ANALYSIS OF A PROBE-BASED VARIABLE SPEED LIMIT SYSTEM - A SIMULATION STUDY

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Outline of Presentation

- Introduction of VSL
- Problem Statement
- Objective of the Study
- Overview of the Methodology
  - Study area
  - Framework
- Results
- Conclusions and Future Work

Introduction

Variable Speed Limit:

- **Is an** ITS solution that enable dynamic change of posted speed limit w.r.t changing traffic condition.

- Objectives: smoothing of traffic flow and improvement in safety.

- **Example: In the case of a bottleneck w**hen VSL system is activated, it lower**s** the average speed, thereby retaining the traffic inflow entering the jammed section and delaying the activation of a downstream bottleneck.

Where Variable Speed Limit?

Bad Weather

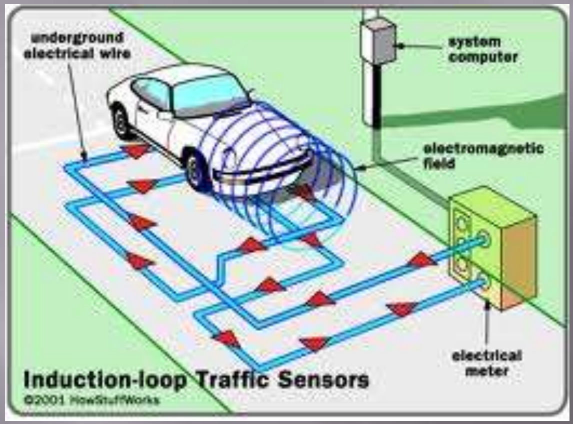
Work Zones

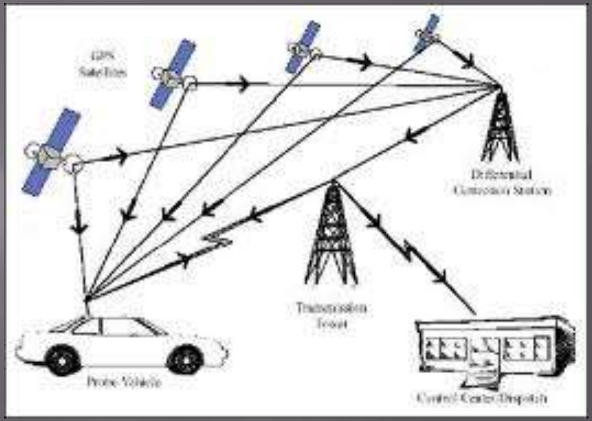
Congestion

Accident

Problem Statement

- Effective VSL system needs a high coverage of vehicular detectors.
- With current advancements in positioning, information and communication technologies, any vehicle that carries a GPS enabled device can act as a mobile sensor able to provide cost-effective and reliable traffic data.





Detector :

Need extensive coverage
Expensive!!!
Provides speed information in the vicinity.

Probe Vehicle :

GPS enabled device
Low cost
Excellent coverage
Can easily detect shockwave formation

Problem Statement

- There is a need, for a cost-effective solution for gathering reliable real traffic data that can also be used as input to advanced traffic control systems.

- **This research examines if speed data collected from vehicular probes can be used as input to design effective VSL**

Objective of the Study

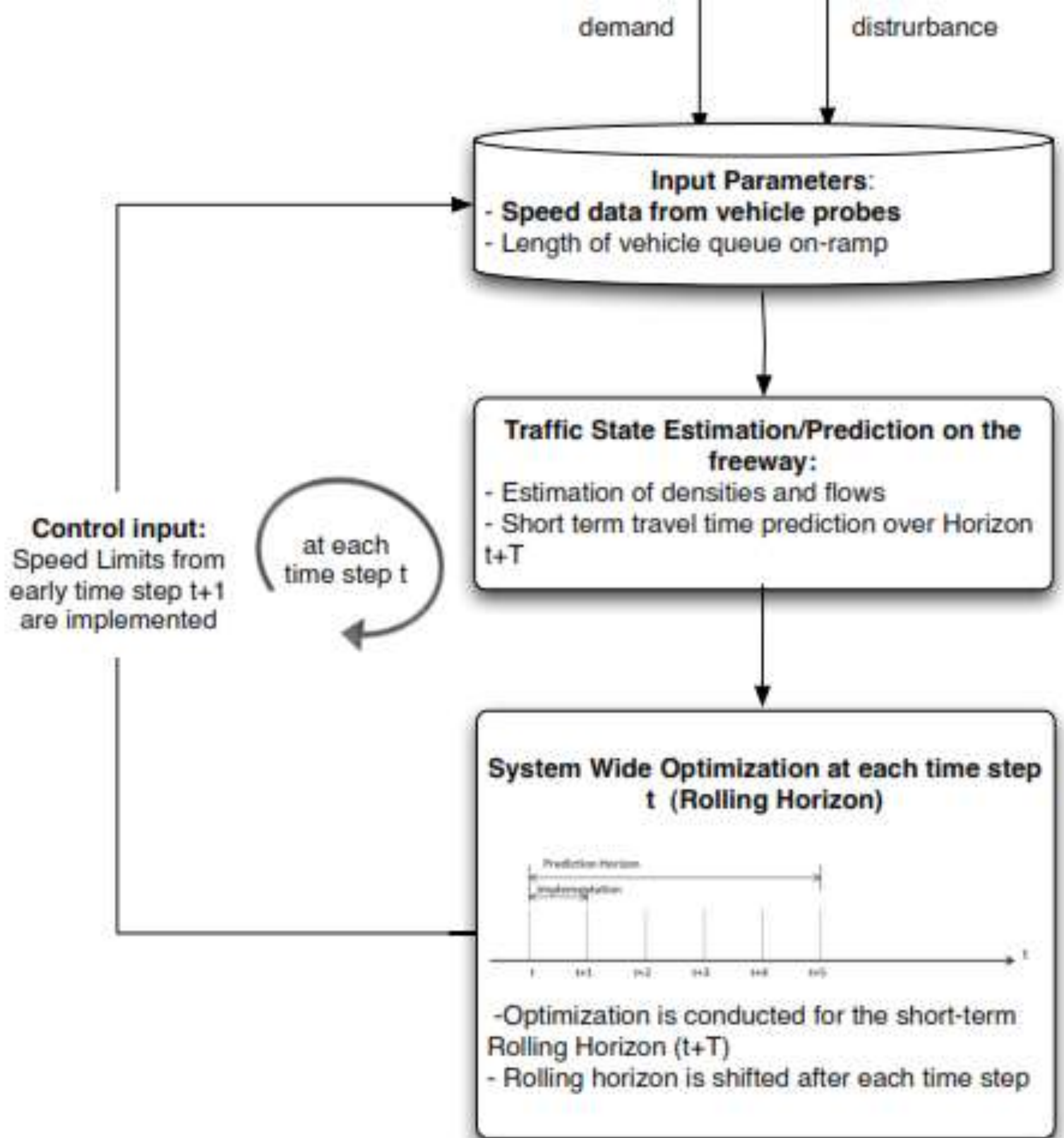
- To evaluate a candidate variable speed limit (VSL) system that takes the space mean speeds (SMSs) from probe vehicles (example connected vehicle or vehicle with a GPS enabled device) as its main input.

- To analyze the improvements that may result by comparing this probe-based control algorithm to the traditional algorithm that uses data from point detectors.

- To carry intensive sensitivity analysis to investigate the impact of the increased proportion of vehicles carrying GPS-enabled devices and the types of vehicles acting as probes for the proposed probe-based algorithm.

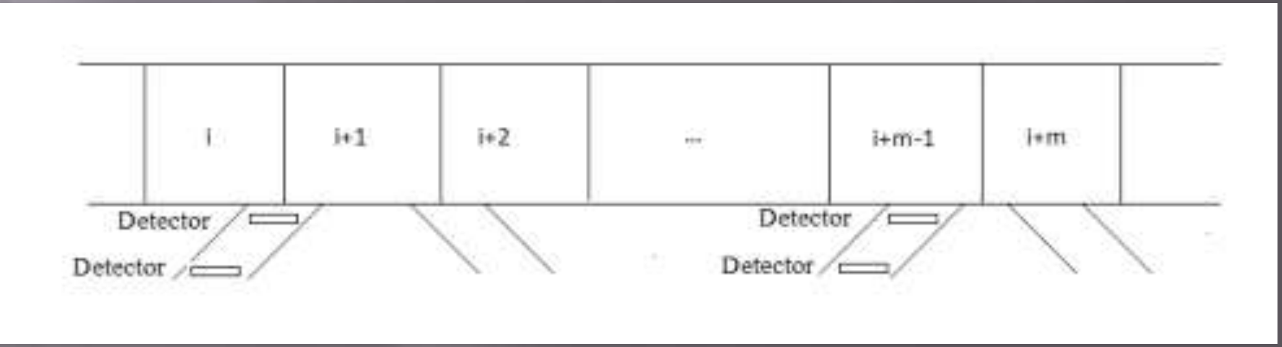
Overview of the Methodology

The Model Predictive Control (MPC) Framework



Traffic Input:

- Using MPC approach, the algorithm used SMS data directly extracted from vehicle probes as main input.
- Paramics microsimulator was used to model the study area, monitor the demand and extract traffic data from the simulated probe vehicles.
- One check-in traffic detector and one check-out detector were installed on the on-ramps to capture the queue length and the flow entering the freeway.



Traffic State Estimation:

- Van Aerde's traffic flow model was used to convert the SMS to densities and flows for each section.

$$k = \frac{1}{C_1 + \frac{C_2}{U_f - U} + C_3 * U} \qquad q = \frac{U}{C_1 + \frac{C_2}{U_f - U} + C_3 * U}$$

Where: U - average SMS speed

C_1 - fixed distance headway constant (km)

C_2 - first variable distance headway constant (km^2/h)

C_3 - second variable distance headway constant (h)

U_f - free speed (km/h)

U_c - speed at capacity (km/h)

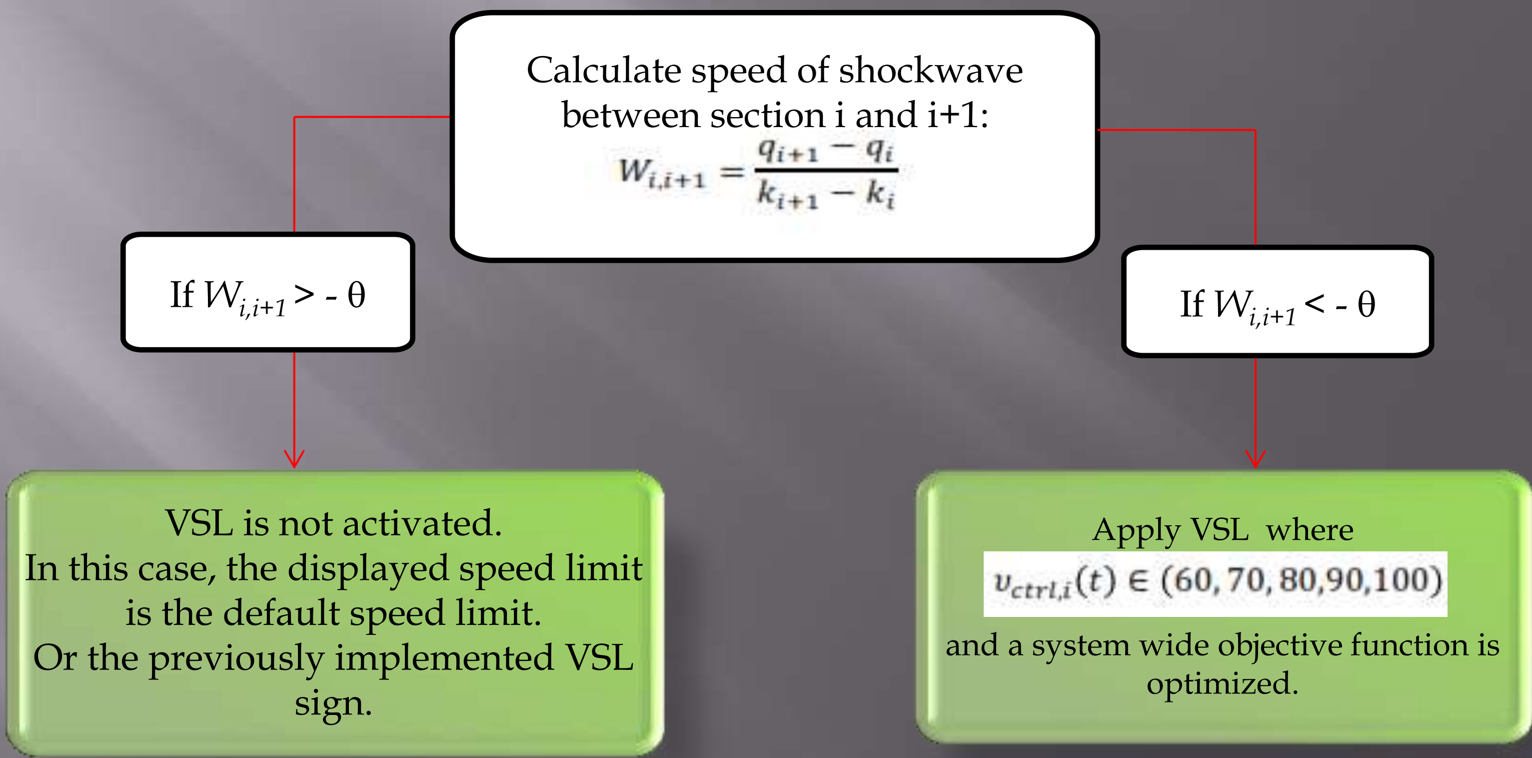
q_c - flow at capacity (veh/h)

k_j - jam density (veh/km)

m - constant used to solve for three headway constants (h/km).

Checking possible occurrence of shockwave:

- The system calculates the speed of the shockwave between sections *i*+1 and *i*, , starting with the downstream and working towards the upstream ones



Traffic State Prediction:

- Mean density using conservation law:

$$k_i(t+1) = k_i(t) + \frac{T}{L\lambda}\left(q_{i-1}(t) - q_i(t)\right)$$

- Evaluation of mean speed:

$$v_i(t+1) = v_i(t) + \frac{T}{\tau}\Big(V\big(k_i(t)\big) - v_i(t)\Big) + \frac{T}{L} v_i(t)\big(v_{i-1}(t) - v_i(t)\big) - \frac{\eta T}{\tau L}\frac{k_{i+1}(t) - k_i(t)}{k_i(t) + \kappa}$$

Where: $T = 30$ (sec) - estimation time step size used in this work

$L = 8$ (km) - total length of the highway stretch

$\tau = 0.005$ (h) - constant that indicates the drivers' swiftness (large τ indicates slower reaction) η - speed anticipation term parameter (km^2/h).

$\kappa = 40$ (veh/km/lane) - speed anticipation term parameter

Traffic State Prediction……….contd.

- Evaluation of mean speed:

$$v_i(t+1) = v_i(t) + \frac{T}{\tau}\left(V\left(k_i(t)\right) - v_i(t)\right) + \frac{T}{L} v_i(t)\left(v_{i-1}(t) - v_i(t)\right) - \frac{\eta T}{\tau L}\frac{k_{i+1}(t) - k_i(t)}{k_i(t) + \kappa}$$

- Where:

$V\left(k_i(t)\right)$ is presented as:

$$V\left(k_i(t)\right) = \min\left((1+\alpha)v_{ctrl,i}(t), v_{free} exp\left[-\frac{1}{a}\left(\frac{k_i(t)}{k_{crit}}\right)^a\right]\right)$$

$v_{ctrl,i}(t)$ - VSL value implemented on segment i at time step t

v_{free} - free-flow speed of traffic

k_{crit} - critical density;

a - parameter of the fundamental diagram, taken to be 1.867 (Hegyi, 2004)

$(1+\alpha)$ - non-compliance factor, where α is taken to be 0.05

On Ramp Queue Length Prediction:

- For network sections that include on-ramps, the length of the queue for the next time step $w_r(t+1)$ is obtained as the current queue, $w_r(t)$, plus the demand, $d_r(t)$, minus the outflow, :

$$\omega_r(t+1) = \omega_r(t) + T(d_r(t) - q_r(t))$$

- Demand and outflow can be extracted from the simulation model by placing two detectors on each on-ramp.
- It is important to note that $w_r(t)$ is indirectly a function of the control value of VSL at time step t as the number of vehicles that are discharged from the on-ramps to the freeway depends on the capacity of the freeway at time t, which in turn is dependent on the posted speed limit at time t.

System wide optimization

Objective Function : Total Time Spent (TTS)

$$TTS(t) = T\sum_{t=1}^{Np}\left\{\sum_{i=1}^{Number\ of\ sections} k_i(t)L\lambda + T\sum_{r=1}^{Number\ of\ on-ramps}\omega_r(t)\right\} + \alpha_{speed}\sum_{t=1}^{Nc}\sum_{i=1}^{Number\ of\ activated\ VSL}\left(\frac{\upsilon_{ctrl,i}(t)-\upsilon_{ctrl,i}(t-1)}{\upsilon_{free}}\right)$$

subject to: $|\upsilon_{ctrl,i}(t+1)-\upsilon_{ctrl,i}(t)| \leq 10,$

$|\upsilon_{ctrl,i}(t)-\upsilon_{ctrl,i+1}(t)| \leq 10.$

where: $k_i(t)$ - section density on segment i at time t transformed from SMS, which are estimated from probes,

L - length of the segment,

λ - number of lanes on the highway,

$w_r(t)$ - queue on ramp r,

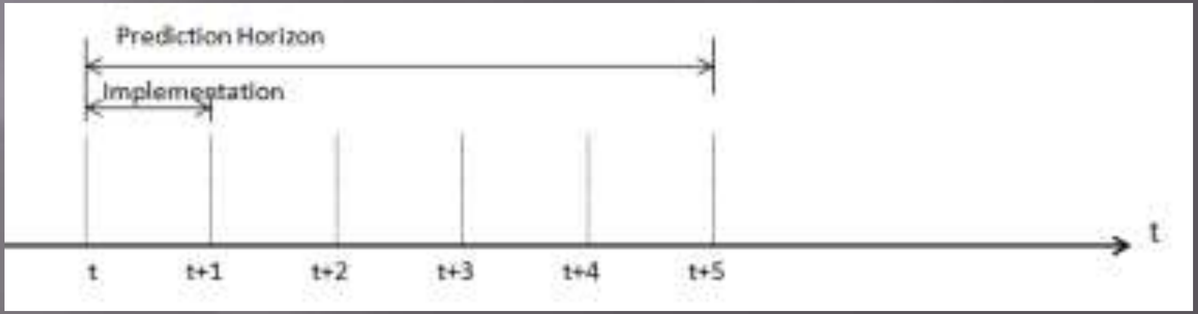
$\upsilon_{ctrl,i}(t)$ - control variable to be determined related to the VMS value indicating the speed limit on section i at time t,

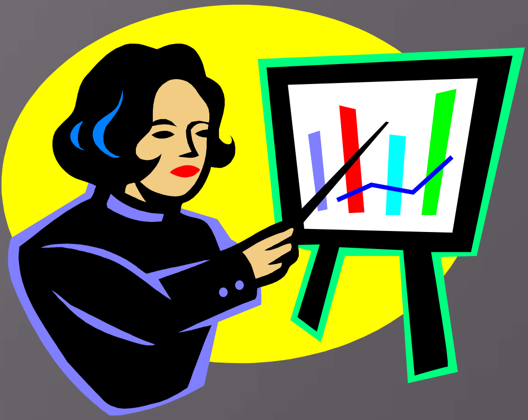
υ_{free} - free flow speed of traffic, taken to be 100 km/h, and

α_{speed} = 2 -a non-negative parameter, expressing the importance of each term (Hegyi et al., 2005).

Control Action

- A rolling horizon control strategy will be adopted for the control action.
- This means that only the anticipated decision variables corresponding to the early horizons will be considered final and implemented.
- The remaining steps will be re-estimated in the succeeding steps in a rolling horizon fashion as new observations become available.





RESULTS

Study Area

High incident occurrence.

Growing congestion.

Major access to Calgary Downtown and Calgary International Airport.

Forecast: fastest growing area over next sixty years.

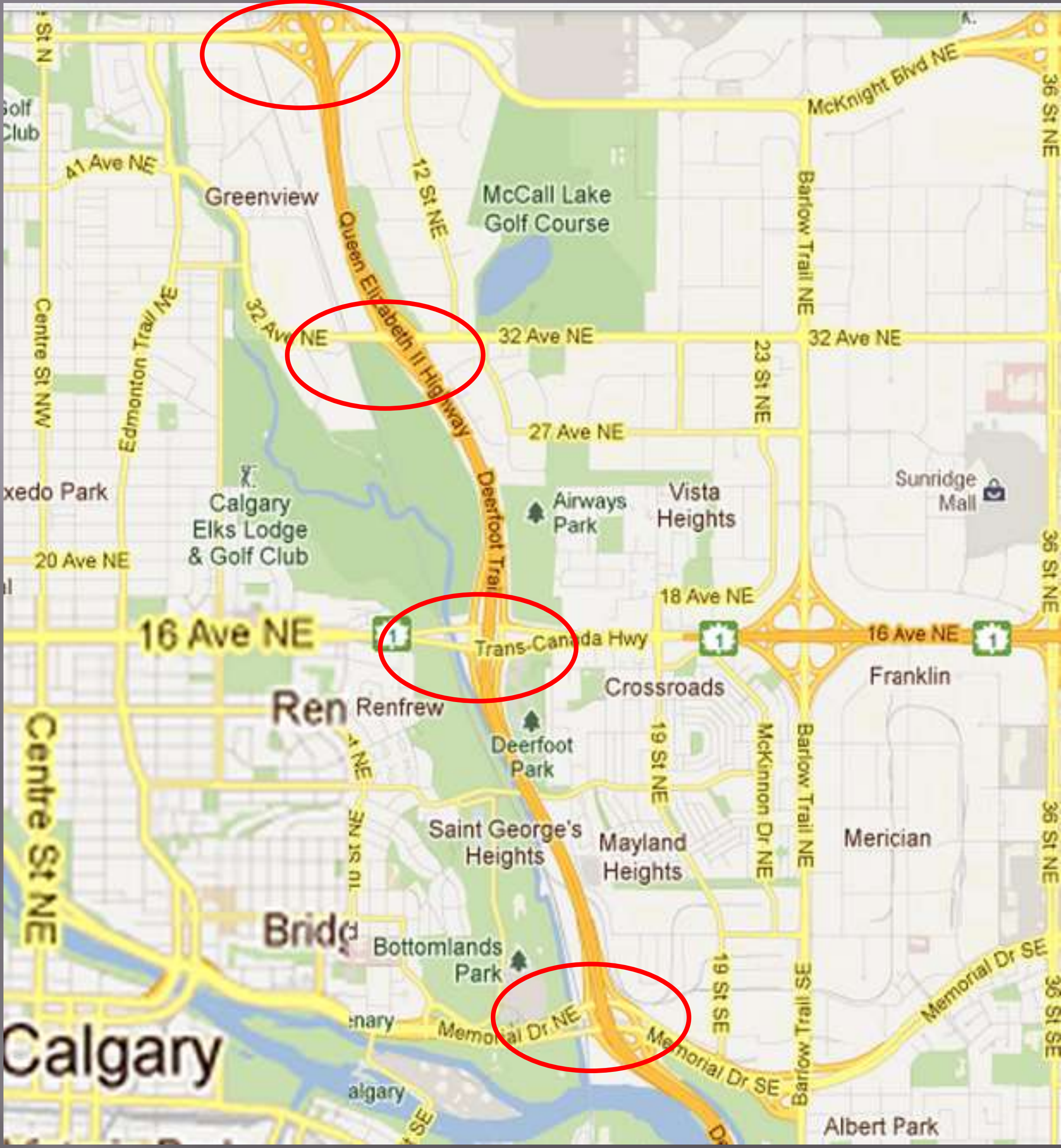


Figure : Deerfoot Trail

Examined Scenario:

- Traffic demand under thee levels of traffic conditions (i.e., loading scenarios of 80%, 100% and, 120%);
- Performance of the algorithm under non-recurrent traffic conditions corresponding to one lane blockage;
- Probe penetration rates (number and composition of probe vehicles in the network) of 2.8%, 6% 10%, 20% and, 40%);
- Probe data collection frequencies of 1, 5 and 10 seconds; and
- Performance of the probe-based VSL compared to the detector-based VSL.

Measures of Effectiveness (MOEs):

- Freeway link delay (sec/veh),
- Freeway link speed variance (km/h),
- Freeway flow (veh/h), and
- Freeway average speed (km/h).

All simulation runs were conducted for 1 hour and 15 minutes (AM peak for southbound traffic) with first fifteen minutes was a warm-up period. All reported runs correspond to the average of 10 Paramics runs with different random seeds.

Results

- Recurrent Congestion (20% Probe)

Scenario Description		Mainline Delay (sec/veh)	Traffic Flow (veh/h)	Average Speed (km/h)	Variance of Speed (km/h)
80% loading	Uncontrolled Case	51	4001	98	9.59
	VSL Case	51	3975	93	9.56
	Change (%)	0.0%	-0.6%	-5.1%	-0.3%
100% loading	Uncontrolled Case	335	4315	75	24.2
	VSL Case	317	4320	73	23.9
	Change (%)	-5.4%	0.1%	-2.7%	-1.24%
120 % loading	Uncontrolled Case	503	4223	66	29.8
	VSL Case	492	4245	63	30.6
	Change (%)	-2.2%	0.5%	-4.5%	2.7%

Summary

- Similar to their detector based counterparts, probe-based VSL systems were shown to be effective for only a limited range of traffic conditions.
- When the freeway conditions are not close to critical (80%), the role of VSL is mainly confined to reducing the speeds and their variance.
- The probe-based VSL was efficient at improving traffic flow for nearly saturated (100%) and saturated (120%)traffic conditions.

Results

- Non-Recurrent Congestion (20%probe with a lane blockage scenario)

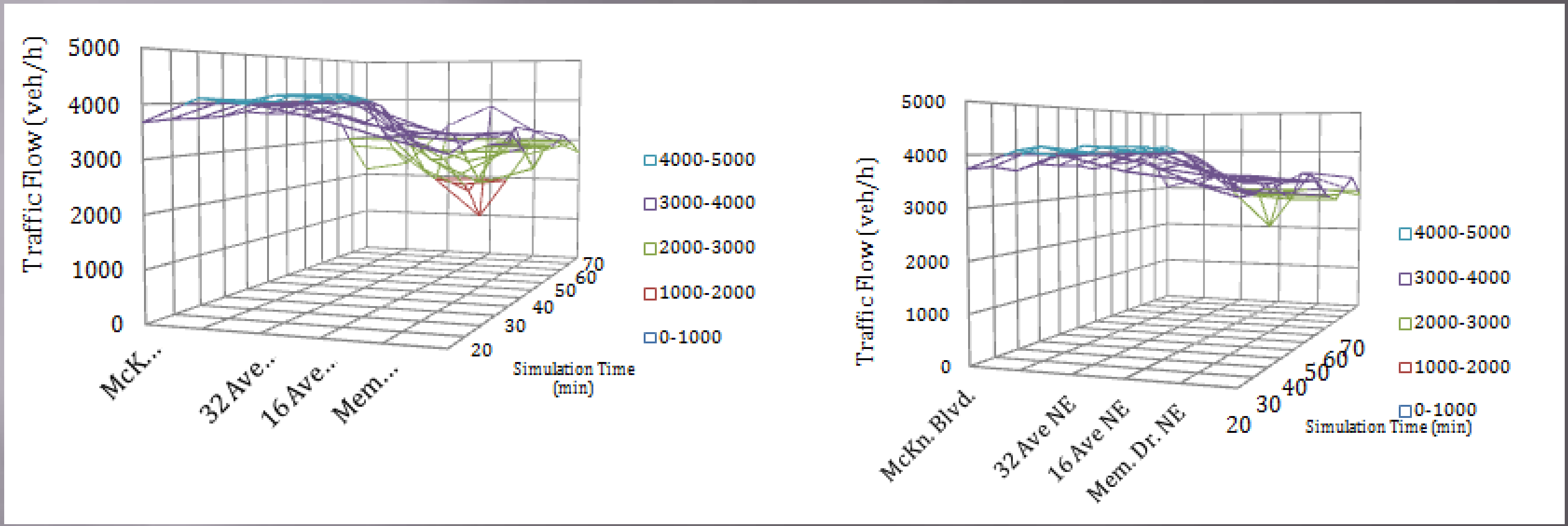
Scenario Description		Mainline Delay (sec/veh)	Traffic Flow (veh/h)	Average Speed (km/h)	Variance of Speed (km/hr)
80% loading	Uncontrolled Case	689	3241	68	29.8
	VSL	491	3502	68	27.2
	% change	-28.74%	8.05%	0.00%	-8.72%
100 % loading	Uncontrolled Case	929	3123	57	35.6
	VSL	855	3319	53	33.6
	% change	-7.97%	6.28%	-7.02%	-5.62%
120% loading	Uncontrolled Case	964	3072	57	36.1
	VSL	886	3249	52	34.7
	% change	-8.09%	5.76%	-8.77%	-3.88%

Summary

- This effectiveness was consistent for all traffic loading levels.

Results

Traffic flow distribution under "no control" (left) and "VSL conditions" (right) at 80% demand



Summary

- The figure shows that the probe-based VSL substantially suppressed the variation of the traffic flow value.

Results

Probe penetration rate sensitivity analysis for recurrent congestion (120% loading)

Scenario Description		Mainline Delay (sec/veh)	Traffic Flow (veh/h)	Average Speed (km/h)	Variance of Speed (km/h)
Uncontrolled case		503	4223	67	29.8
VSL	2.8% probes	666	3743	57	37
	6% probes	756	3578	52	32.7
	10% probes	497	4218	63	29.2
	20% probes	492	4245	63	30.6
	40% probes	497	4212	60	28.5

Su

- With data extracted from commercial vehicles only, the probe-based VSL system was not able to effectively manage traffic .
- Relying on only commercial vehicles to report traffic state seemed to send erroneous messages due to the relatively lower speed of heavy vehicles, resulting in the VSL being triggered unnecessarily.
- 20% penetration rate was shown to result in the best performance

Results

Comparison of Probe-Based and Detector-Based VSL Control Systems

120% loading	Recurrent congestion	Uncontrolled Case		503	4223	66	29.8
		Detector-based VSL		501	4234	63	28.6
		Probe-Based VSL	10% Probes	497	4218	63	29.2
			20% Probes	492	4245	63	30.6
			40% Probes	497	4212	60	28.5
	Incident - one lane closed	No VSL		964	3072	57	36.1
		Detector-based		839	3311	52	34.5
		Probe-Based VSL	10% Probes	927	3229	50	35.1
			20% Probes	886	3249	52	34.7
			40% Probes	877	3318	51	34.7

Summary

- In recurrent congestion , the probe-based VSL system demonstrated the ability to improve traffic conditions.
- In the scenarios of a minor accident , the detector-based VSL showed higher levels of improvement .

Conclusions

- Overall, the findings from this paper indicate the efficiency of probe-based VSL in harmonizing speed for the examined range of traffic conditions.
- However, the improvement in delays and throughput were shown to be limited to some traffic conditions.
- Probe-based VSL always result in significant and consistent improvement at a 20% penetration rate.
- Relying on commercial vehicles to report traffic state seemed to send erroneous messages due to the relatively lower speed of heavy vehicles, resulting in the VSL being triggered unnecessarily.
- Finally, probe-based data collection proved to be a strong alternative to that of the classic point detector.

Future Work

- It is important to examine the performance of a VSL algorithm that is capable of fusing data from both detector and probe sources. A system that fuses both static (loop detectors) and mobile sensors (GPS-enabled mobile phones) is expected to provide significant advantages over single-source data.

- The possible latency of information and errors that may be due to the inaccuracy of GPS device estimation were not accounted in this paper. Future research can examine the impact of such factors as part of a sensitivity analysis.

- In the future, Integrating the operation of VSL algorithm and ramp metering need to be evaluated.

Thank You.