Optimized Time-Dependent Congestion Pricing System for Large Networks:

Integrating Distributed Optimization, Departure-Time Choice, and Dynamic Traffic Assignment in the GTA

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Outline

- Motivation
- Theory
- U of T’s Framework and System
- Application to the GTA
- Conclusions and Future Research

What is Congestion Pricing?

- Road pricing is any system that directly charges motorists for the use of a road or network of roads.

- Congestion pricing refers to road tolls intended to <u>*reduce* traffic congestion</u> or to *distribute* it more evenly over <u>time</u> and <u>space</u>.

Congestion Pricing Inevitable

- Much like traffic lights are!
- Viable congestion control tool
- Revenue is a (welcomed?) by product
- Why inevitable?
  - Demand/Supply > 1.0 ---→ Congestion
  - Spills over longer periods and larger space
  - Constrained supply (space, $, environment)
  - Ever increasing demand
  - Ever increasing congestion until it chokes the metropolis
- Not a matter of if, but when, where and how

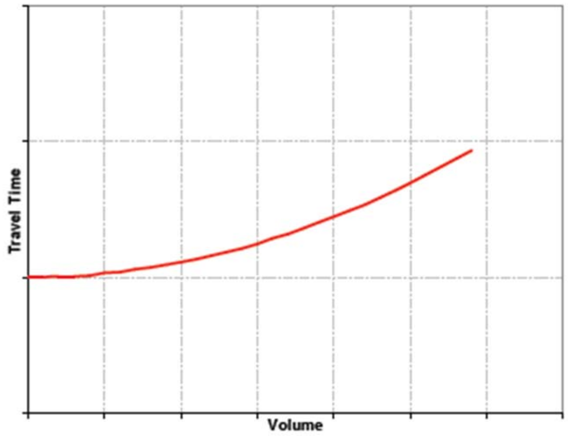
Evidence Why Congestion Pricing?

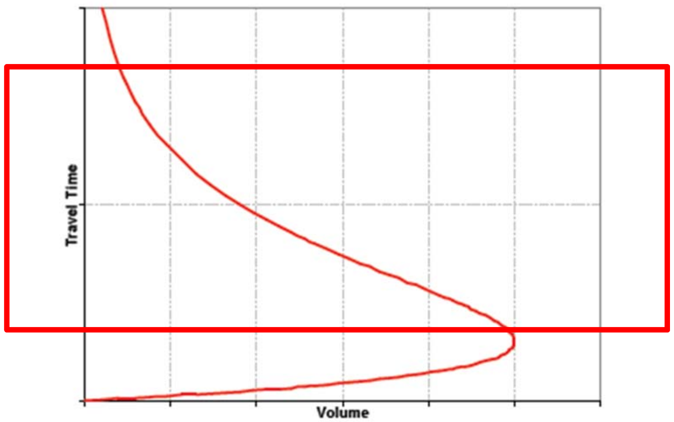
Tragedy of the commons *(Hardin, 1968)*.

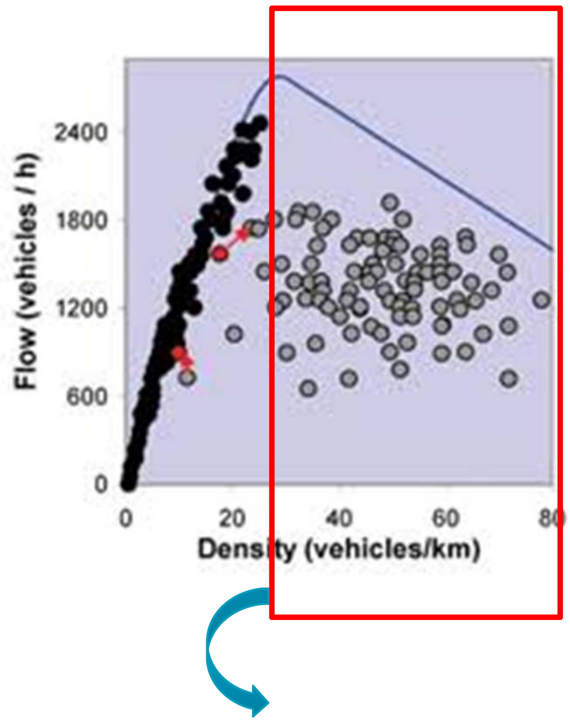
VKT is quite responsive to price, as opposed to transit/capacity expansions *(Duranton and Turner, 2011)*.

Therefore, policy makers should emphasize *not only* on improving the supply of alternative modes *but also* on financial disincentives for auto use.

Traffic 101: what is congestion?

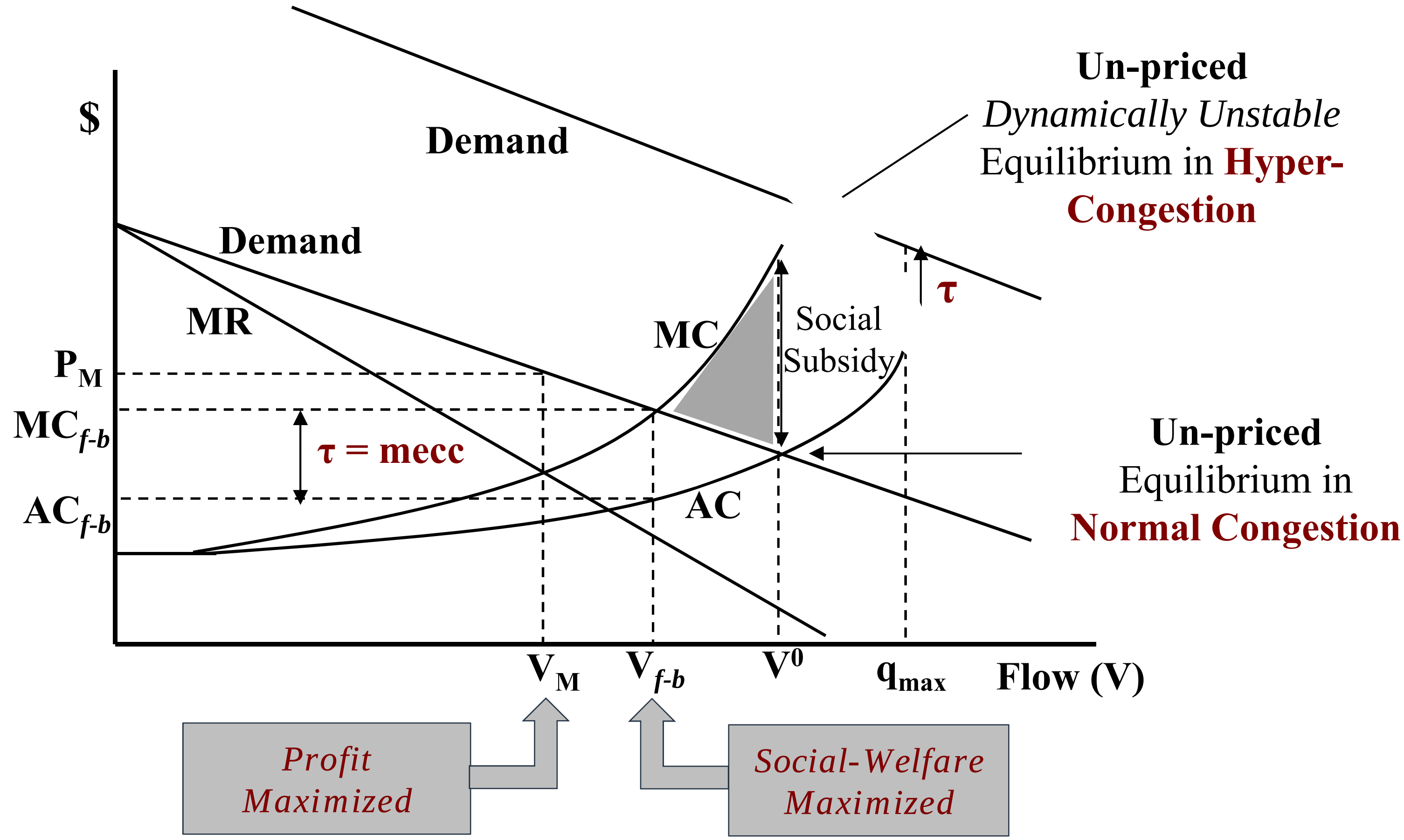






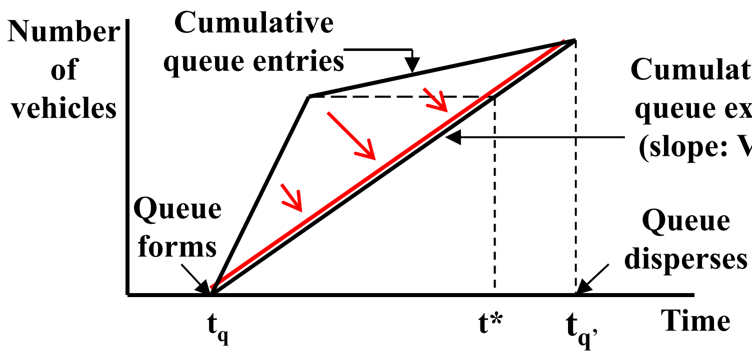
- Hyper-congestion, or
- Supercritical congestion

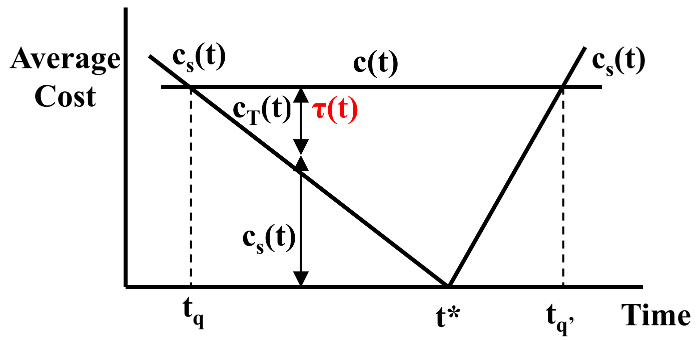
Pricing with Static Congestion



Dynamic Hyper-Congestion Pricing

The Basic Bottleneck Model





Optimal pricing in the Bottleneck Model

Departure-time rescheduling.

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Generalized Dynamic Congestion Pricing

Objective

- Eliminating hyper-congestion through <u>spatio-temporal</u> traffic redistribution

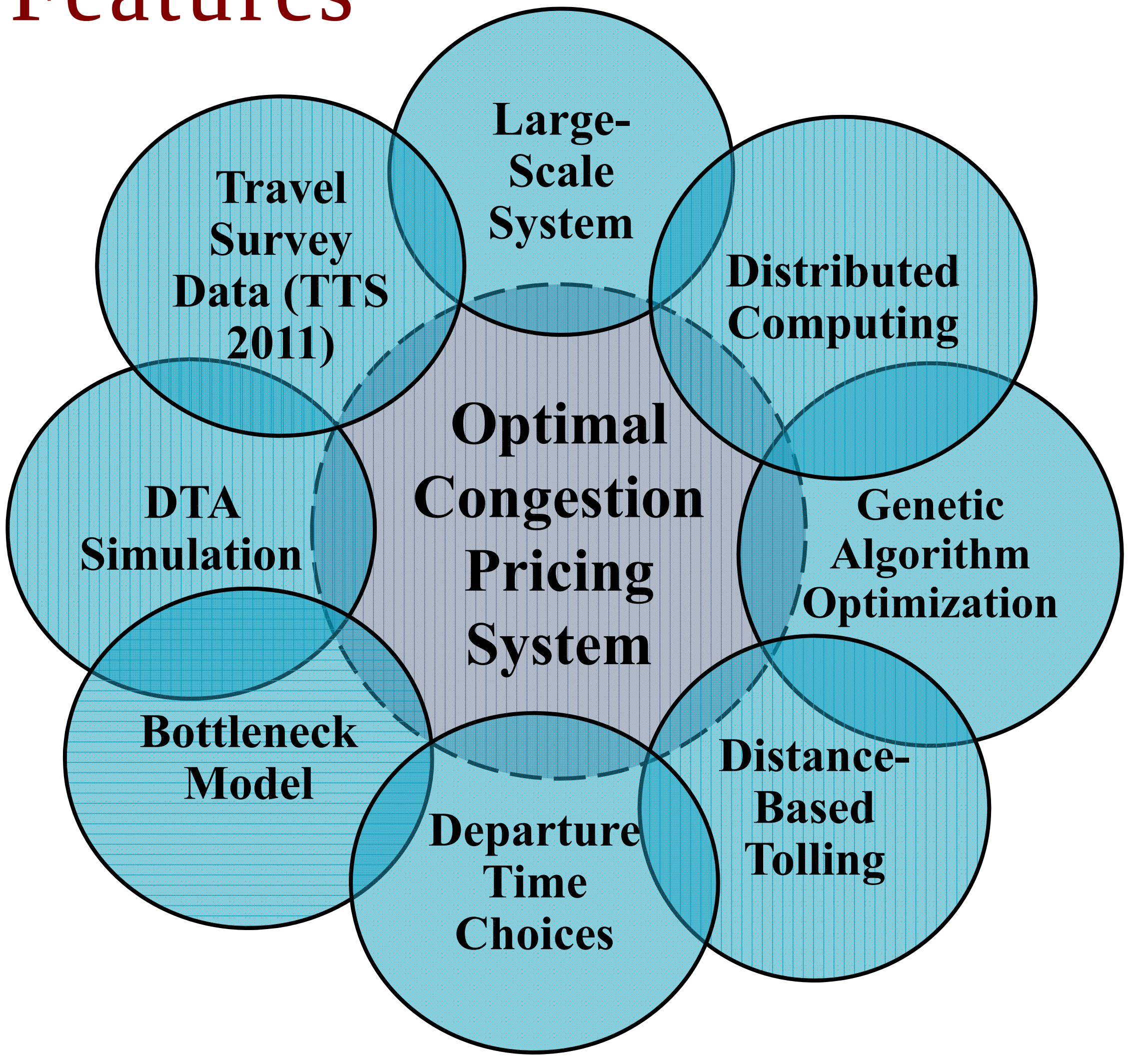
Method

- Time-dependent distance-based tolling.

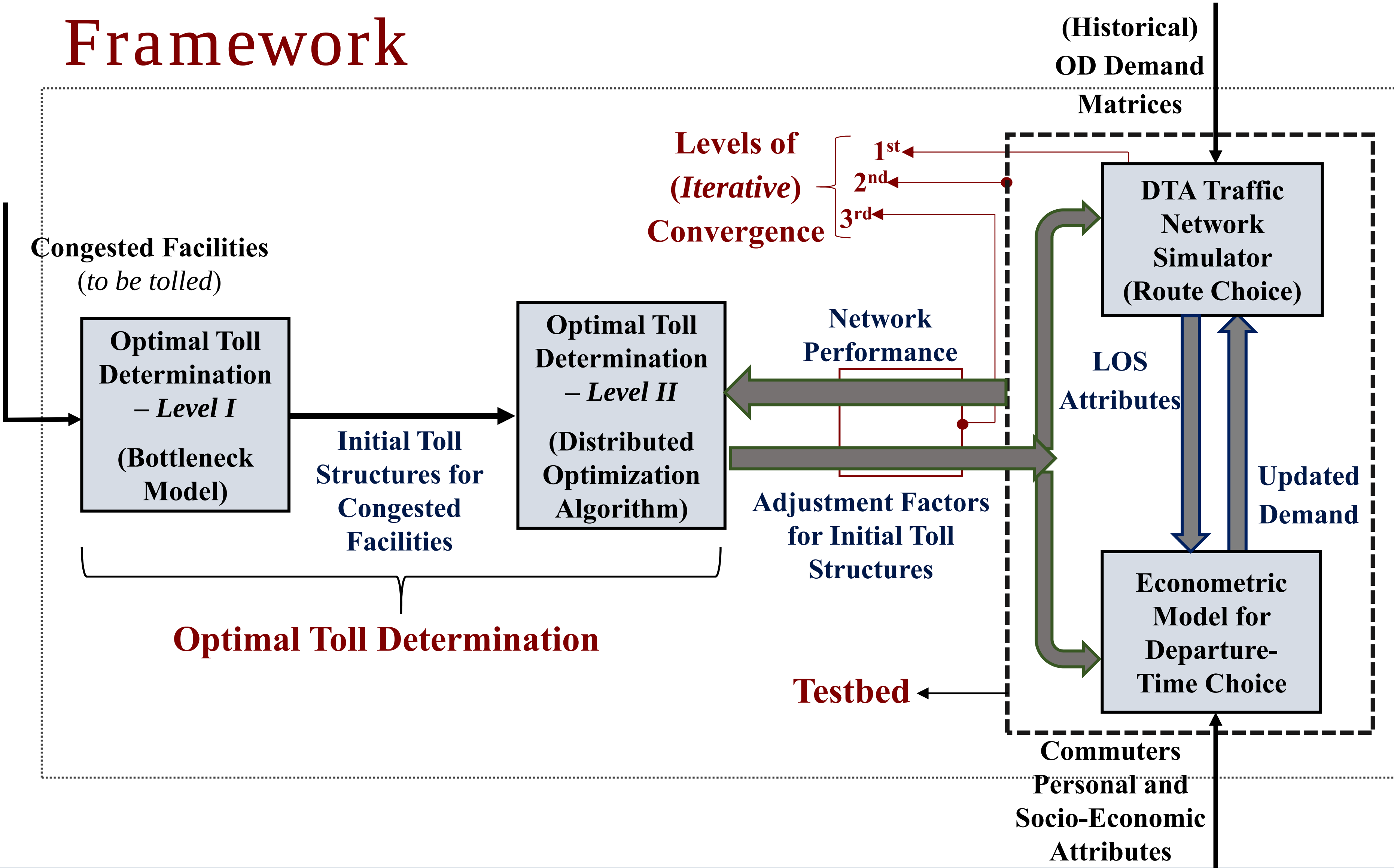
Impact

- Departure time shift.
- Route shift.
- Mode shift (if transit capacity exists).

Optimal Congestion Pricing System
Design Features



Optimal Congestion Pricing System Framework

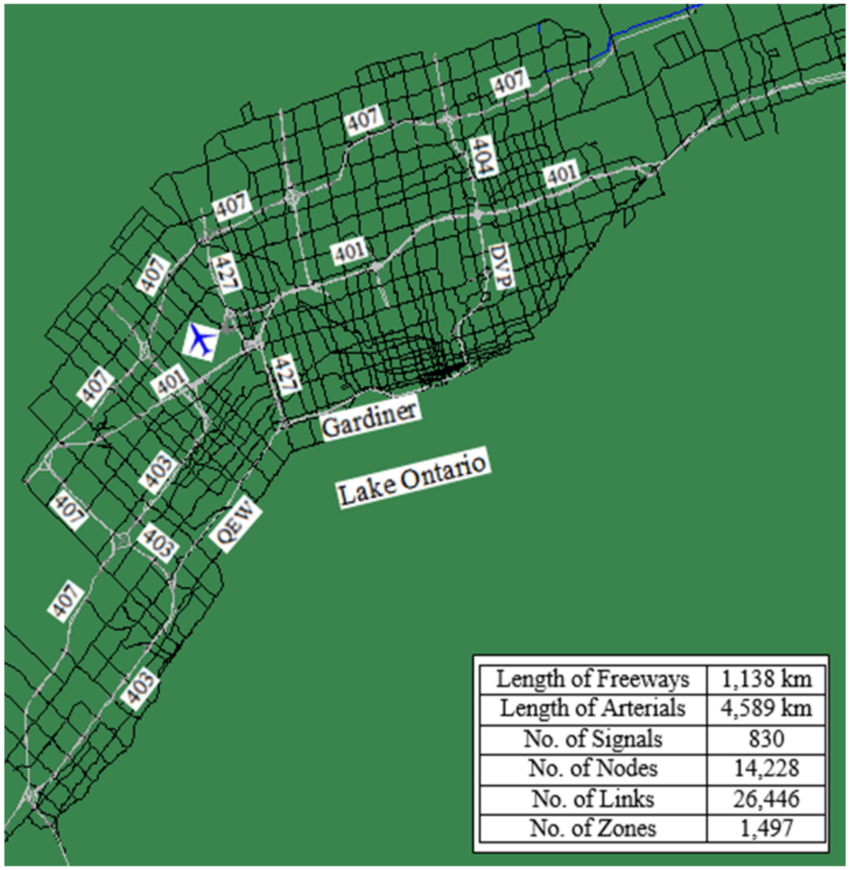


Greater Toronto Area Case Study

1- DTA Simulation Model for the GTA

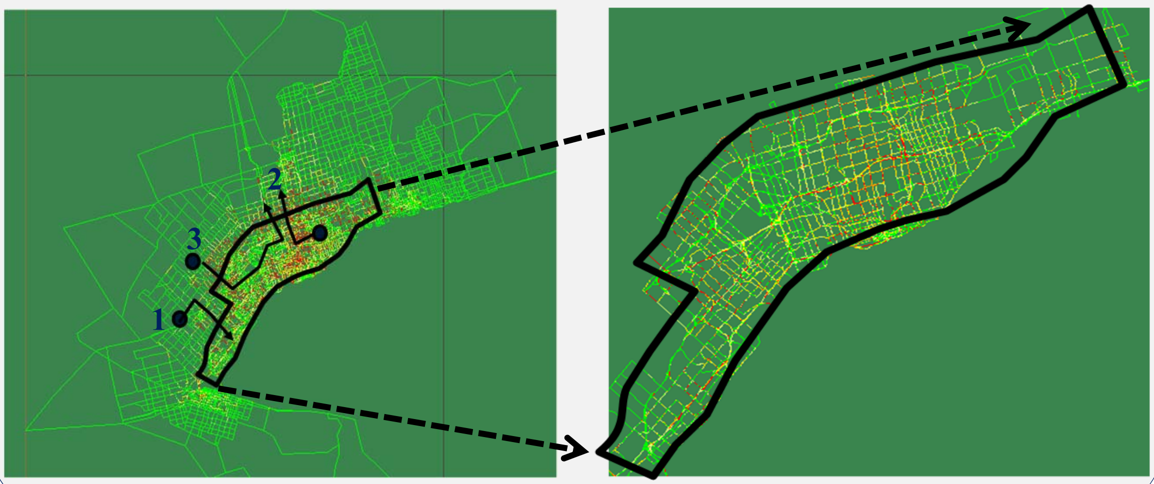
Main Features

- DTA, mesoscopic (DynusT).
- Large size.
- GIS database from LIO.
- OD matrices: 6-10:30 am.
- Background demand.
- Calibrated and validated.

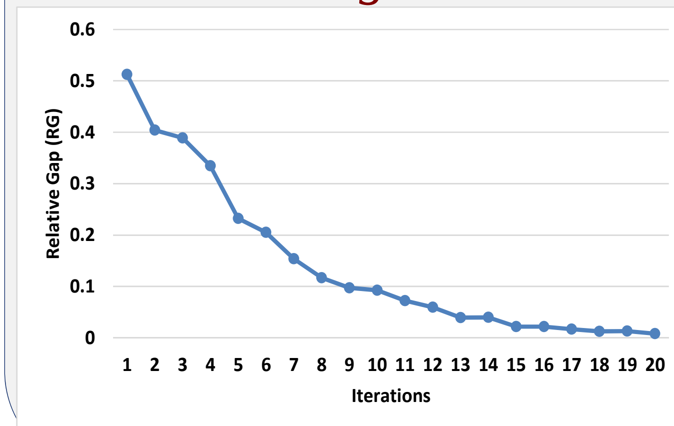


1- DTA Simulation Model for the GTA (*cont'd*)

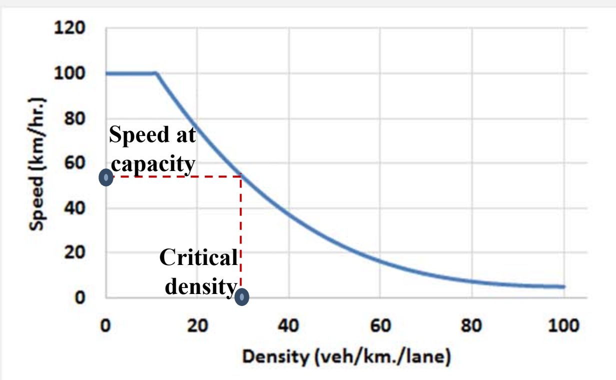
Adding background demand

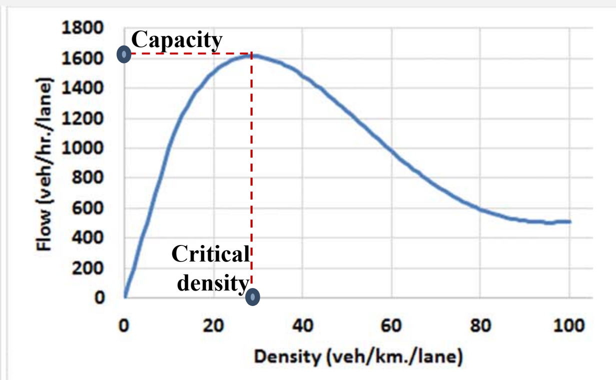


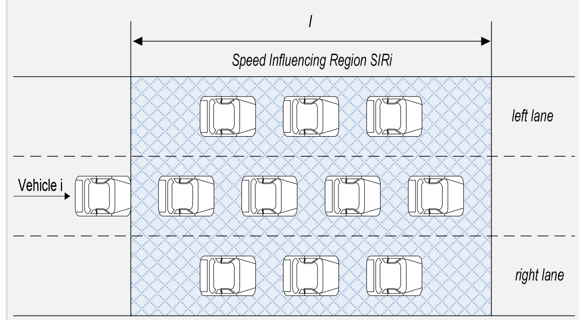
GTA simulation model Convergence



Traffic simulation in DynusT



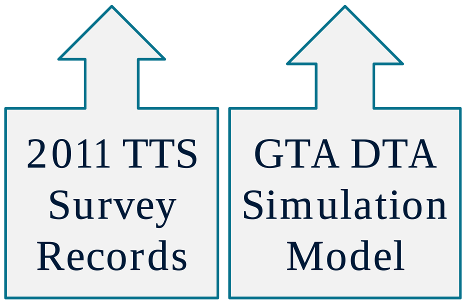


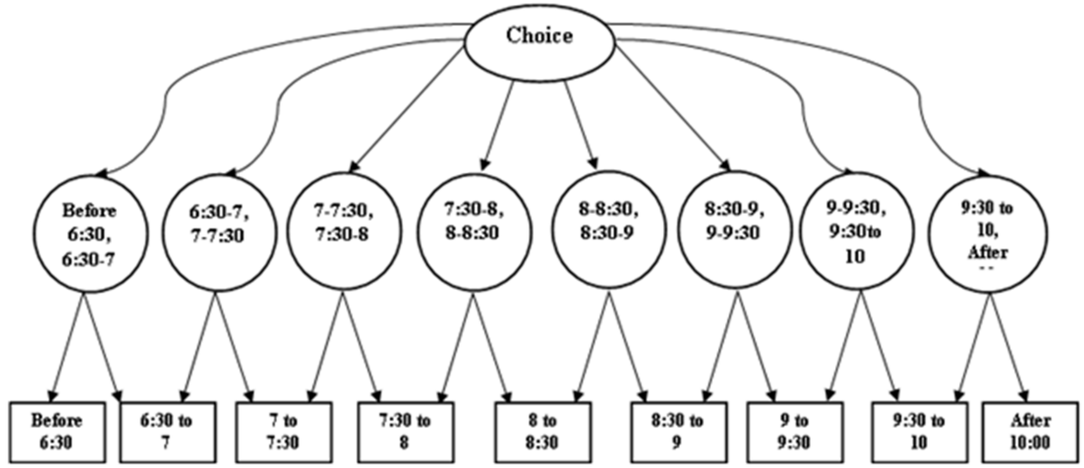


2- Departure-Time Choice Model *(Sasic and Habib, 2013)*

Model Variables

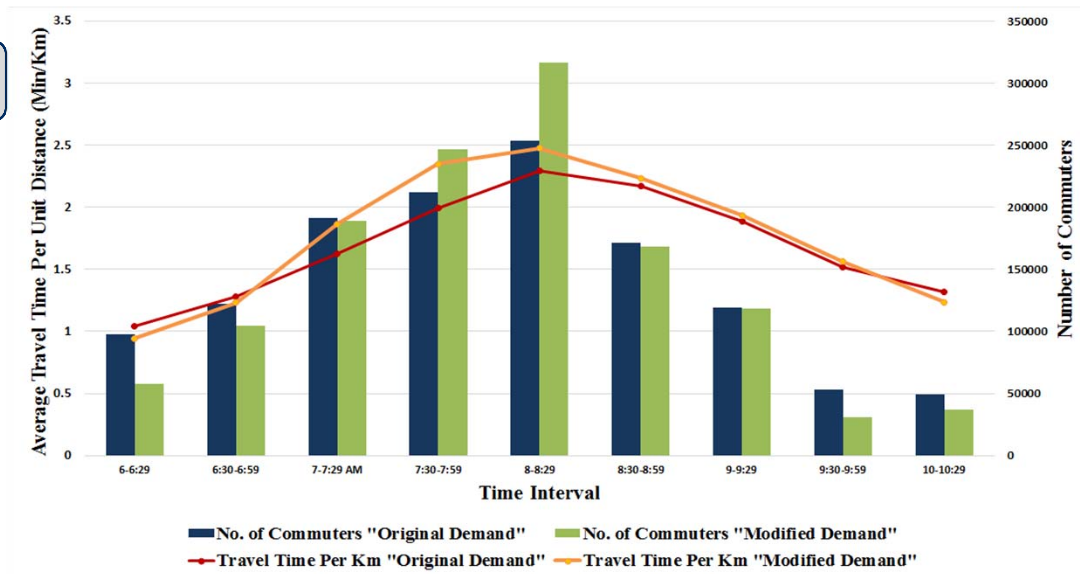
- Driver and LOS attributes.





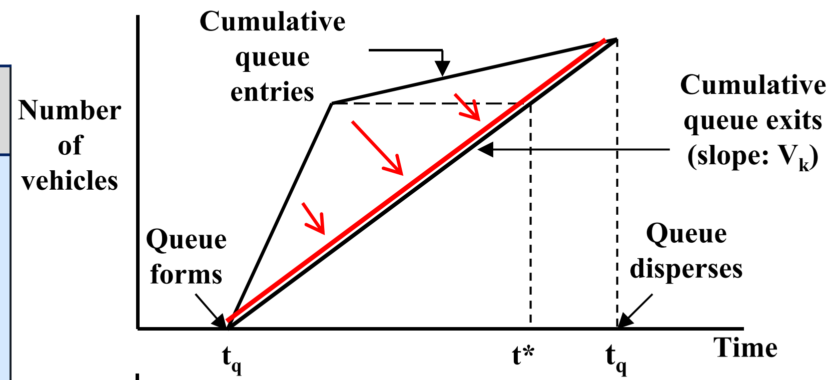
Model Retrofitting for 2011

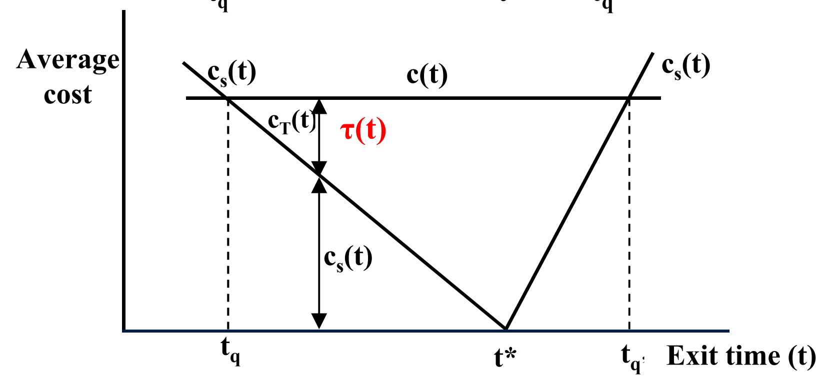
- Updating ASC's (2011 TTS data).
- Integrating schedule-delay and toll cost components.
- Recalibrating travel time coefficients.
- Model validation.



3- Toll Determination – Level I: The Bottleneck Model

Model Assumptions	Our Implementation
- Homogeneous drivers. - Single desired arrival time. - Only departure-time choice. - No driver attributes.	- Heterogeneous drivers. - Distribution of desired arrival times. - Route and departure-time choices. - Considers driver attributes.





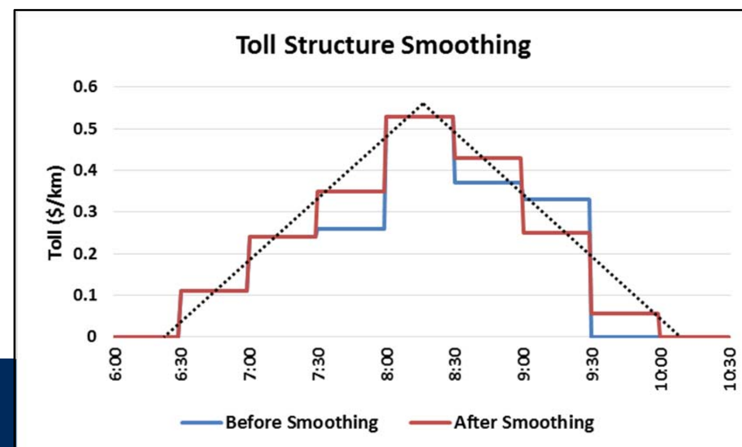
Initial (sub-optimal) step-toll structure determination procedure:

1- Travel time (hence queueing-delay) estimation.

2- Identify the tolling period and set the max toll value.

3- Determine the full toll structure.

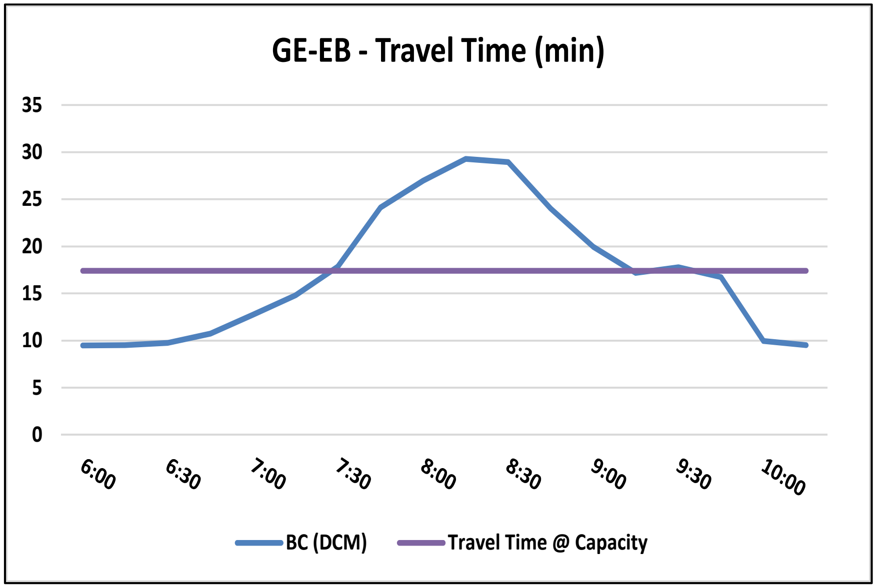
4- Toll structure smoothing.



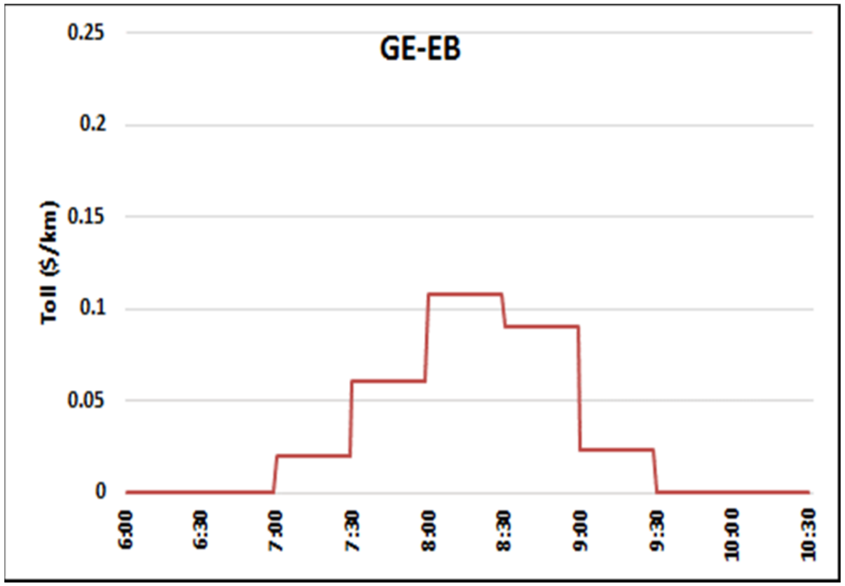
Queueing-Delay Estimation Example (GE- Eastbound)

Queueing-delay is calculated as the excess travel time over the value of "travel time at capacity" on the congested facility.

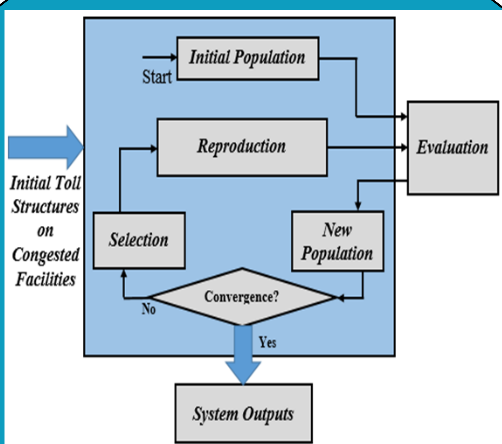
Base-case travel time



Initial toll structure



4- Toll Determination – Level II: Distributed Genetic Algorithm *(Mohamed, 2007)*



Decision Variables

- Scale factors for initial toll structures.
- Variables’ ranges.

Objective Function

- Total travel times then utilization levels (flow*speed).
- Optimization problem segmentation for “quasi-flat” fitness phenomenon.

Distributed Computing

- Apache Ignite: Map-reduce paradigm.
- Calibration of Parallel cluster.
- Linear speedup.

(I) Simple Tolling Scenario: GE

Tolled Route (GE)

- 18 km (427 to DVP).
- 6 to 10 lanes wide.
- 90,000 morning commuting trips on the GE corridor.

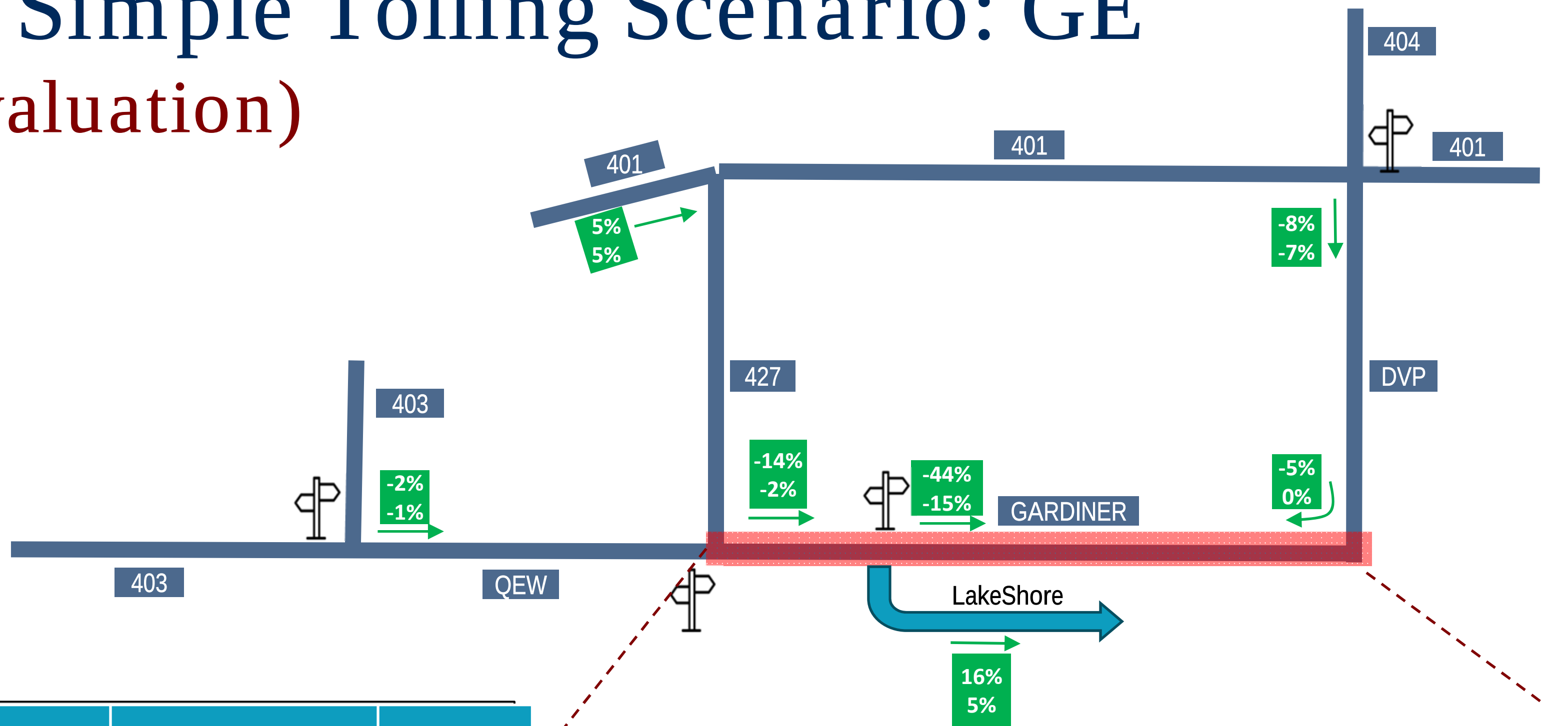
Purpose of the Scenario

- Test the effectiveness of first-level of optimal toll determination.
- Compare flat and variable tolling through the integrated testbed.

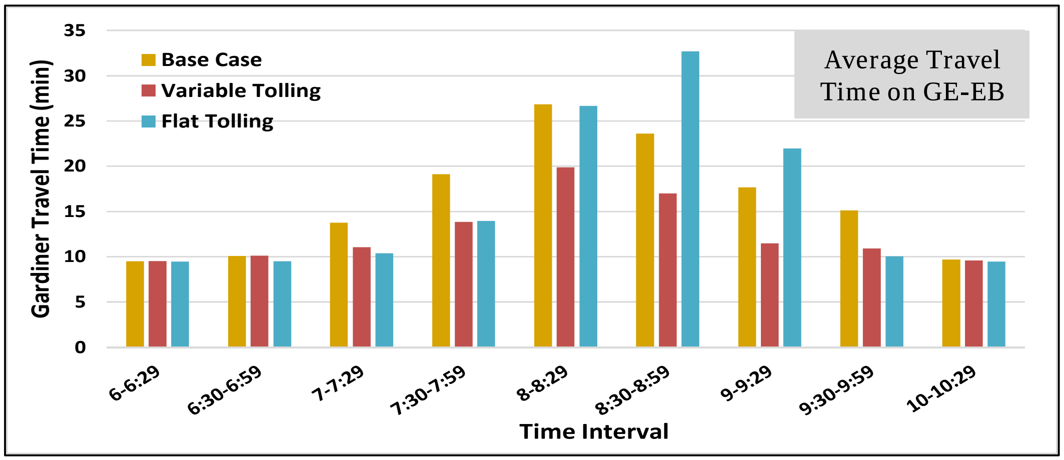
Assumptions

- Queueing-delay estimated based on all corridor users (on both directions).
- Same toll for EB and WB directions of the GE.

(I) Simple Tolling Scenario: GE
(Evaluation)



% Travel Time Savings	Variable Toll	Flat Toll
GE-EB (tolled route)	25% (8-8:30 am)	-ve ?
GE Corridor	9.5%	2%
Network-Wide	1.7%	0.6%



(II) Extended Tolling Scenario: GE, DVP, and 401 Express

1

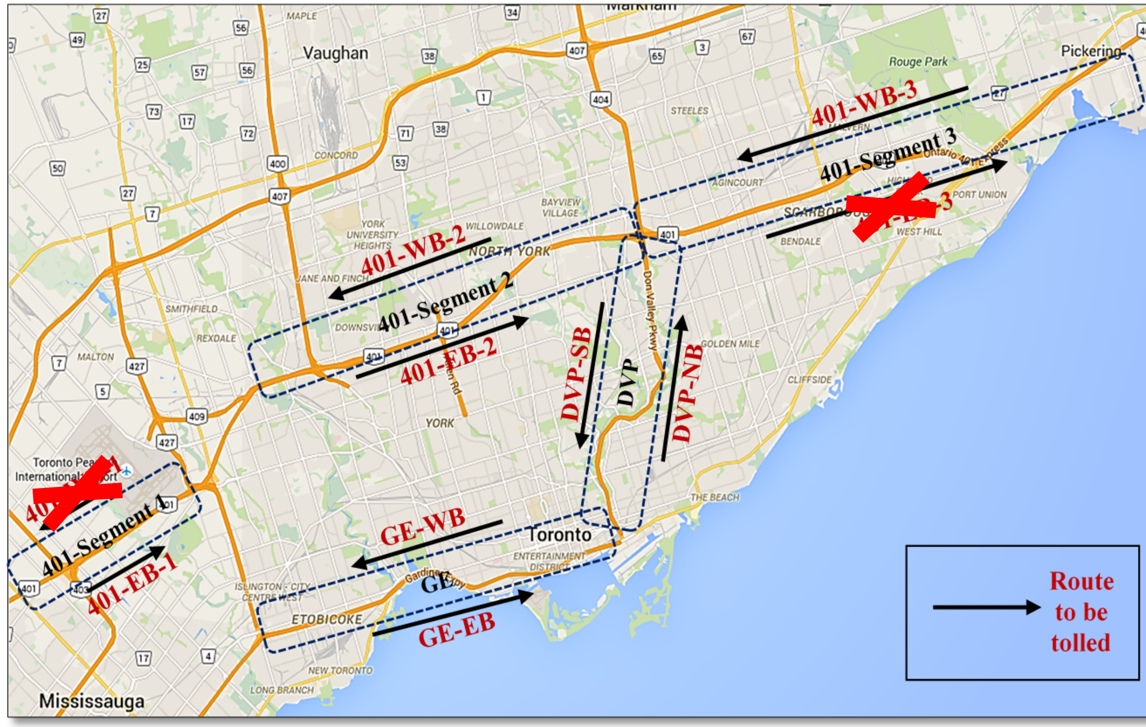
GE-EB
DVP-NB

2

401-EB-1
401-EB-2

3

401-WB-3
401-WB-2
DVP-SB
GE-WB



(II) Extended Tolling Scenario: GE, DVP, and 401 Express - Correlation Matrix

	GE-EB	GE-WB	DVP-NB	DVP-SB	401-EB-1	401-EB-2	401-WB-2	401-WB-3
GE-EB	35976							
GE-WB	11 (0.0%)	42904						
DVP-NB	6576 (23.4%)	238 (0.7%)	26883					
DVP-SB	0 (0.0%)	11481 (35.7%)	394 (1.3%)	32969				
401-EB-1	2523 (8.0%)	3 (0.0%)	67 (0.2%)	284 (0.9%)	29864			
401-EB-2	0 (0.0%)	450 (1.1%)	26 (0.1%)	1596 (4.7%)	10809 (38.6%)	36910		
401-WB-2	661 (1.7%)	0 (0.0%)	3284 (9.9%)	346 (0.9%)	0 (0.0%)	0 (0.0%)	42781	
401-WB-3	157 (0.4%)	2094 (5.2%)	209 (0.6%)	6332 (19.0%)	0 (0.0%)	1 (0.0%)	12856 (36.7%)	40086

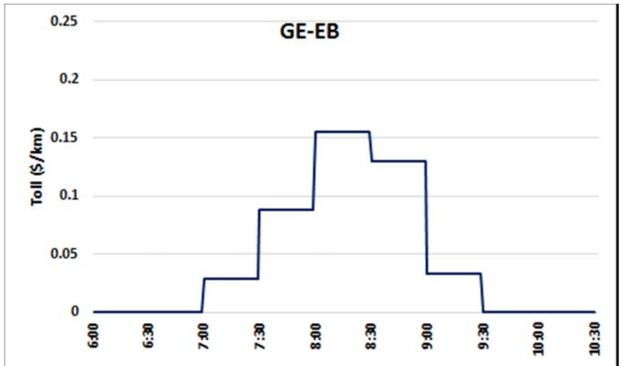
(II) Extended Tolling Scenario: GE, DVP, and 401 Express – Execution Time

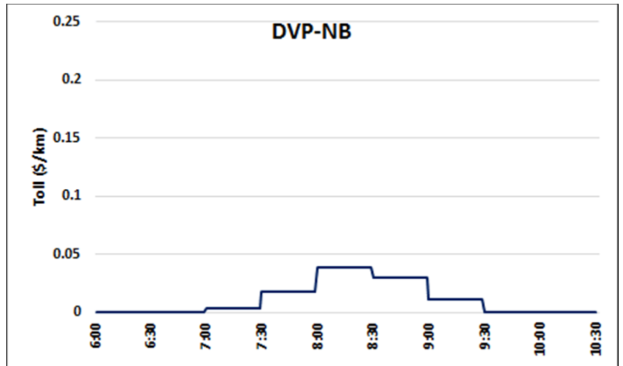
	Population Size	# of Generations	Execution Time (Parallel Mode**)	Execution Time (Serial Mode*)
Optimization Problem 1	16	3	198 hours (8.25 days)	828 hours (5 weeks)
Optimization Problem 2	10	3	108 hours (4.5 days)	450 hours (2.7 weeks)
Optimization Problem 3	10	6	216 hours (9 days)	972 hours (6 weeks)
Total	--	--	522 hours (**22 days**)	2250 hours (**3 months**)

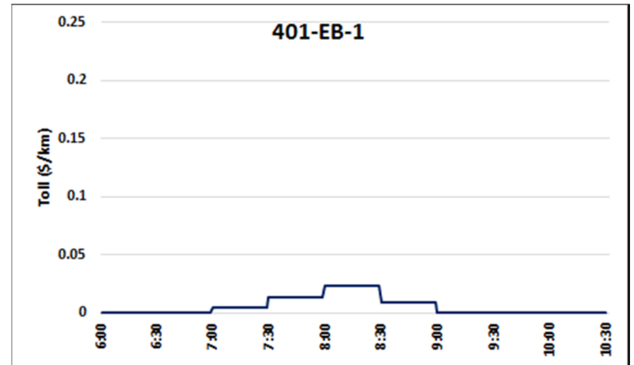
***Serial Mode**: Intel Core i7-3770 processor @ 3.40 GHz with 16 GB of RAM memory.

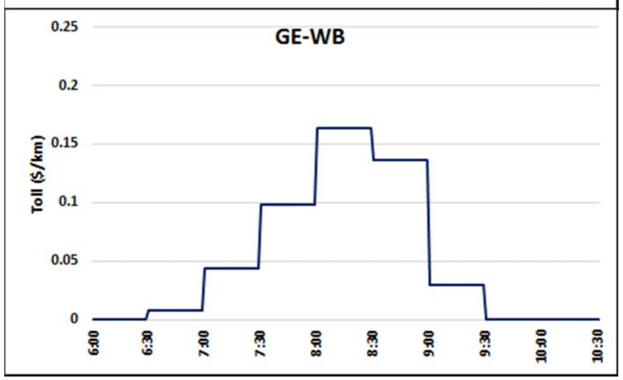
****Parallel Mode**: a parallel cluster of five computers having the above specs.

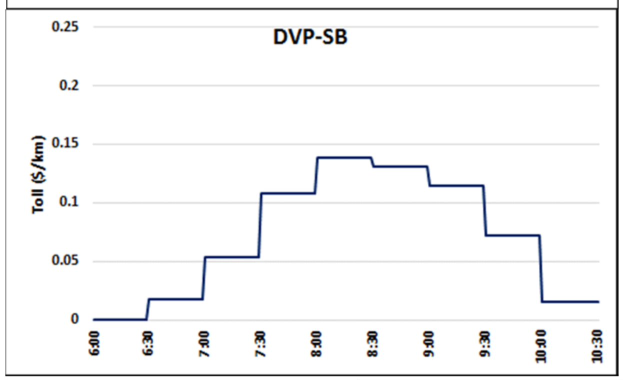
(II) Extended Tolling Scenario: GE, DVP, and 401 Express (Optimal Toll Structures)

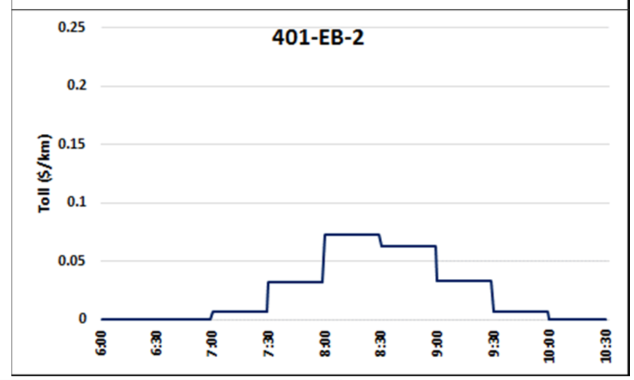


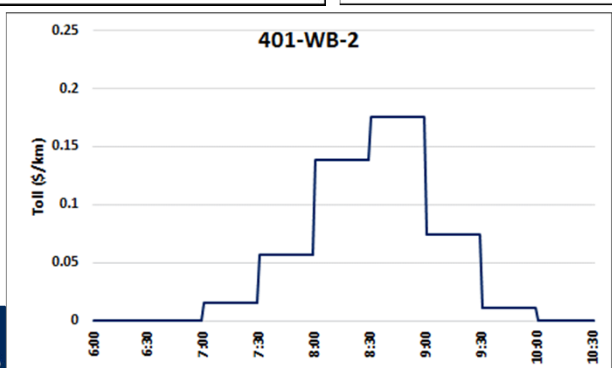


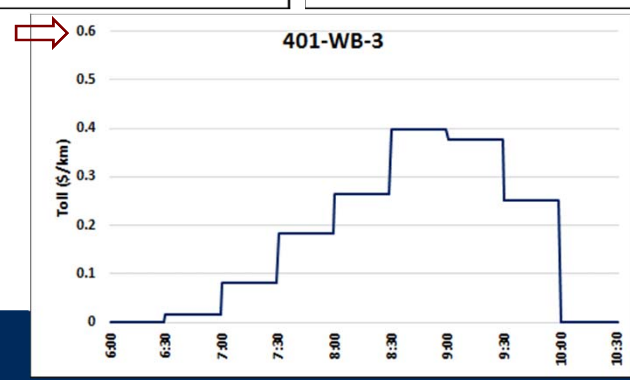












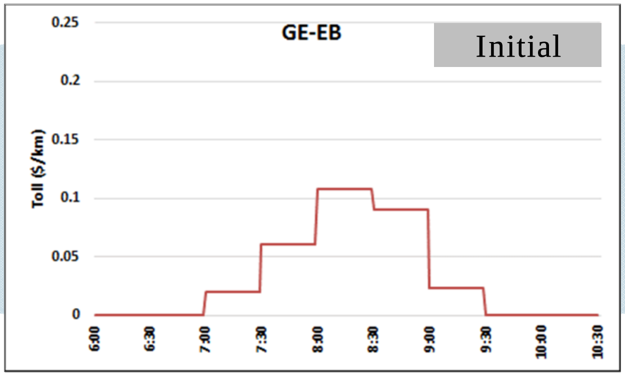
(II) Extended Tolling Scenario: GE, DVP, and 401 Express (Total Travel Time Savings)

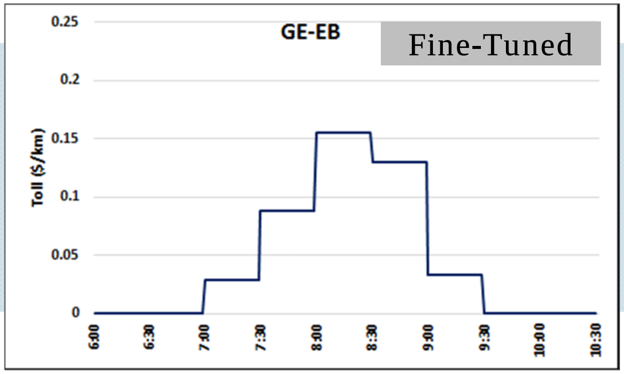
Network-Wide (2 million trips)	• 10,313 hr. (1.7%)*
Trips using tolled corridors (455,000 trips)	• 7831 hr. (2.91%)*
Trips using tolled routes (220,000 trips)	• 12,457 hr. (7.5%)*

** percentages are calculated relative to the total base case travel times of each group.*

(II) Extended Tolling Scenario: GE, DVP, and 401 Express (Corridor Analysis Ex. 1: GE-EB)

Toll Structure

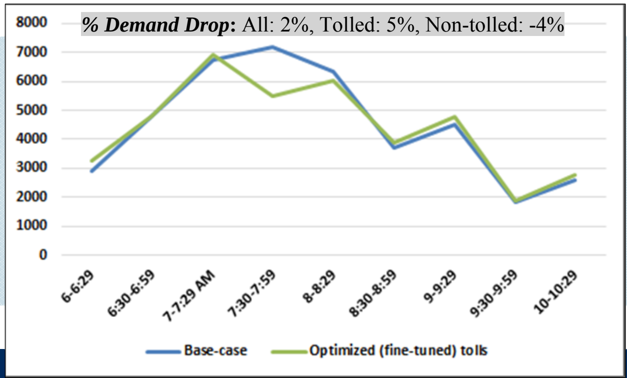


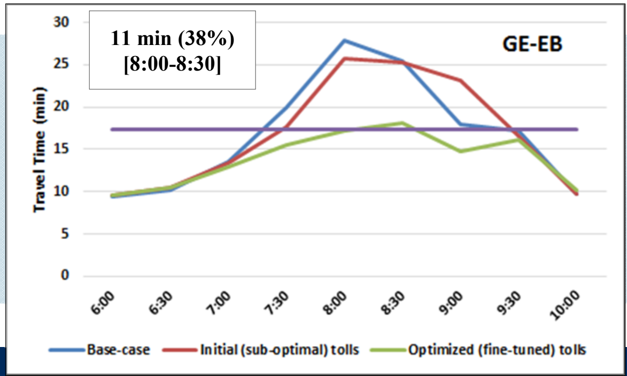


Utilization Level

Route	Base-Case	Initial Toll Structures	Fine-Tuned Toll Structures
GE-EB (*Tolled*)	7.20E8	7.39E8 ▲	7.58E8 ▲▲
GE-EB (*Parallel*)	9.48E8	9.69E8 ▲	9.57E8 ▲▼
GE-EB (*Corridor*)	**1.67E9**	**1.71E9** ▲	**1.71E9** ▲▲

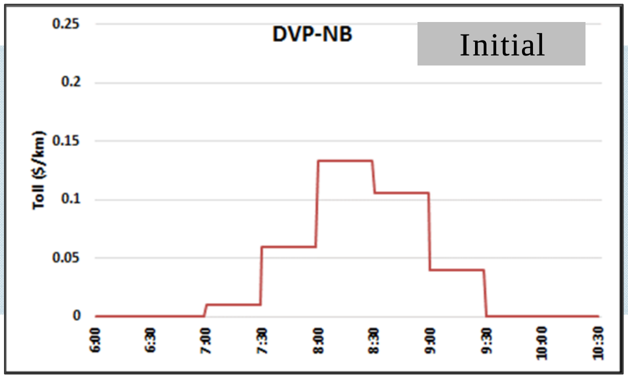
Tolled Route

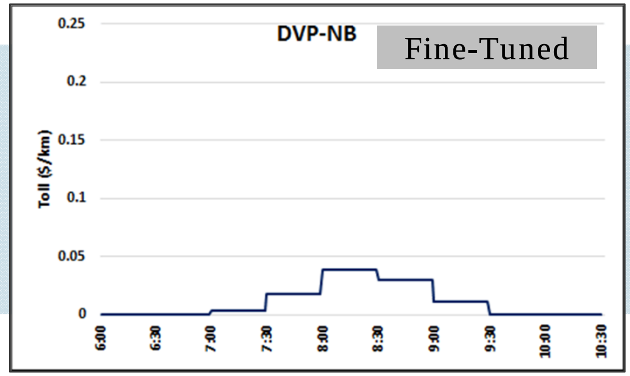




(II) Extended Tolling Scenario: GE, DVP, and 401 Express (Corridor Analysis Ex. 2: DVP-NB)

Toll Structure

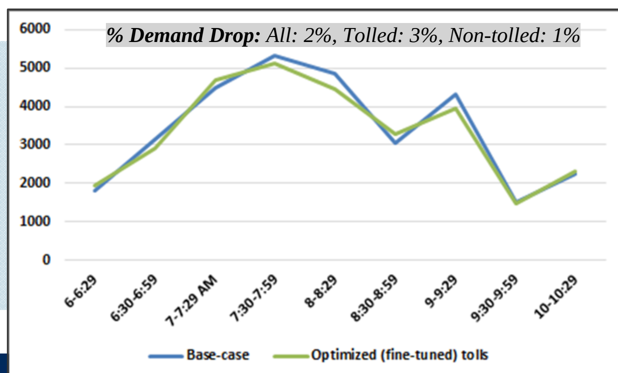


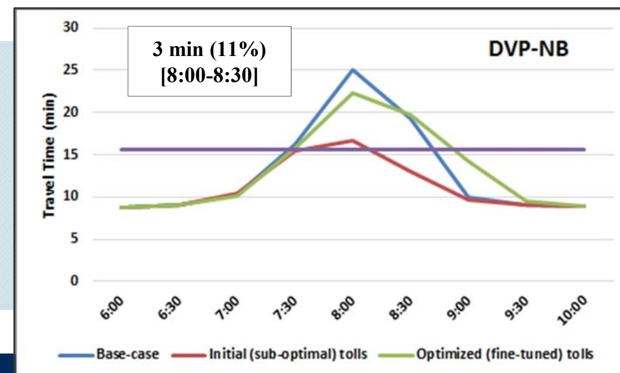


Utilization Level

Route	Base-Case	Initial Toll Structures	Fine-Tuned Toll Structures
DVP-NB (*Tolled*)	8.37E8	8.45E8 ▲	8.27E8 ▼▼
DVP-NB (*Parallel*)	4.18E8	4.16E8 ▼	4.18E8 ▲▲
DVP-NB (*Corridor*)	**1.25E9**	**1.26E9** ▲	**1.25E9** ▲▼

Tolled Route





(II) Extended Tolling Scenario: GE, DVP, and 401 Express (Annual Benefit-Cost Analysis)

<table>
<tr><th>Entity</th><th colspan="2">Overall Costs
($ Millions)</th><th colspan="2">Overall Benefits
($ Millions)</th><th>Benefit-Cost Ratio</th></tr>
<tr><td rowspan="3">Government (Producer)</td><td>Capital Cost:</td><td>Annual Cost:</td><td>Toll Revenues</td><td>Travel Time Savings</td><td rowspan="3">2.15
(after 1st year)</td></tr>
<tr><td>88.5</td><td>73.2</td><td>76.8</td><td>80.5</td></tr>
<tr><td colspan="2">Total Producer Costs:
<u>1st year</u>: 161.7
<u>After 1st year</u>: 73.2</td><td colspan="2">Total Producer Benefits: 157.3</td></tr>
<tr><td rowspan="3">Toll Payers (Consumers)</td><td colspan="2" rowspan="3">Toll Paid: 76.8</td><td>Travel Time Savings</td><td>Schedule-Delay Savings</td><td rowspan="3">1.61</td></tr>
<tr><td>97.2</td><td>26.4</td></tr>
<tr><td colspan="2">Total Consumer Benefits: 123.6</td></tr>
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Conclusions

- The optimal congestion pricing system developed in this research provides a comprehensive tool for optimal time-dependent tolling strategies determination and evaluation in large-scale networks.
- The results demonstrate that:
  - More benefits are attained from variable tolling due to departure-time rescheduling as opposed to re-routing only in case of flat tolling.
  - Widespread spatial re-distributions of traffic are observed across the regional network in response to tolling significant – yet limited – highways.
  - Optimal variable pricing that mirrors temporal and spatial congestion patterns induces departure-time re-scheduling and rerouting, resulting in improved average travel times and schedule-delays at all scales in addition to benefits to toll payers.

Conclusions

- Optimal toll levels intended to manage traffic demand are significantly lower than those intended to maximize toll revenues.
- Toll payers benefit from tolling even before toll revenues are spent.
- Tolling policies determined offer a win-win solution in which travel times and overall network performance are improved while raising funds to invest in sustainable transportation infrastructure.

Research General Contributions

Designing

A system for optimal congestion pricing determination and evaluation in large networks.

Developing

The different system modules for the GTA region.

Integrating

The large-scale computationally-intensive modules developed.

Key Contributions

- Developing the optimal congestion pricing system by integrating distinct modules.
- Incorporating a 3-level nested feedback structure in the large-scale optimal congestion pricing system (unlike one-shot approaches).
- Building, calibrating, and validating a large-scale DTA mesoscopic simulation model for the GTA, based on the most recent available data.
- Simulating commuters' departure-time choices through an econometric model that considers drivers' attributes.
- Deriving the initial toll structures based on a conceptual model of dynamic congestion pricing (the Bottleneck Model).
- Applying a GA to adjust/fine-tune the initial toll structures for optimal network performance.
- Distributing the computations of the GA on a parallel computing cluster.
- Implementing the (full) optimal congestion pricing system through an extended scenario of tolling multiple highways in the GTA region.

Future Research

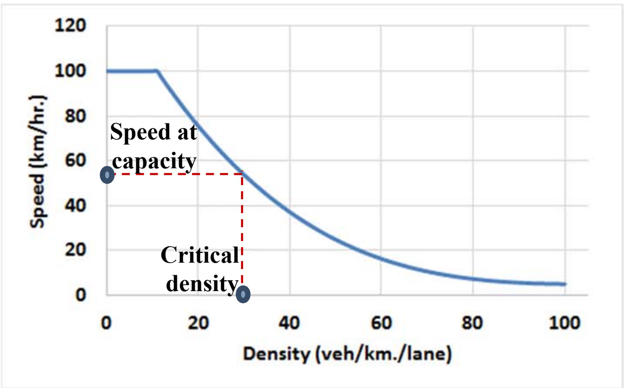
1. Considering mode-choice and other possible behavioural responses of pricing.
2. Including transit demand and integrating the transit network details along with a transit assignment module.
3. Including truck demand.
4. Re-estimating the departure-time choice model based on joint RP (TTS data) and SP data surveys incorporating toll information.
5. Developing an online toll regulator to update the optimal tolls based on real-time traffic measurements.

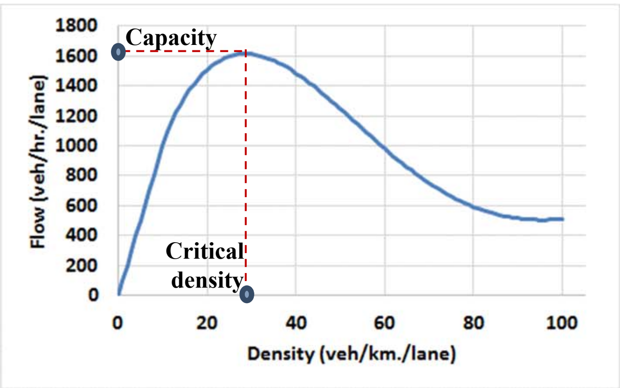
Thank you

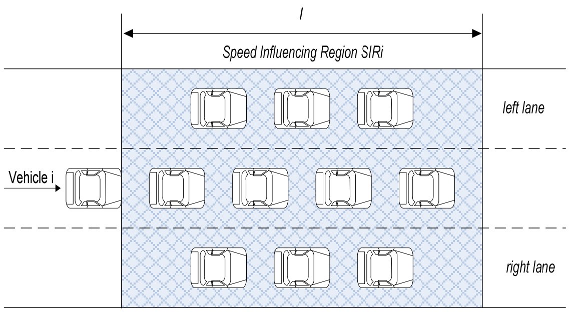
Questions?

Traffic Simulation in DynusT

- Anisotropic Mesoscopic Simulation (AMS).
- Speed Influencing Region (SIR) = 240 Metres.
- Speed of vehicle *i* is determined using a macroscopic v-k relationship based on the density in SIR*i*.







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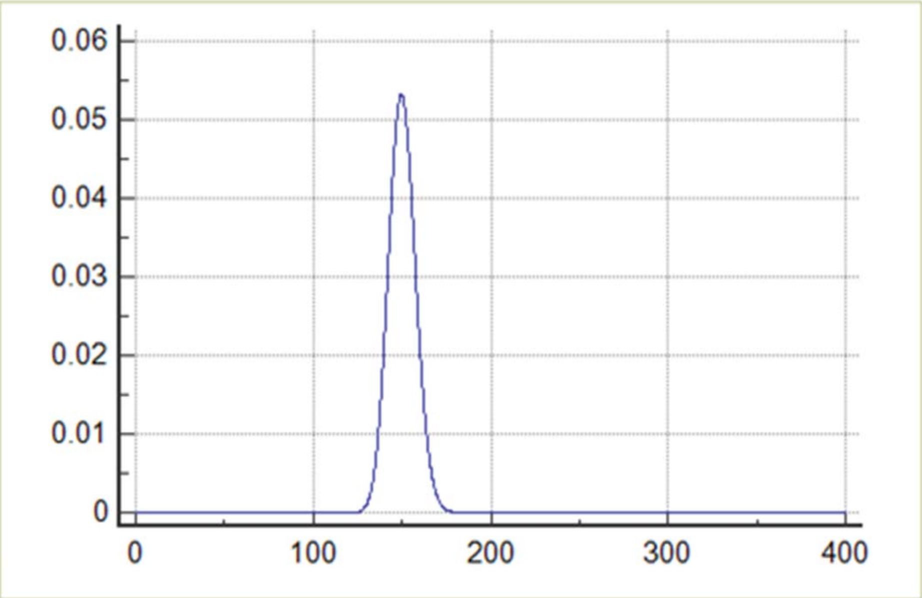
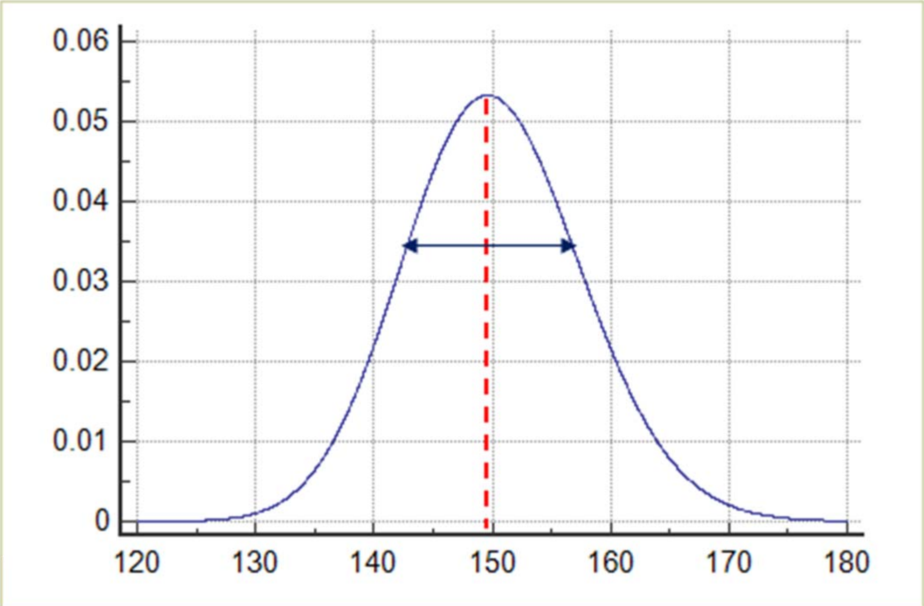
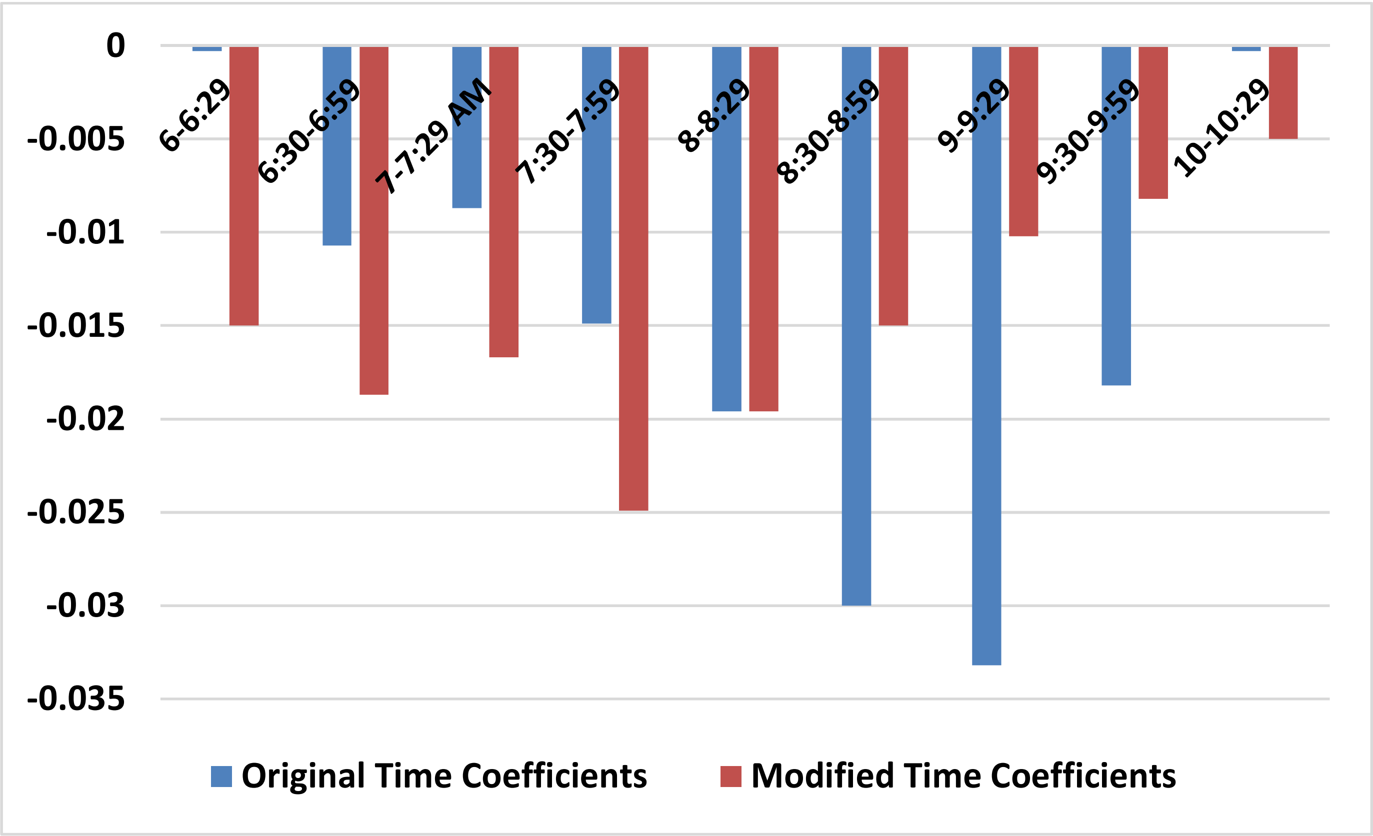
Desired Arrival Time Distribution

- X is lognormally distributed → ln(X) has a normal distribution with Mu and Sigma.
- ln(X) = (Mu + Sigma * Z) → X= $e^{(Mu + Sigma * Z)}$
- Mu = ln(150) and sigma = 0.05 (in ln(min)).





Original vs. Modified IVTT Coefficients



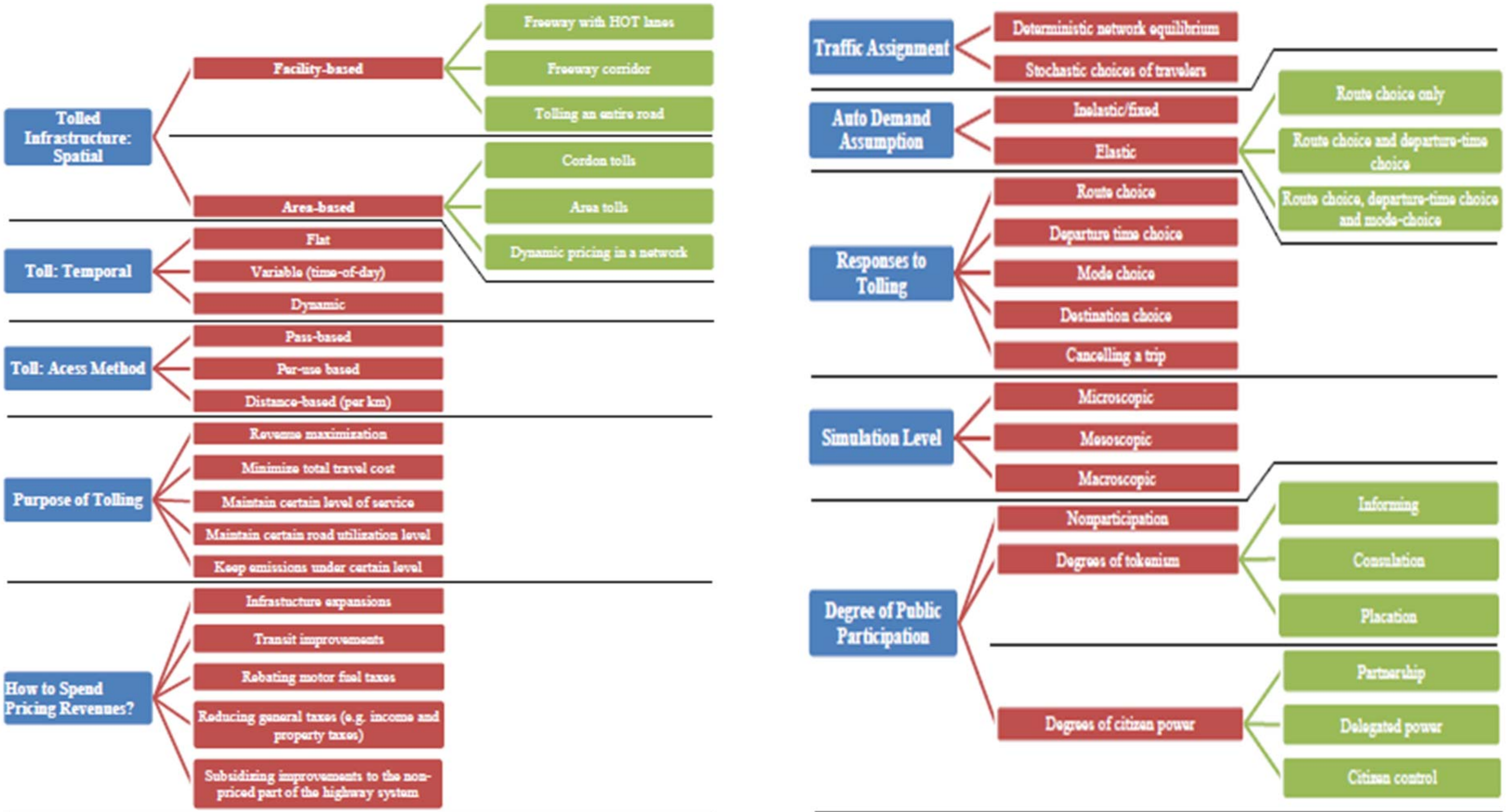
Congestion Pricing Policies: Objectives and Impacts

Pricing Policy	Objectives/Impacts	Example(s)
Cordon tolls	Reduce downtown traffic	– London Congestion Pricing – Stockholm Congestion Pricing
HOT lanes	Encourage carpooling	– I-15 HOT Lanes, San-Diego, CA – I-394 in Minnesota – SR-167 in Seattle
For Profit (Monopoly) pricing	Maximize profits	– ETR 407 (Express Toll Route)
Variable tolls	Control congestion (temporal and/or spatial distribution)	– Singapore Electronic Road Pricing
– **Distance-based fees** – **Pay as you drive (PAYD) insurance**	– Reduce automobile use – Reduce emissions	– "MileMeter", Texas, US – "Real Insurance PAYD", Australia
Bottleneck pricing	Reschedule departure-time (without altering route-choice, mode-choice, or miles driven)	----

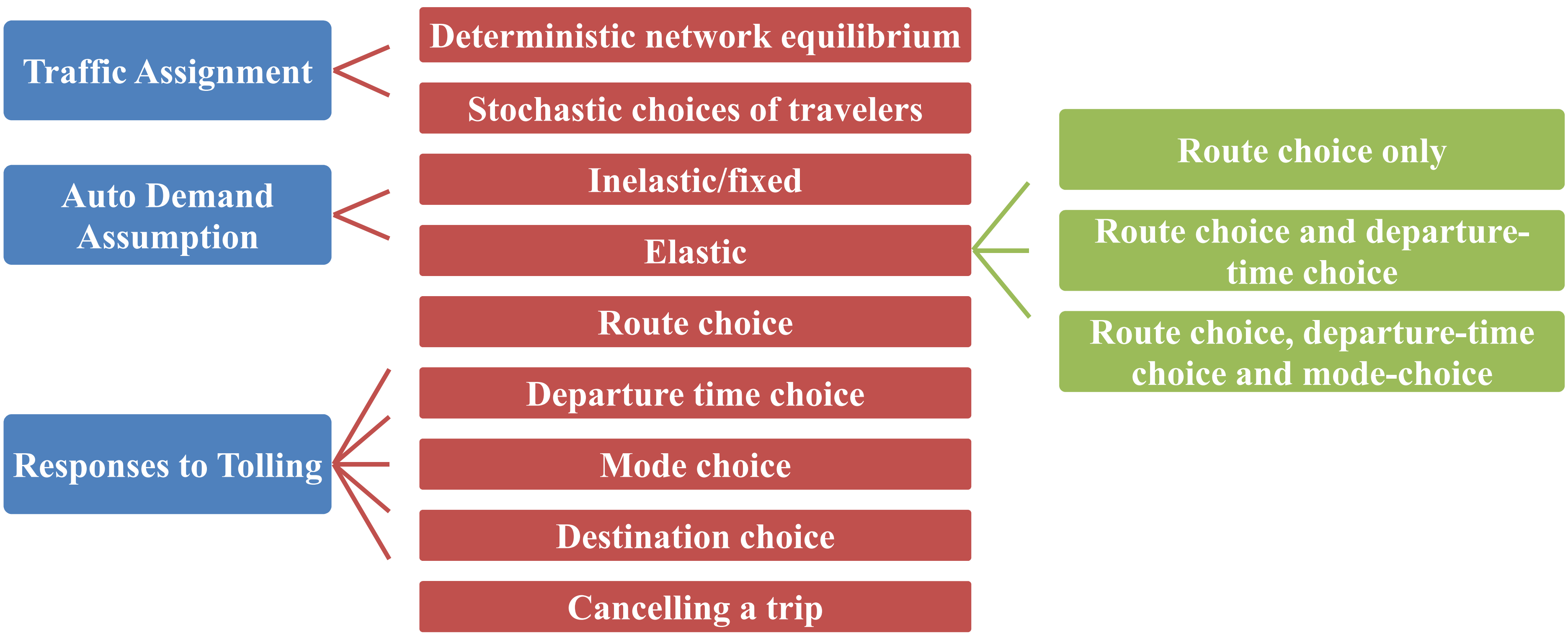
Congestion Pricing Decision Making Process

Operations Side

Analysis Side



Congestion-Pricing Decision Making Process – *Analysis Side*



Congestion-Pricing Decision Making Process – *Analysis Side*

- **Simulation Level**
  - Microscopic
  - Mesoscopic
  - Macroscopic
- **Degree of Public Participation**
  - Nonparticipation
  - Degrees of tokenism
    - Informing
    - Consultation
    - Placation
  - Degrees of citizen power
    - Partnership
    - Delegated power
    - Citizen control

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Congestion-Pricing Decision Making Process – *Operations Side*

- **Tolled Infrastructure: Spatial**
  - **Facility-based**
    - **Freeway with HOT lanes**
    - **Freeway corridor**
    - **Tolling an entire road**
  - **Area-based**
    - **Cordon tolls**
    - **Area tolls**
    - **Dynamic pricing in a network**

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Congestion-Pricing Decision Making Process – *Operations Side*

Toll: Temporal

- Flat
- Variable (time-of-day)
- Dynamic

Toll: Acess Method

- Pass-based
- Per-use based
- Distance-based (per km)

Congestion-Pricing Decision Making Process – *Operations Side*

Fee Collection Options

- **Toll Booths**
- **Pass**
- **Electronic Tolling**
- **Optical Vehicle Recognition**
- **GPS**

Congestion-Pricing Decision Making Process – *Operations Side*

Purpose of Tolling

- **Revenue maximization**
- **Minimize total travel cost**
- **Maintain certain level of service**
- **Maintain certain road utilization level**
- **Keep emissions under certain level**

Congestion-Pricing Decision Making Process – *Operations Side*

How to Spend Pricing Revenues?

- **Infrastucture expansions**
- **Transit improvements**
- **Rebating motor fuel taxes**
- **Reducing general taxes (e.g. income and property taxes)**
- **Subsidizing improvements to the non-priced part of the highway system**

International Experience

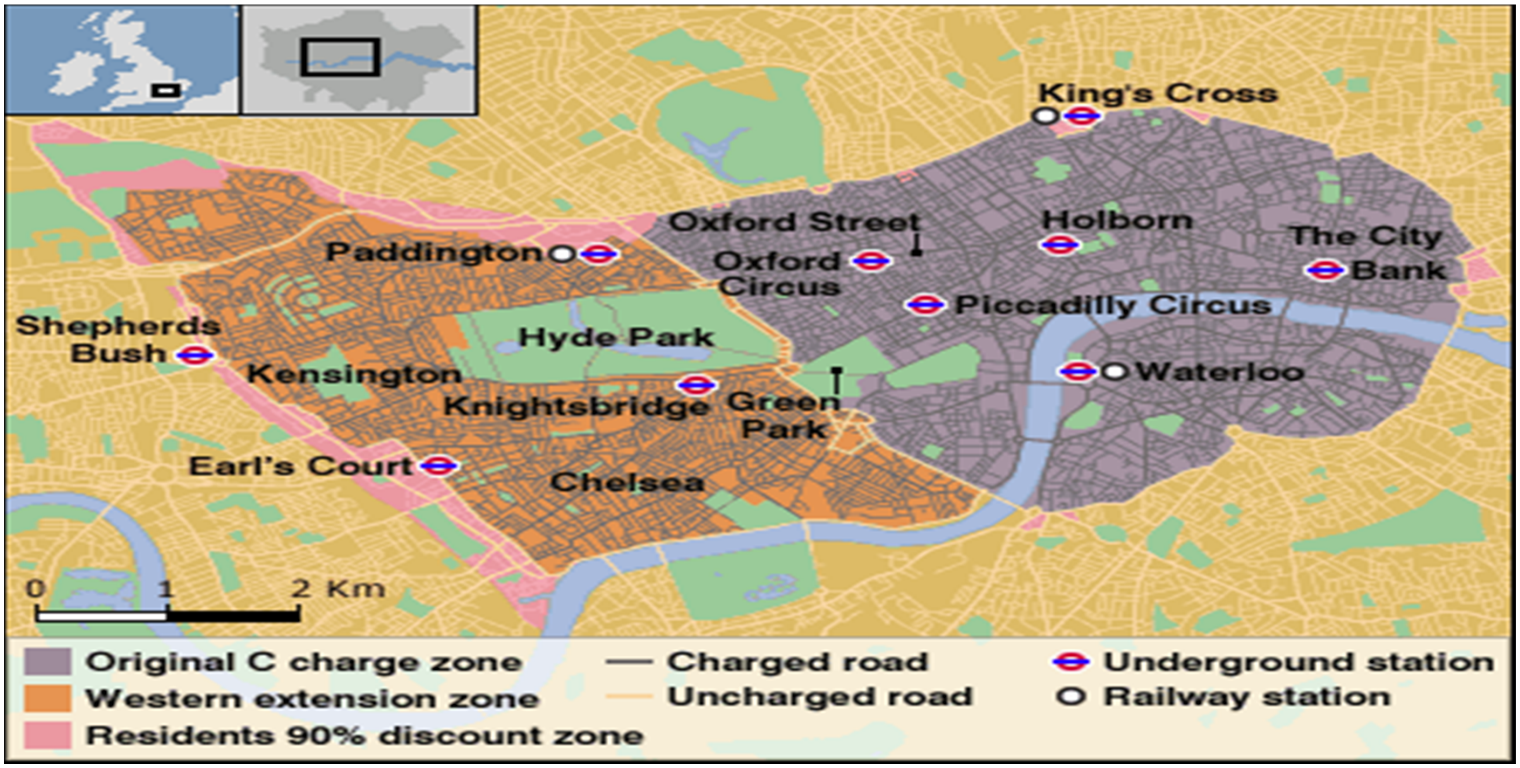
USA, UK, France, Norway, Sweden, Germany, Switzerland, Singapore, and Australia have implemented major road pricing projects.

London Congestion Pricing

- In service since 2003.
- The first congestion pricing program in a major European city.
- £11.5 daily cordon fee (flat price) for driving in "Central London Congestion Pricing Zone" during weekdays (from 7am to 6pm) (one time per chargeable day).
- Bus and taxi service improved.
- Accidents and air pollution declined in city center.
- After 1 year of cordon tolls and during charging:
  - Traffic circulating within the zone decreased by 15%.
  - Traffic entering the zone decreased by 18%.
  - Congestion (measured as the actual minus the free-flow travel time per km) decreased by 30% within the zone.

London Congestion Pricing

The Central London Congestion Pricing Zone



Stockholm Congestion Charge

- Public support increased after a 7-months trial in 2006.
- Charge based on time of day, and up to a max charge per day.
- Vehicles entering “Stockholm City Center” on weekdays (from 6:30am to 6:30pm) charged $1.29 to $4.11 per trip, with a max daily charge of $8.
- Traffic volumes reduced by ~25%.
- Public transit ridership increased by 40,000 users per day.

Stockholm Congestion Charge

- Uses electronic transponders to bill cars.
- Non-equipped cars are photographed, matched to a motor vehicle database and then billed.

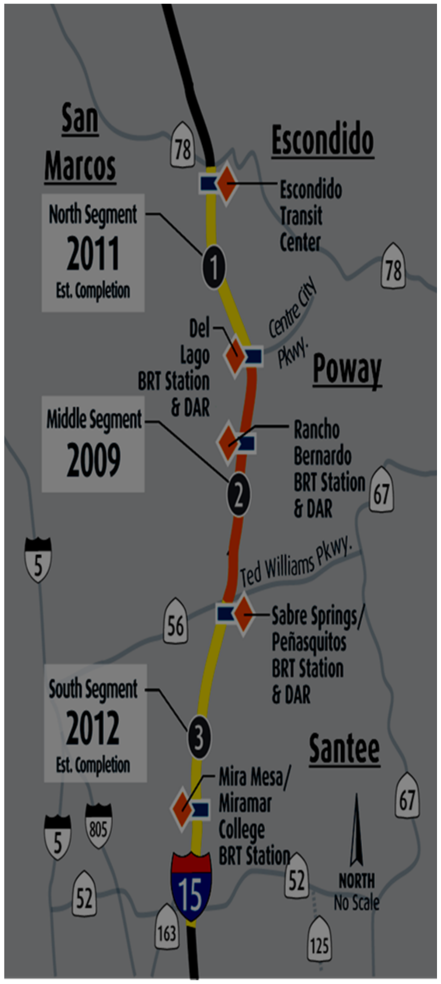
Time of day	Tax
00:00 – 06:29	0 SEK
06:30 – 06:59	10 SEK
07:00 – 07:29	15 SEK
07:30 – 08:29	20 SEK
08:30 – 08:59	15 SEK
09:00 – 15:29	10 SEK
15:30 – 15:59	15 SEK
16:00 – 17:29	20 SEK
17:30 – 17:59	15 SEK
18:00 – 18:29	10 SEK
18:30 – 23:59	0 SEK

I-15 HOT Lanes, San Diego, CA

- First significant congestion pricing project (i.e., price mirrors congestion).
- Implemented in 1996 along the 13 km HOV section of I-15 in San Diego. The HOT lanes on I-15 are now about 32 km long.
- Convert HOV to HOT; solo drivers pay tolls to use HOV during peak periods.
- In 1998, automated and dynamic pricing scheme.

I-15 HOT Lanes, San Diego, CA

- Toll levels determined from congestion level to maintain “free-flow” conditions in the HOV lane.
- Tolls updated every 6 minutes ($0.5 to $4) (closed-loop regulator).
- Toll level displayed on real-time sign.
- Success in congestion minimization.



407 ETR (Express Toll Route)

- Multi-lane, electronic Hwy running 107 km across the top of the GTA from HYWY 403 (in Oakville) to HYWY 48 (in Markham).
- Constructed in a partnership between “Canadian Highways International Corporation” and the Province of Ontario.
- Currently owned by 407-ETR International Inc.

407 ETR (Express Toll Route)

- Current Rate Chart:

Regular Zone Rate		
Peak Period	*Mon-Fri: 6am-7am, 9am-10am, 3pm-4pm, 6pm-7pm*	28.30¢ /km
Peak Hours	*Mon-Fri: 7am-9am, 4pm-6pm*	30.20¢ /km
Light Zone Rate		
Peak Period	*Mon-Fri: 6am-7am, 9am-10am, 3pm-4pm, 6pm-7pm*	26.90¢ /km
Peak Hours	*Mon-Fri: 7am-9am, 4pm-6pm*	28.70¢ /km
Midday Rate (entire highway)	*Weekdays 10am-3pm*	24.06¢ /km
Midday Rate (entire highway)	*Weekends & Holidays 11am-7pm*	22.25¢ /km
Off Peak Rate (entire highway)	*Weekdays 7pm-6am, Weekends & Holidays 7pm-11am*	19.35¢ /km

- Speeds on Hwy 407 ~ double free Hwys.
- High level of user satisfaction.
- Monopoly price!