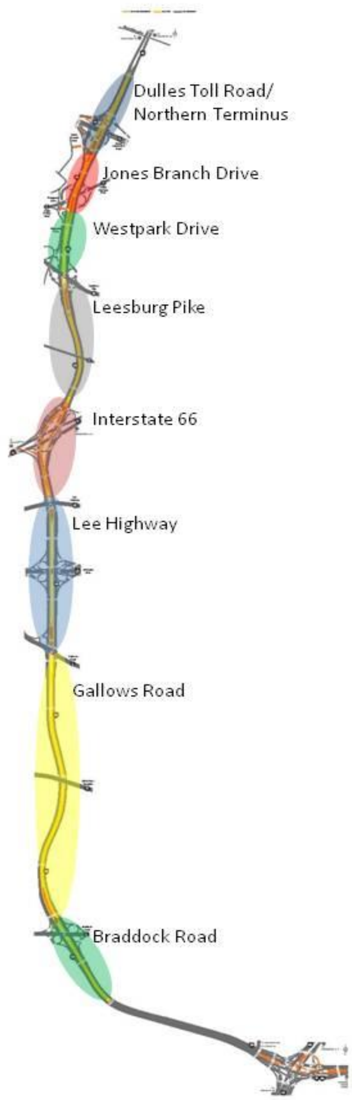
- Inter-connectivity between multiple HOV facilities. The Beltway HOT Lanes connect directly to both the Interstate-66 (HOV-2 lanes) and the Interstate 95/395 (HOV-3 lanes), which are freeways that do not currently have HOV inter-connectivity between them. The Beltway HOT Lanes offer a significant regional benefit in providing continuous HOV access throughout the major corridors of Northern Virginia.

- HOT Lanes access is via direct ramps with the cross-arterials. The HOT Lanes do not have slip-ramp access to and from the general purpose lanes. Instead, there are interchanges to connect the cross-arterials and the HOT Lanes directly. This is different approach from most managed lanes facilities in the United States for parallel roads, and creates more of an express-lanes feel while maintaining good access to key highways and arterial connections along the corridor.

- Revenue is a key objective in addition to traffic operations. The majority of project funding for the Beltway HOT Lanes comes from the private sector, which requires an acceptable return on investment.

- Safetea-Lu requirements call for a 45 mph average corridor speed. The Federal Highway Administration requires managed lanes to operate at 45 mph and above for a 180 day running average, for 90 percent of the time during the morning and evening peak periods. The dynamic toll algorithm will be instrumental in helping to achieve this objective, which would be considerably more difficult to manage under fixed toll conditions.

Figure 2 – Schematic of HOT Lanes Zones

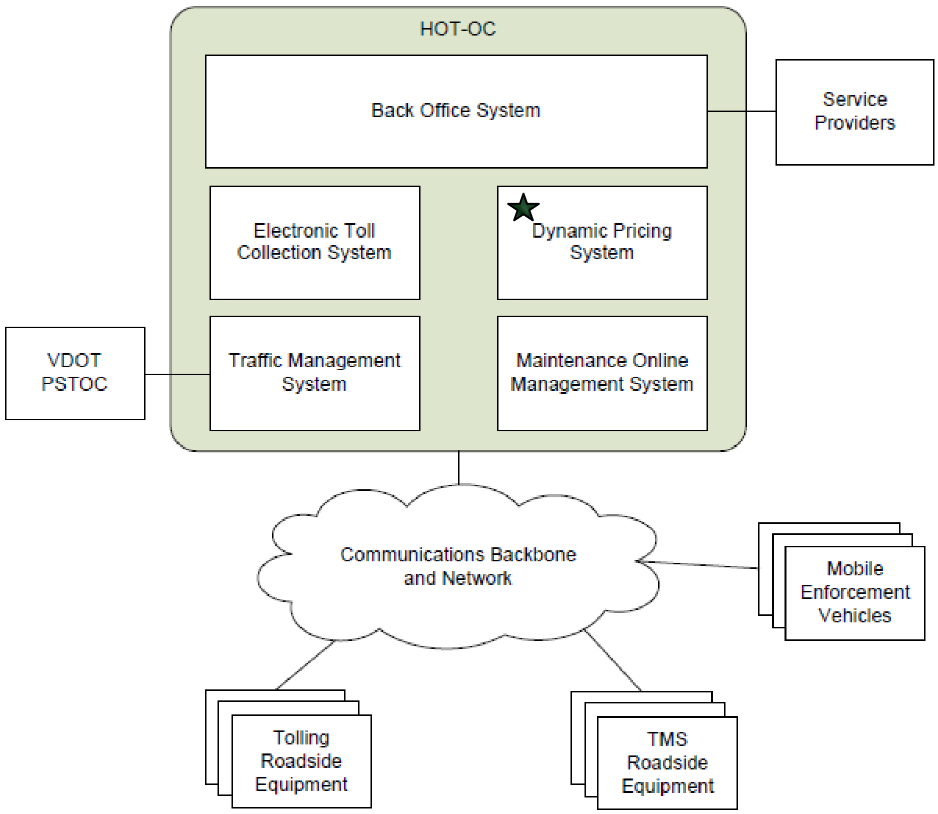


SYSTEM OVERVIEW

The Capital Beltway I-495 HOT Lanes will use dynamic toll pricing to influence customer behavior and maintain the desirable speed and level of service. The Electronic Toll Collection (ETC) Subsystem supports E-ZPass-compatible transponder payment and image-based vehicle (violation) enforcement. A Dynamic Pricing Subsystem (DPS) uses traffic data provided by the Traffic Management System (TMS) to determine toll rates. The Dynamic Toll Algorithm (DTA) is a feature within the DPS (see following page). The resulting toll rates are provided to the TMS for display to the public on Dynamic Message Signs (DMS) and used to determine trip charges. A Back Office System (BOS) provides trip construction and pricing. High Occupancy Vehicle (HOV) lane occupancy enforcement is provided through a Mobile Enforcement Subsystem (MES) deployed on the roadside in Virginia State Police (VSP) vehicles.

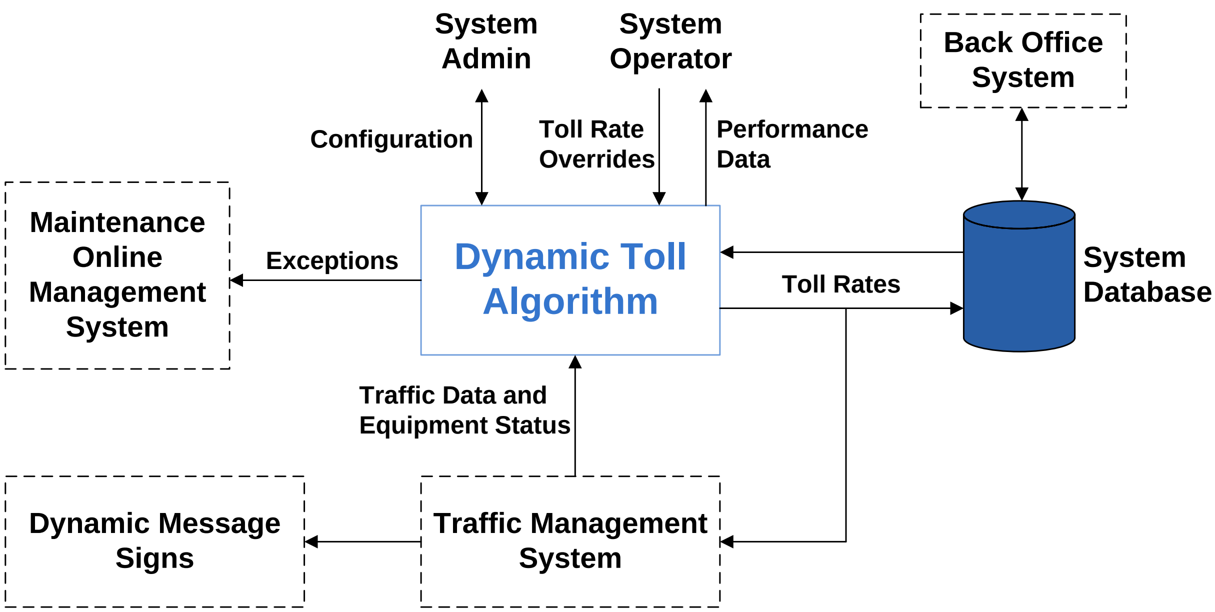
Typical Capital Beltway HOT Lane users will have registered E-ZPass customer accounts and their vehicles will carry switchable E-ZPass-compatible transponders that allow users to set a switch to declare a vehicle occupancy state of 'HOV' or 'Toll.' When a vehicle with a switchable transponder passes a HOT Lane Tolling Point, the state of the switch is determined by the ETC Subsystem. The ETC Subsystem reports all transactions to the BOS. Subsystem faults are reported to and worked via the Maintenance On-Line Management System (MOMS), which also manages an inventory of spare parts. A system overview is presented in Figure 3 below.

Figure 3 – System Overview



The DPS interfaces with the TMS and the BOS. The DPS obtains traffic data from the TMS (via Wavetronix - Smart Sensor HD detectors spaced approximately three per mile), implements the DTA, and provides toll prices to the TMS and a database shared with the BOS. The TMS conveys the toll prices to customers via the DMS, and the BOS uses the toll prices to support trip rating, customer support via web and other communication channels, and operational reporting. The DPS is configured by authorized system administrators, and is monitored and controlled by authorized supervisors. It reports its operational status and significant events (e.g., sign exceptions, rate exceptions) to MOMS. The DPS context is illustrated in Figure 4.

Figure 4 - Dynamic Pricing System (DPS) Context



DYNAMIC TOLL ALGORITHM

The Beltway HOT Lanes network covers a large geographic area with many interchanges, and features a complicated tolling system. Given the size and complexity of the network, an effective means to examine, develop and test the system capabilities of the DTA prior to implementation was considered essential. Since the DTA is responsible for making real-time adjustments to the toll prices based on prevailing traffic demand, it is a crucial element to the success of the Beltway HOT Lanes. Hence, a new and distinctive micro-simulation traffic environment was created and used for testing the DTA.

A very limited number of real-world algorithms currently exist for dynamic pricing on toll roads, and none (including the one proposed for the Capital Beltway project) was currently available in any existing simulation environment capable of accurately reflecting the fully dynamic nature of the DTA and traffic responses to it. This lead to the examination of various software capabilities and the selection of TransModeler as the analysis package of choice. Caliper Corporation (developer of TransModeler) worked in partnership with Transurban to code the complex system in the software necessary to reflect the real-world implementation of the DTA for the project.

Caliper's development of the algorithm simulation environment within TransModeler was completed in two parts. First, the algorithm itself was developed in an environment separate from that of TransModeler to emulate the algorithm's external mechanics (e.g., measurement of vehicle counts and speeds, and update of dynamic message signs) and internal logic (e.g., calculation of traffic densities and rates).

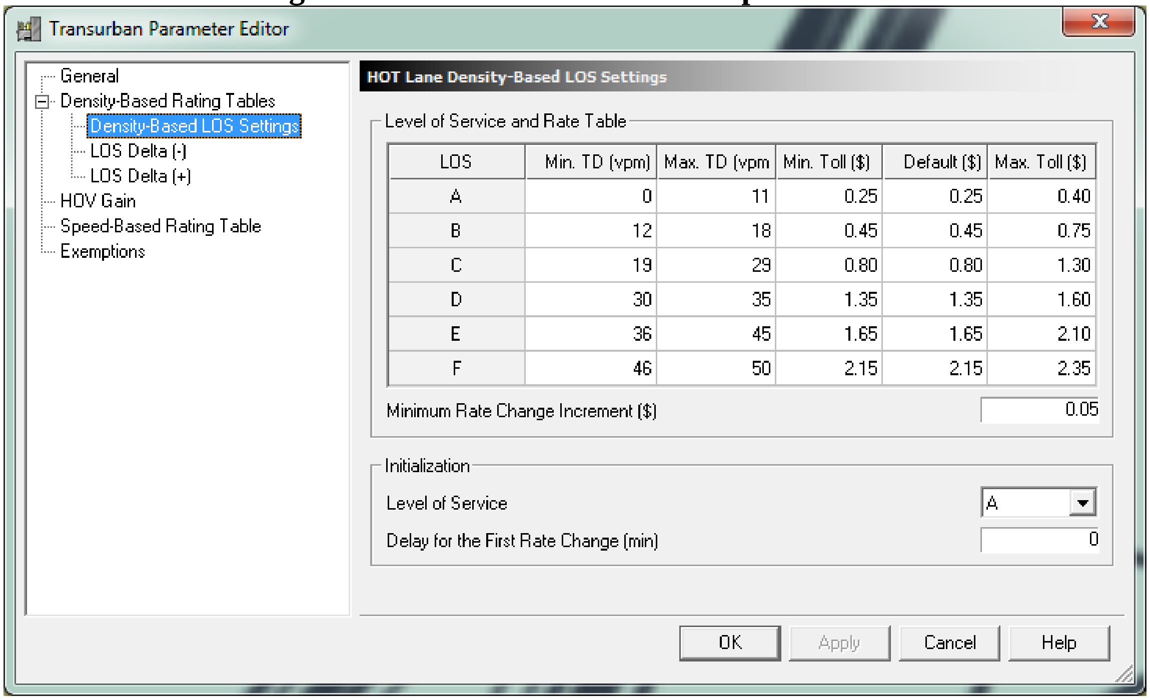
Second, TransModeler's own functionality was extended to add better support for zone-based toll algorithms and to add previously non-existing support for destination-based algorithms where the cost is a function of where the customer enters the facility and where the customer leaves. The total trip cost is the sum of the zone-based rates a user passes between the origin and destination, and can be bounded by minimum and maximum rates.

The MnPass algorithm, which was developed by Raytheon Highway Transportation Systems Management and VESystems for the Minnesota Department of Transportation, is based on the concept of maintaining Level of Service "C" or better (based on the Highway Capacity Manual's methodology for freeways) in the HOT lanes on I-394 in Minneapolis (1). MnPass adjusts toll prices in pre-defined freeway segments based on the changes in density of traffic measured between specified time intervals. The MnPass algorithm was deemed a good baseline starting-point to use for the Beltway HOT Lanes' DTA framework since the density-based approach effectively accommodates a multi-segment network with many interchanges. However, several elements were identified early in the process that had to be addressed through algorithm modification to better fit the specific needs of the Beltway HOT Lanes. Hence, a modified algorithm is being created to retain the positive features of MnPass but tailored to address several issues of concern related specifically to the project.

The DTA simulation environment within TransModeler is highly configurable, allowing users to set parameters that define alternative strategies for time-based pricing, or dynamic, traffic-based pricing formats. A user-friendly graphical user interface (GUI) was created to facilitate managing the input parameters of the algorithm, both at the global and local (zone) levels. The LOS and rate parameter inputs determine the range of traffic densities that define each level of service A-F. These parameters also give various rate constraints, including a minimum and maximum rate per level of service. The Delta value input is the calculated change in Traffic Density between consecutive rate change updates. A change in rate is determined using a lookup table based on the current calculated Traffic Density and the rise or fall (i.e., delta) in density relative the Traffic Density calculated in the prior time interval.

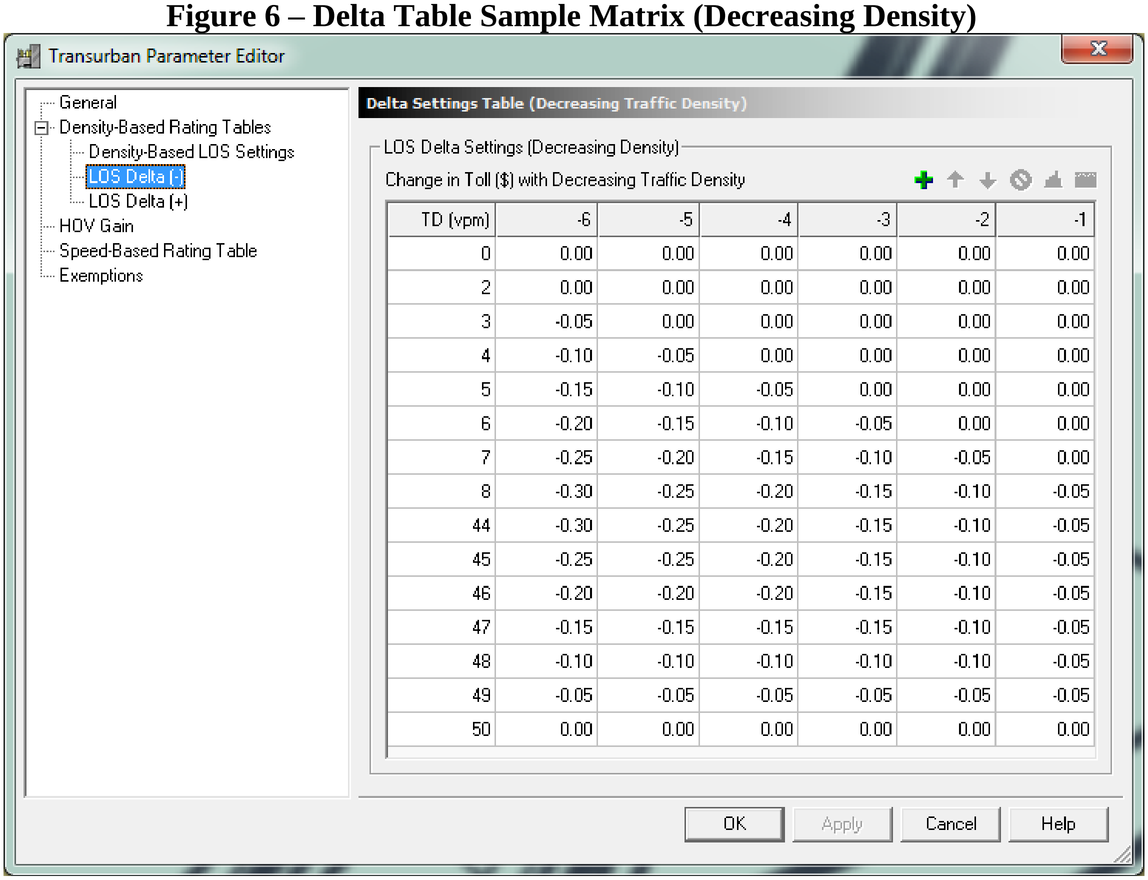
Together, the Density measures (as determined by the volume and speed collected by the lane detectors), and the Delta matrix values, are used to determine the changes in toll price between time periods for each specific zone. Figure 5 illustrates a sample matrix of LOS and possible price ranges and Figure 6 shows a sample Delta matrix that defines a change in price per change in traffic density at various levels from the TransModeler simulation environment.

Figure 5 – LOS and Toll Price Sample Matrix



LOS	Min. TD (vpm)	Max. TD (vpm	Min. Toll ($)	Default ($)	Max. Toll ($)
A	0	11	0.25	0.25	0.40
B	12	18	0.45	0.45	0.75
C	19	29	0.80	0.80	1.30
D	30	35	1.35	1.35	1.60
E	36	45	1.65	1.65	2.10
F	46	50	2.15	2.15	2.35

Figure 6 – Delta Table Sample Matrix (Decreasing Density)



TD (vpm)	-6	-5	-4	-3	-2	-1
0	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	-0.05	0.00	0.00	0.00	0.00	0.00
4	-0.10	-0.05	0.00	0.00	0.00	0.00
5	-0.15	-0.10	-0.05	0.00	0.00	0.00
6	-0.20	-0.15	-0.10	-0.05	0.00	0.00
7	-0.25	-0.20	-0.15	-0.10	-0.05	0.00
8	-0.30	-0.25	-0.20	-0.15	-0.10	-0.05
44	-0.30	-0.25	-0.20	-0.15	-0.10	-0.05
45	-0.25	-0.25	-0.20	-0.15	-0.10	-0.05
46	-0.20	-0.20	-0.20	-0.15	-0.10	-0.05
47	-0.15	-0.15	-0.15	-0.15	-0.10	-0.05
48	-0.10	-0.10	-0.10	-0.10	-0.10	-0.05
49	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
50	0.00	0.00	0.00	0.00	0.00	0.00

BENEFITS OF THE SIMULATION ENVIRONMENT TESTING

The following paragraphs offer a high-level summary of the major benefits of the simulation environment testing process:

- Identification of system/DTA weaknesses and flaws, the most significant include:

  a) there is no revenue maximization function;
  b) there is no speed component to ensure meeting Safetea-Lu (45 mph minimum) requirements;
  c) toll rates may stay at a certain level that is too high or low if traffic density remains constant; and
  d) toll rates would often change based on LOS changes instead of delta values, which may cause steep price changes over a brief period of time.

- Capability enhancements for the DTA, the most notable of these include:

  a) A new speed-based toll premium that can address situations where the pure density-based toll rates are not sufficiently regulating traffic flow at speeds near or below 45 miles per hour; and
  b) an HOV percentage factor that can be introduced to account for situations where higher or lower toll rates are appropriate for various HOV percentage situations to influence behavior of the toll-paying category of vehicles.

- Timely and integrated discussions with the system provider:

  The system design process was enhanced by making it possible to suggest improvements to the algorithm during the course of the planning with the System Integrator, and modifications to DTA were made based on discovered limitations in the initial design of the system. There are vast operational and revenue benefits that will result by making these modifications prior to project opening, which will result in significant time and dollar savings. Transurban has been able to engage more directly in the entire process from contracting through design and implementation through the use of the simulation environment. The simulation model outputs were shared with the System Integrator to facilitate system preparation and implementation as well.

- Creation of an independent test platform for system verification and concept algorithm assessments:

  The LOS and Toll Price, and Delta matrices (as shown Figures 5 and 6) are critical input parameters that have a primary impact on the behavior and success of the DTA. Additionally, the price update and data collection time intervals are important parameters of the DTA in optimizing traffic operations and revenue since these values influence the frequency and amount of price changes.

If these input values are too short or too long, then the DTA would not be able to adjust the price into the optimal range, resulting in under-performing traffic operations and sub-optimal revenues. While it is unlikely that all of the initially modeled inputs will be optimal to accommodate field conditions, the testing process will help to narrow down the parameters into a more management level of unknowns and optimal ranges for operations.

After the HOT Lanes are opened to the public and other challenges and opportunities are identified, potential future solutions can be tested and evaluated based on their merits through testing via the simulation tool without significant resource investment in measures that might not be effective upon implementation.

Subsequent phases of the project will also be able to benefit through:

- Improved understanding of DTA capabilities.
- Strategic development of the algorithm framework that governs toll prices.
- Optimization of system parameters.
- Incident planning and management.
- Guidance and training for operators.
- Input to reporting guidelines.

Hence, the analysis of the DTA in the simulation environment has yielded significant positive outcomes for the Beltway HOT Lanes project of Northern Virginia.

ACKNOWLEDGEMENT

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REFERENCES

(1) Nick Thompson, " MnPass Dynamic Pricing", Minnesota DOT, December 2005, pp. 1 – 3