Strategic Highway Improvements: Quantifying Benefits using Traffic Simulation

Yannis Stogios, Bruce Hellinga and Bob Stephenson

ABSTRACT

Freeway systems form the primary transportation infrastructure for automobile traffic in most urban centres in North America. Most of these freeways experience congestion for increasingly longer periods of the day. While increases in system capacity would mitigate this congestion, current fiscal restraints and increasing costs of construction associated with insufficient right of way and heavily developed adjacent lands have generally severely limited the opportunities for increasing capacity by expanding these systems. As a result of these increasing fiscal pressures, many transportation authorities are examining their freeway systems more closely to determine if opportunities exist to make cost effective geometric improvements to alleviate congestion at specific bottleneck locations.

A critical element of this process is the quantification of benefits and costs associated with each potential improvement. Costs, which are generally incurred by constructing the geometric improvements, are typically well defined. However, the benefits associated with potential improvements are generally much more difficult to quantify. Benefits can be associated with several factors, including decreases in the level of congestion, decreases in the accident risk associated with the section of roadway, decreases in the quantity of emissions released, and decreases in the quantity of fuel consumed. Furthermore, it is normally not obvious what impact the local improvement will have on traffic conditions on other parts of the roadway network. Traffic simulation models provide an opportunity to objectively quantify the travel time, safety and environmental benefits of potential improvements. These benefits can be used in conjunction with the associated costs to provide a mechanism for prioritizing highway improvements.

This paper describes such an analysis that was carried out for a 30-km section of Highway 401 in Toronto, Canada. Highway 401 is the backbone of southern Ontario's freeway network stretching from the Michigan border in the west to the Quebec border in the east. Through Toronto, Highway 401 expands to a complex express/collector system of twelve to fourteen lanes of traffic with volumes exceeding 350,000 vehicles per day. Given its complexity and degree of congestion, conventional traffic analysis methods cannot be applied to this network. It is possible that an improvement may relieve the bottleneck it was designed to relieve, only to cause traffic to slow downstream at the next bottleneck, which had never previously shown itself as a problem. A traffic simulation approach was therefore adopted to analyze operational deficiencies and potential improvements. The paper describes the process methodology and results, as well as some important lessons that were learned regarding the use of simulation models to quantify benefits.

Strategic Highway Improvements: Quantifying Benefits using Traffic Simulation

Yannis Stogios[(a)], Bruce Hellinga[(b)] and Bob Stephenson[(c)]

1.0 INTRODUCTION

This paper discusses the process of using a traffic micro-simulation model to quantify the expected benefits of proposed highway improvements. The process was implemented in a study that was initiated by the Ministry of Transportation of Ontario (MTO) in order to investigate needs for rehabilitation and operational improvements on a 30-km section of Highway 401 in Toronto, Canada.

In the past, the assessment of the effects of proposed improvements on traffic operations was made primarily on the basis of engineering judgment and traditional Highway Capacity Manual (HCM) analysis techniques. However, with this type of analysis, it is normally not obvious what impact the local improvement will have on traffic conditions on other parts of the roadway network. In a heavily utilized highway, it is possible that an improvement may relieve the bottleneck it was designed to relieve, only to cause traffic to slow downstream at the next bottleneck, which was not previously a problem. Furthermore, HCM techniques are not well suited for addressing the dynamic effects of traffic congestion, non-standard roadway configurations, and situations outside the limits of validity of the underlying models (e.g. weaving analysis models).

A traffic simulation model provides a unique opportunity to overcome these analytical challenges and objectively quantify the travel time, safety and environmental benefits of potential improvements. Simulation models are particularly useful in situations where multiple traffic impedances exist, and understanding the interactions between them is critical to understanding the traffic performance of the overall system. A well-designed and calibrated simulation model, that provides a reasonably accurate representation of the system, allows the traffic engineer to accurately analyze and make decisions about the cost effectiveness of potential improvements prior to making recommendations that could lead to expensive investments in infrastructure.

2.0 BACKGROUND

Highway 401 is the backbone of southern Ontario's provincial highway network, stretching from the Michigan border in the west to the Quebec border in the east. Through urban areas, Highway 401 plays a double role in that it also forms a central part of the urban road network. This is especially true in Toronto, where it expands to twelve lanes in a complex express/collector system. Local commuter traffic along with long-distance intercity traffic cause volumes to exceed 350,000 vehicles per day, including 45,000 trucks. These traffic volumes make the section of Highway 401 through Toronto one of the busiest urban freeways in North America, second only to the Santa Monica freeway in Los Angeles, California.

The core of this section of Highway 401 was built many years ago, and was expanded to its current dimensions in the 1960's. It underwent a major rehabilitation in the late 1970's and early 1980's, at which time appropriate operational improvements were also included in the work programs. Much of Highway 401's pavement, structures, lighting, drainage and roadside features are now ready for a second generation of rehabilitation.

At the same time, a number of operational deficiencies are known to exist in the subject section of the highway, as evidenced by consistently recurring congestion during peak commuting periods. The economic cost of congestion in the Greater Toronto Area is significant and, therefore, strategically placed operational improvements to this key transportation facility have a potential for improving the competitiveness of Ontario as a whole. A previous study (1) had analyzed this section of Highway 401 in 1991 and identified numerous consistent traffic bottlenecks and the operational deficiencies that caused those bottlenecks. The same study had proposed certain improvements as well as the need for assessing the effects of those improvements on a system-wide basis.

The MTO determined that, while traffic is disrupted and contractors mobilized for the upcoming rehabilitation projects, any cost-effective operational improvements should be coordinated into the programs in order to minimize overall traffic disruption and project costs. Within this context, the MTO commissioned a new study in 1996, for the area shown in Figure 1, with the purposes of: identifying the rehabilitation needs of the existing infrastructure; assessing the need for operational improvements; evaluating the potential for an express/collector system for the section of Highway 401 between Highway 427 and Highway 409; and, developing an implementation strategy incorporating all rehabilitation and operational improvements.

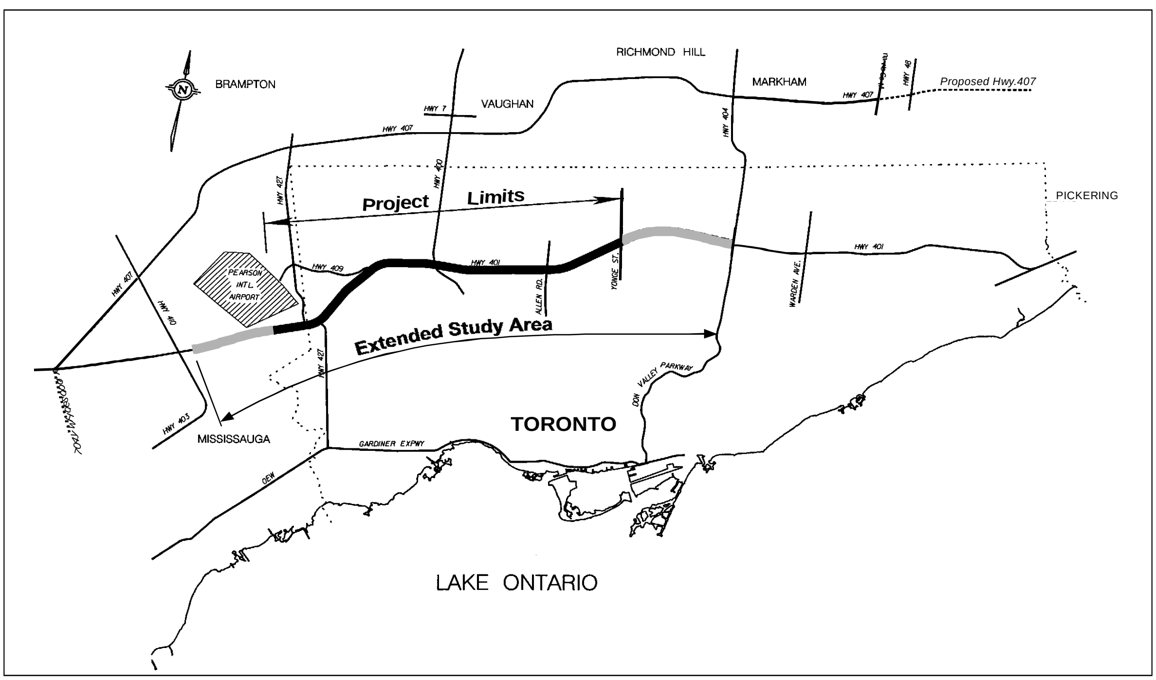


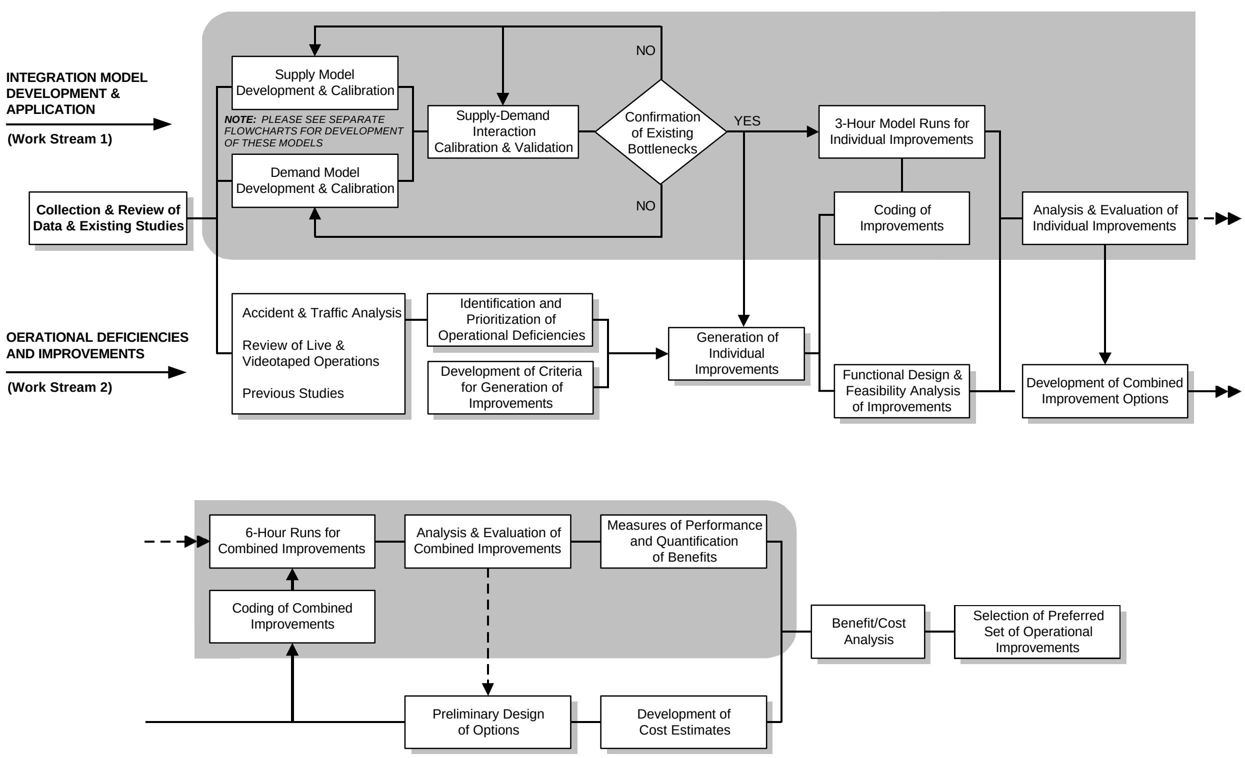
Figure 1
Project Location

The second of these four components of the study is the subject of this paper. The next section presents briefly the overall process that was followed in this operational analysis component of the study. Subsequent sections present the identification of operational deficiencies and potential improvements, the development of the simulation model, as well as its application to quantify the benefits of the proposed improvements. There is a section that discusses some lessons that were learned in the course of this study, while the last section of the paper summarizes the conclusions and recommendations of the authors based on their experience with the process.

3.0 OPERATIONAL ANALYSIS PROCESS

The operational analysis component of the study followed two parallel streams of work as shown in the flowchart in Figure 2. One stream dealt with the identification and analysis of deficiencies in order to develop potential improvements, while the other stream developed the simulation model. The products of the two streams were brought together through the application of the model in order to quantify the benefits associated with the various operational improvements.

Figure 2: Operational Analysis Process



Operational deficiencies in the study area were identified through a process that involved detailed analysis of traffic and accident data, field investigations, and review of previous studies and other sources of relevant information. Likely causes of these deficiencies were also identified, and potential operational improvements were then developed to address the deficiencies. The improvements were designed to a conceptual level of detail (and later to a preliminary design level of detail) in order to assess their feasibility and estimate construction costs.

The benefits associated with the improvements were established using a traffic simulation model developed within the INTEGRATION software package framework. Three-hour simulation runs, using actual traffic data from the afternoon / evening peak period, were used to assess the impact of the operational improvements. Changes in traffic flows were observed both on the computer screen during the simulation and through speed/flow curves. Improvements were assessed in terms of their ability to relieve a specific bottleneck, and also in terms of their downstream and upstream effects. These observations were used to group individual improvements into combinations for further assessment.

Individual operational improvements were combined into a series of improvement options for the purpose of evaluation. Combinations of operational improvements were then simulated using six-hour model runs, and the results analyzed in the same way as the individual improvements. Estimated travel times were used to establish a benefit to the highway users in dollar terms. Benefit/cost ratios were calculated for each operational improvement or combination, and the results were used to prioritize the options.

4.0 IDENTIFIED BOTTLENECKS AND POTENTIAL IMPROVEMENTS

The study employed a systematic approach to identifying operational deficiencies in the study area. Accident and traffic data as well as previous studies and other sources of information as discussed below were reviewed in order to identify possible deficiencies.

The MTO Advanced Traffic Management Systems (ATMS) office provided traffic data from the COMPASS freeway traffic management system (2). A ‘typical’ traffic day was selected as a baseline for the study. The ‘typical’ day was selected to avoid summer vacation period, winter driving conditions, weekend driving patterns, construction, and major collisions or incidents on Highway 401. After careful review of data and consideration of all these factors, Thursday, September 14, 1995, was selected as the ‘typical’ day. Traffic data were obtained from over 300 COMPASS traffic counting locations (loop detector stations) in the study area, in 20 second increments over the full 24-hour day. These data were also used to calibrate the model input parameters, as described in the next section.

The COMPASS data were compiled and summarized for the purpose of reviewing overall traffic performance across the facility, using three-dimensional time-space speed and volume graphs such as those shown in Figure 3 and Figure 4. The figures clearly showed the slowdowns during morning and evening peak periods. As well, some general observations became evident for the section of Highway 401 in the study area:

Figure 3: Sample Time-Space Series of Observed Speeds (COMPASS)

(Westbound Collector – Yonge St. to Islington Ave.)

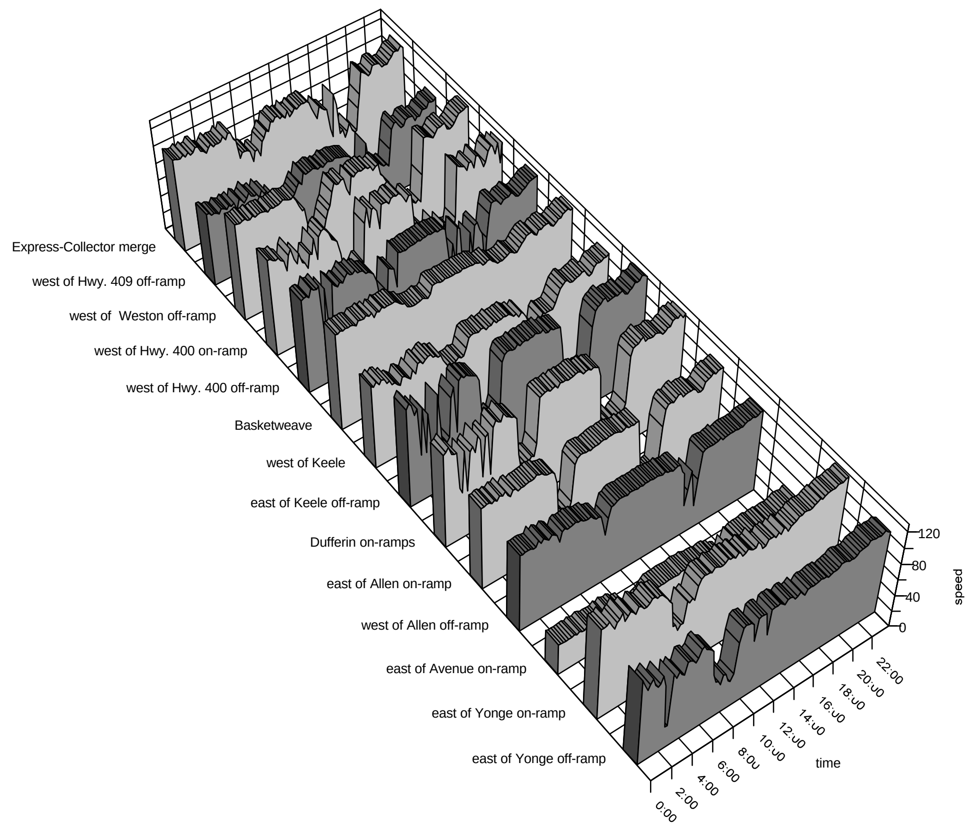
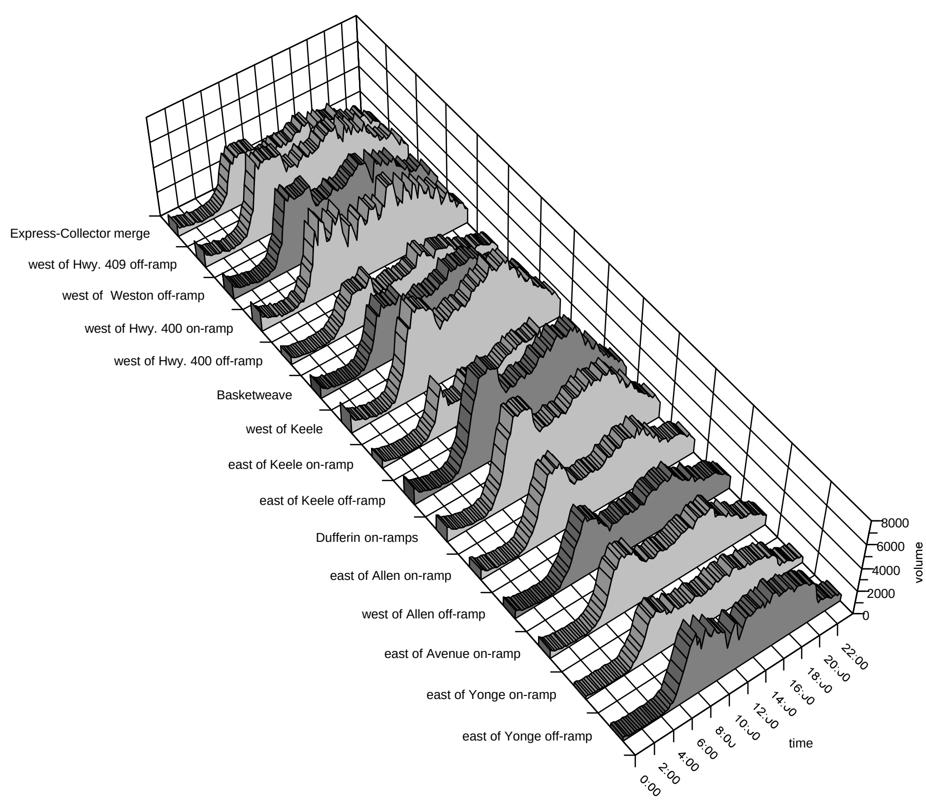


Figure 4: Sample Time-Space Series of Observed Volumes (COMPASS)

(Westbound Collector – Yonge St. to Islington Ave.)



- There appear to be four distinct periods of traffic conditions during a typical weekday 24-hour period: i) the morning peak period; ii) the mid-day off-peak period; iii) the afternoon / evening peak period; and iv) the night / early morning off-peak period.

- In general, peak period congestion characteristics (high traffic flows, low speeds) are experienced for two to two and a half hours in the morning peak period (i.e. sometime between 6:30 a.m. and 9:30 a.m. to 10:00 a.m., depending on location); in the afternoon, congestion is experienced over longer periods of time starting around 2:00 p.m. and lasting until almost 7:00 p.m.

- Traffic flows are very low early in the morning, increase significantly and are usually higher in the morning peak period than in the rest of the day, drop slightly and remain stable through the day and then, during the afternoon / evening peak period, they increase moderately over mid-day levels and remain like that until late in the evening.

- Speeds drop significantly (especially upstream of bottleneck locations) in the morning peak period, but only for a relatively short period of time; in the afternoon / evening peak there are significant speed reductions over extended periods of time.

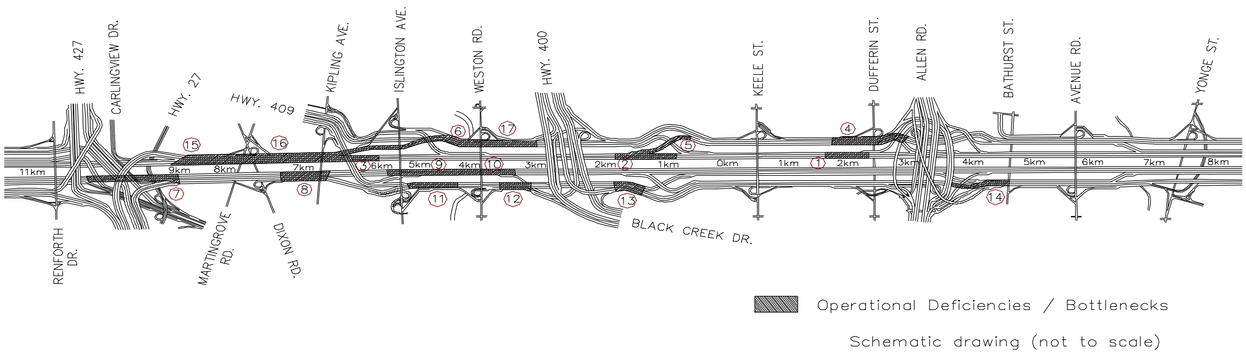
- The afternoon / evening peak period is more extended than the morning and features significant speed reductions, even though observed flows are not as high as in the morning. During the periods of congestion, the observed flows reflect the capacity of the network, rather than the traffic demands (which must be larger). It is likely that, in the afternoon / evening peak period, traffic patterns are more diverse than in the morning and include non-work related trips in addition to commuter trips; resulting in a demand that is larger than in the morning.

- Locations of congestion are relatively consistent in both the morning and afternoon / evening peak periods, although the intensity may be slightly different.

Disaggregate accident data from 1988 through 1993 were obtained from MTO's Accident Information System and used to identify potential areas of operational or geometric deficiencies. Analysis of accident data revealed seven locations with excessive accident history.

In addition to the traffic and accident data, members of the study team reviewed real time and videotaped COMPASS CCTV camera output for both the morning and afternoon / evening peak periods. The results of a speed-delay study (3) from five floating vehicles travelling Highway 401 over a 3-day period in June 1991, as well as the findings of the previous Highway 401 Operational Study (1), along with personal experience driving in the study area were also considered in identifying operational deficiencies. This process yielded a long list of potential operational deficiencies. A series of working sessions with selected members of the study team and a consensus approach were then used to reduce the list of problem areas to a short list of clearly defined operational deficiencies as shown in Figure 5 and described in Table 1.

Figure 5: Operational Deficiencies



Data related to the locations of the identified operational deficiencies were further analyzed to identify the most likely causes of traffic problems and develop operational improvements to correct them. Apart from addressing the noted deficiencies, candidate improvements were required to meet a number of practical operational, geometric and constructability criteria in order to be considered further in the analysis. Specifically, candidate improvements were required to: adhere to recognized lane balance and continuity principles; follow the existing mainline horizontal and vertical alignment of Highway 401; be signable and not preclude installation of ATMS equipment or high mast lighting; and, not result in peak hour closures of roadways during construction.

Thirteen operational improvements were developed, generally taking the form of lane and ramp additions, as well as highway entry / exit and transfer re-configurations. Each improvement was developed on an individual basis in response to a given deficiency. These improvements are described also in Table 1 beside the deficiencies they address.

5.0 SIMULATION MODEL DEVELOPMENT

INTEGRATION Model Structure

INTEGRATION is a traffic modelling software package that allows micro-simulation of traffic operations on a road network (4). It is microscopic because of its capability to trace and control the unique behaviour of each vehicle as it moves through the network. Travel within an urban area is viewed by INTEGRATION as an interrelated sequence of six decisions that the traveller makes in order to complete a particular trip. Three of the decisions are made prior to starting the trip; three others are revisited repeatedly once a particular trip has been initiated. Prior to commencing a trip the traveller decides the destination of the trip, the mode of transportation and the time of departure. Once en-

Westbound	1	lack of capacity in express just west of Allen Rd. on-ramp; causes congestion at merge of Allen Rd. on-ramp with express lanes	5	switch Allen Rd. transfer from express-collector to collector-express; necessitates an additional express lane from Allen Rd. transfer westerly, dropping as “must exit” at the basketweave
	6	lack of continuity in collector lanes (3 collector lanes plus 2 lanes from Hwy 400 going into 3 lanes west of Weston Rd. as 2 lanes are dropped at Weston Rd.); causes congestion west of Hwy 400	6	add a collector lane from Hwy 400 on-ramp to Islington Ave.
	17	Hwy 400 on-ramp access into collector lanes only; causes congestion on collector lanes west of Hwy 400 / 401 interchange	13	provide new ramp from SB Hwy 400 to WB Hwy 401 express lanes
Eastbound	7	lack of capacity through Hwy 427 area; causes local congestion	7	add a lane from Eglinton Ave. on-ramp through Dixon Rd. on-ramp
	8	3 express lanes plus 3 lanes from Hwy 427 going into 4 express lanes at Dixon / Martingrove; causes congestion at Hwy 427 merge	8	add a lane through Dixon/Martingrove
	9	lack of capacity through Hwy 409 interchange in express lanes; causes congestion just west of express-collector diverge	9	add an express lane from express-collector diverge to Hwy 400 off-ramp, dropped as “must exit” at Hwy 400 off-ramp
	10	lack of lane continuity from Hwy 409 on-ramp; causes congestion between Hwy 409 merge with express and Hwy 400 off-ramp	10	add an express lane from Hwy 409 to Hwy 400 off-ramp, dropped as “must
	11	lack of capacity and lane continuity in collector lanes east of Hwy 409; causes congestion between Hwy 409 and Weston Rd.	11	add a lane from Weston Rd. off-ramp to Hwy 400 off-ramp, dropped as “must
	14	lack of lane continuity and capacity east of Allen Rd.; causes congestion at merge of Allen Rd. on-ramp with collector lanes	12	add a lane from Allen Rd. on-ramp to Avenue Rd. on-ramp

route the driver chooses its route, speed (headway) and lane of travel. These latter three choices provide the base model logic used by INTEGRATION and are revisited several times after the trip has commenced.

The INTEGRATION model requires a minimum of five input data files (nodes, links, traffic signals, origin-destination traffic demands, incidents) which provide information about the network structure (e.g. number of lanes, speed change lanes, ramps, express/collector transfers, roadway/profile curvature) and its traffic demands and operations (e.g. traffic signals, lane blocking due to incidents). Other optional input files can provide data about detector locations, lane striping, etc.

Key output files generated by INTEGRATION include:

- Link Statistics (such as link volumes, free flow travel time, total travel time, average travel time, average speed, average percentage of stops, maximum observed number of vehicles on the link), and
- Network Statistics (such as total travel time, total distance travelled, average network speed, average trip time/vehicle, average trip time, total network stops, average network stops, as well as total network fuel consumption and emissions statistics).

Scope of Model

The scope of the simulation model used in the study was defined in terms of eight categories:

Spatial: The limits of the network used for modelling purposes extended well beyond the limits of the study area, stretching from just west of Dixie Road in the west to just east of Highway 404 in the east. These buffer areas east and west of the study were chosen for the following reasons:

- to capture the impacts on (and from) critical sections of Highway 401 and interchange facilities outside the study area
- to capture the full length of queuing, in the case of significant queuing extending beyond the study limits
- to avoid (or at least minimize) simulation problems at the boundaries of the model network (inherent in all modelling exercises)

Temporal: The afternoon / evening peak period was selected for simulating and assessing traffic operations on Highway 401. Although traffic flows in the afternoon / evening peak period may not be as high as in the morning peak, speeds are usually lower and the congestion period longer than in the morning, as discussed in the previous section. The 6 hours between 2:00 p.m. and 8:00 p.m. were selected for simulation to capture the building and dissipation of traffic congestion.

Seasonal: September was chosen as a time of the year that is typical of average traffic conditions on Highway 401, because it is not within peak holiday season, highway maintenance/construction is generally over, weather conditions are still good, and traffic is generally stable.

Weekly: A typical weekday (Tuesday, Wednesday, or Thursday) was chosen as representative of average commuter traffic patterns on Highway 401.

Terminal: Ramp terminals with all connecting roadways, including most traffic signals at ramp intersections, were included in the model to capture their impacts on (or from) traffic operations on the mainline of Highway 401.

Time Horizon: 1995 was chosen as the base year, representative of existing conditions, because the ATMS office indicated that the 1996 COMPASS data would be unreliable for development and calibration of the model.

Temporal Resolution: The network was loaded with varying rates of traffic demand in 15-minute increments to capture the temporal variation of traffic.

Vehicle/Driver Population Resolution: The model simulated the existing (1995) mix of vehicles (passenger cars, buses, trucks) and drivers' knowledge of local traffic conditions).

Road Network (Supply) Development and Calibration

The process for developing and calibrating the supply side of the INTEGRATION model is depicted in the flowchart in Figure 6. The road network coded for this analysis included 550 nodes, 696 links, 53 zones, 16 interchanges, 302 detector stations, and 15 traffic signals.

Figure 6: INTEGRATION Supply Model Development

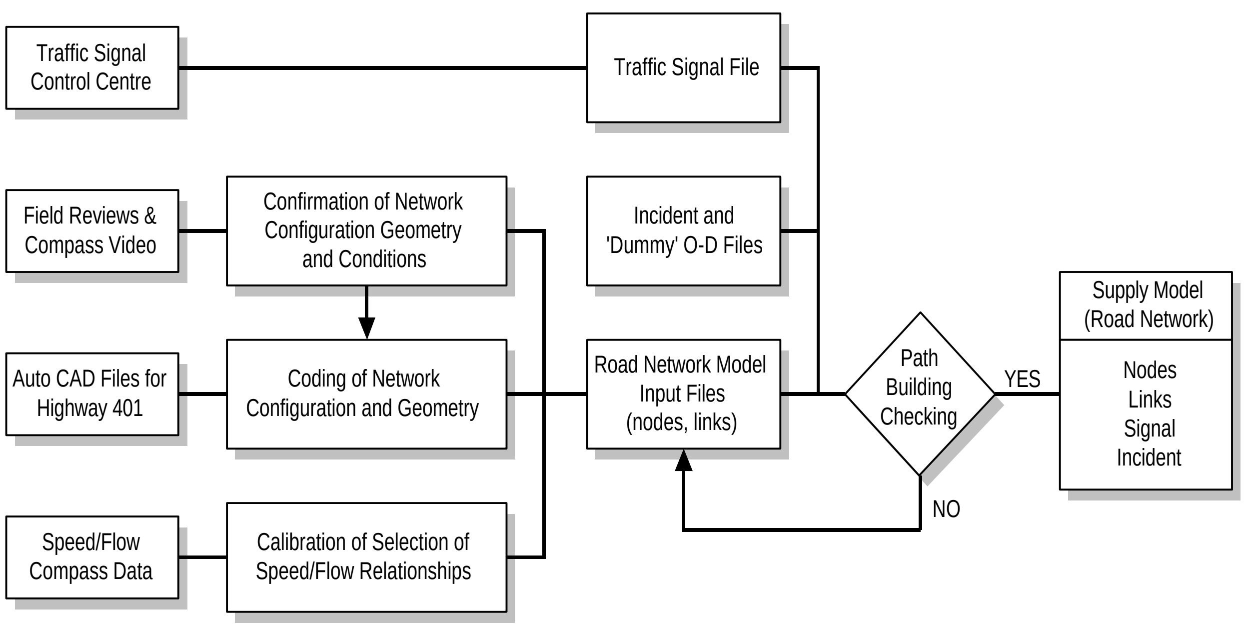


Table 2 shows the length of the various sections of the network (study area and buffer areas).

Table 2: Network Length by Facility (km)

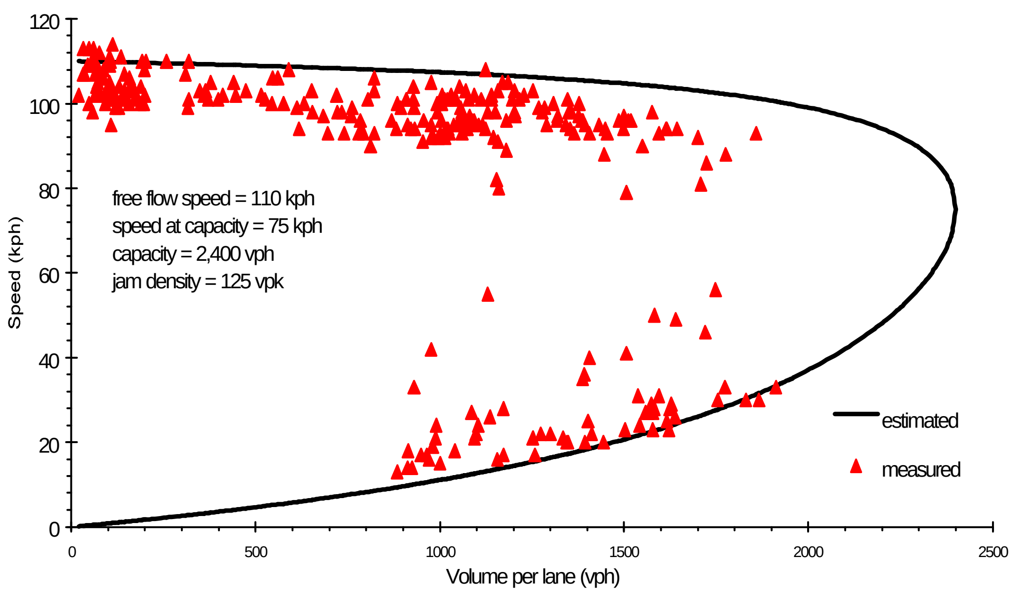
	Renforth-Dixie (west end buffer)	Yonge–Renforth	Hwy 404 - Yonge (east end buffer)	Total
WB Collector	4.7	14.0	5.9	24.3
WB Express	4.6	19.4	6.4	30.6
EB Express	5.1	19.3	5.3	29.7
EB Collector	4.5	14.5	6.0	25.0

Nodes were created wherever there was a change in the number of lanes, the start and end of an acceleration or deceleration lane, a signalized intersection, a Changeable Message Sign (CMS) location and/or other elements of the network structure. As well, 'dummy' nodes were introduced to capture changes in the geometrics (horizontal curves). These nodes do not affect the functionality of the model; rather, they improve the graphical presentation of the network.

Once the node and link files were created, paths were checked to ensure that no illogical paths were available for moving through the network. Further coding adjustments were made and additional turn prohibitions were introduced to rectify any evident problems.

In INTEGRATION, the behaviour of vehicles under various operating conditions is defined by a speed / flow relationship between four operational characteristics (parameters) namely, free flow speed (S_f) speed at capacity (S_c), capacity (V_c) and jam density (D_j). Speed / flow relationships were calibrated for approximately 40 representative locations in the Highway 401 Study area using COMPASS data from the corresponding detector stations. Figure 7 shows a typical speed/flow curve.

Figure 7: Typical Speed-Flow Curve



The COMPASS data were partitioned into 15-minute increments over a 24-hour period. The measured speeds and volumes were used to plot scattered points and the calculated speed was plotted as a line graph. The four parameters were then adjusted to fit a curve through the scattered points. Table 3 summarizes typical speed / flow parameters as calibrated for simulation purposes.

Table 3: Typical Speed/Flow Parameters in the Study Area

	Eastbound	***Westbound***
Express lanes		
Free Flow Speed	115 km/h	120km/h
Capacity	2100 veh/h	2200 veh/h
Speed at Capacity	80 km/h	85 km/h
Jam Density	125 veh/km	125 veh/km
Collector lanes		
Free Flow Speed	110 km/h	115 km/h
Capacity	2000 veh/h	2100 veh/h
Speed at Capacity	80 km/h	80 km/h
Jam Density	125 veh/km	125 veh/km

Trip Table (Demand) Development and Calibration

Since the actual origins and destinations of traffic demands on the freeway were not known, a separate software package called Queen's O-D (QOD) was used to create a synthetic origin-destination (O-D) trip table to load the network (5). Output provided by QOD was used to calibrate the simulated network demand against the observed COMPASS data.

The flowchart in Figure 8 shows the process used for the development of the trip table.

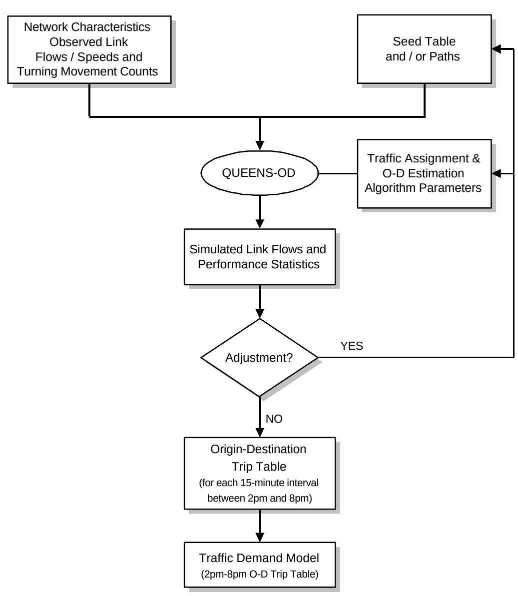


Figure 8: INTEGRATION Demand Model Development (Queen's O-D)

The network characteristics (observed link flows/speeds and turning movement counts) are provided in the node, link and link flow files; these along with a seed table (containing a default demand value for all possible origins/destinations in the network) are used as input to QOD. As shown in the flow chart, QOD follows an iterative procedure to generate a synthetic O-D trip table to match the observed network flows as closely as possibly. This procedure consists of the following steps:

1. assign the seed (original) O-D trip table to the network
2. estimate the flows resulting for each link
3. compare the estimated flows with the observed flows
4. estimate performance statistics and correction factors
5. apply correction factors to the seed table to obtain a revised traffic demand table
6. repeat steps 1 to 5 until a pre-defined number of iterations and/or performance thresholds are satisfied.

QOD produces a simulated origin-destination trip table and provides the simulated link flows and performance statistics resulting from this table. Where these statistics indicated that an adjustment is required, the input data and the estimation methodology and parameters were revised and QOD re-run until a satisfactory level of correlation was established. This procedure was run for each 15-minute interval within the 6-hour simulation period to produce 24 partial origin-destination trip tables (one for each of the 15-minute intervals). The partial trip tables were then combined to produce the overall (6-hour) O-D trip table. The correlation (R^2) between the observed link flows and those estimated by QOD ranged from 0.95 to 0.96.

Model Calibration and Validation (Supply-Demand Interaction)

Once the two components of the model, namely the road network (supply) and the trip table (demand), were developed, they were brought together as inputs to the INTEGRATION system. A series of base model runs were then undertaken in order to calibrate the model and validate it with the observed values for speeds and flows. The calibration process involved primarily the following type of adjustments:

- changes to the traffic assignment techniques (e.g. macroscopic/microscopic assignments, frequency of travel time updates, etc.)
- adjustments to the traffic demand table, especially for origins-destinations outside the immediate study area where large discrepancies were observed between initial simulated and observed ramp flows (e.g. Bayview, Leslie, Dixie ramps)
- adjustments to speed/flow parameters for selected links
- minor changes to the network.

For model validation purposes, a series of plots were created which directly compared the existing speeds and volumes from COMPASS and from INTEGRATION runs at the COMPASS station locations. The variation between the two sources was assessed from the plots (Figures 9a and 9b), and compared to the daily variation of speeds and flows as recorded by the COMPASS system (Figures 10a and 10b) for four weekdays in September 1995 with the most reliable data. The calibrated model was generally successful in replicating actual traffic conditions within the range of observed daily speed and flow variations.

Figure 9a: Variation between Observed and Simulated Peak Hour Speeds (kph)

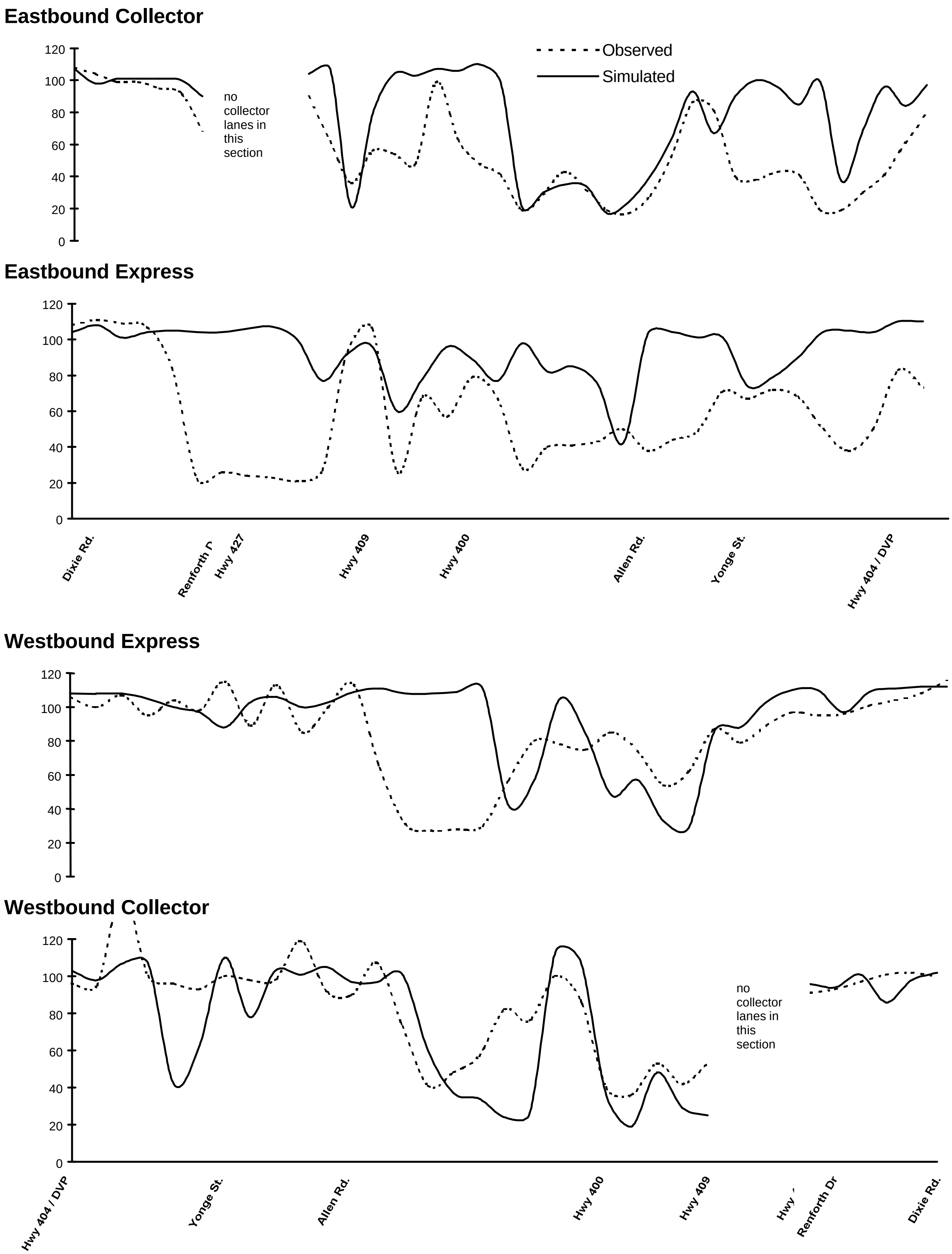
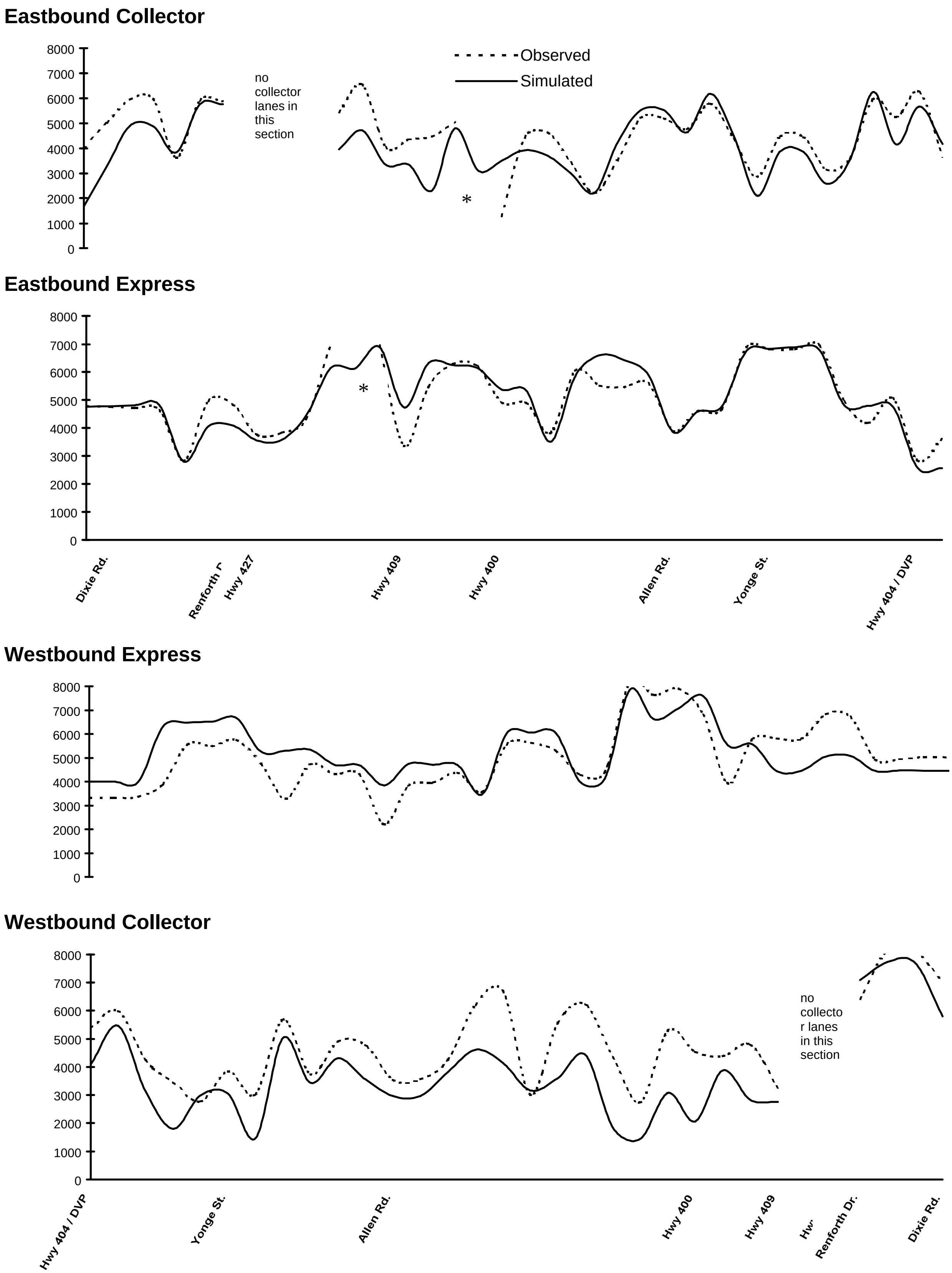


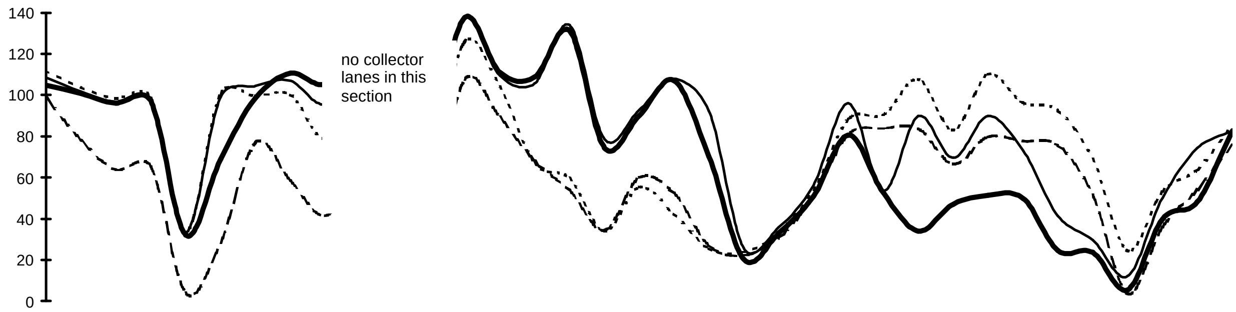
Figure 9b: Variation between Observed and Simulated Peak Hour Volumes (vph)



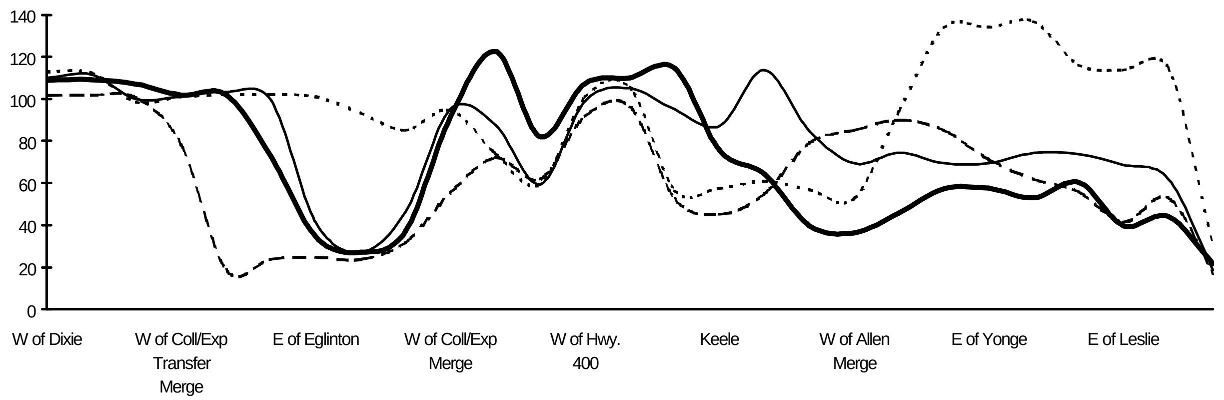
* COMPASS data were not available

Figure 10a: Daily Variation of Observed Speeds (kph) – 4:30 p.m.

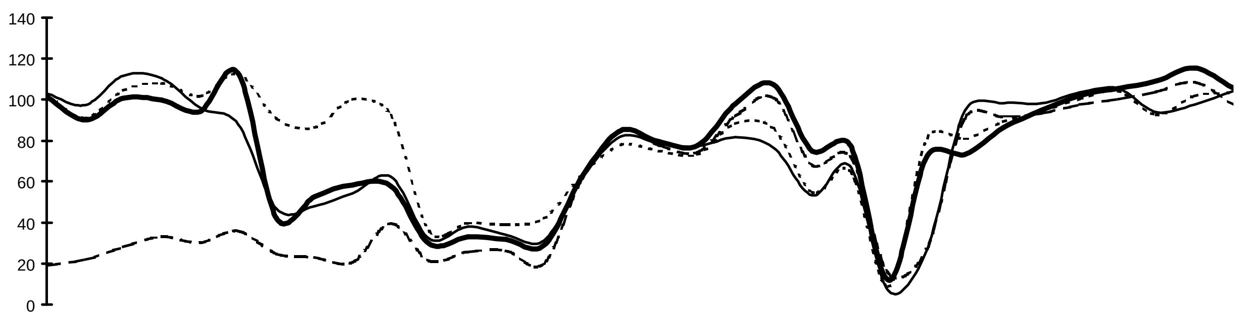
Eastbound Collector



Eastbound Express



Westbound Express



Westbound Collector

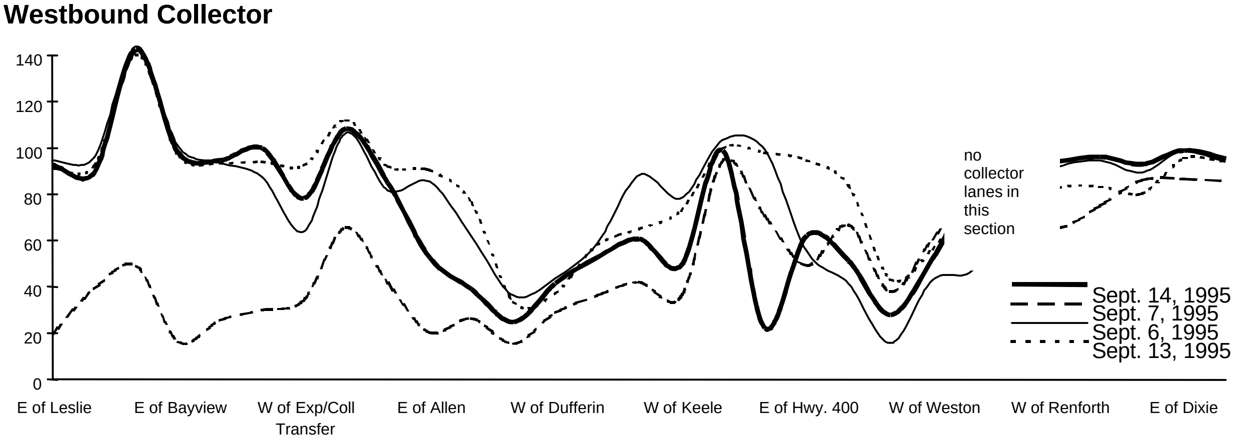
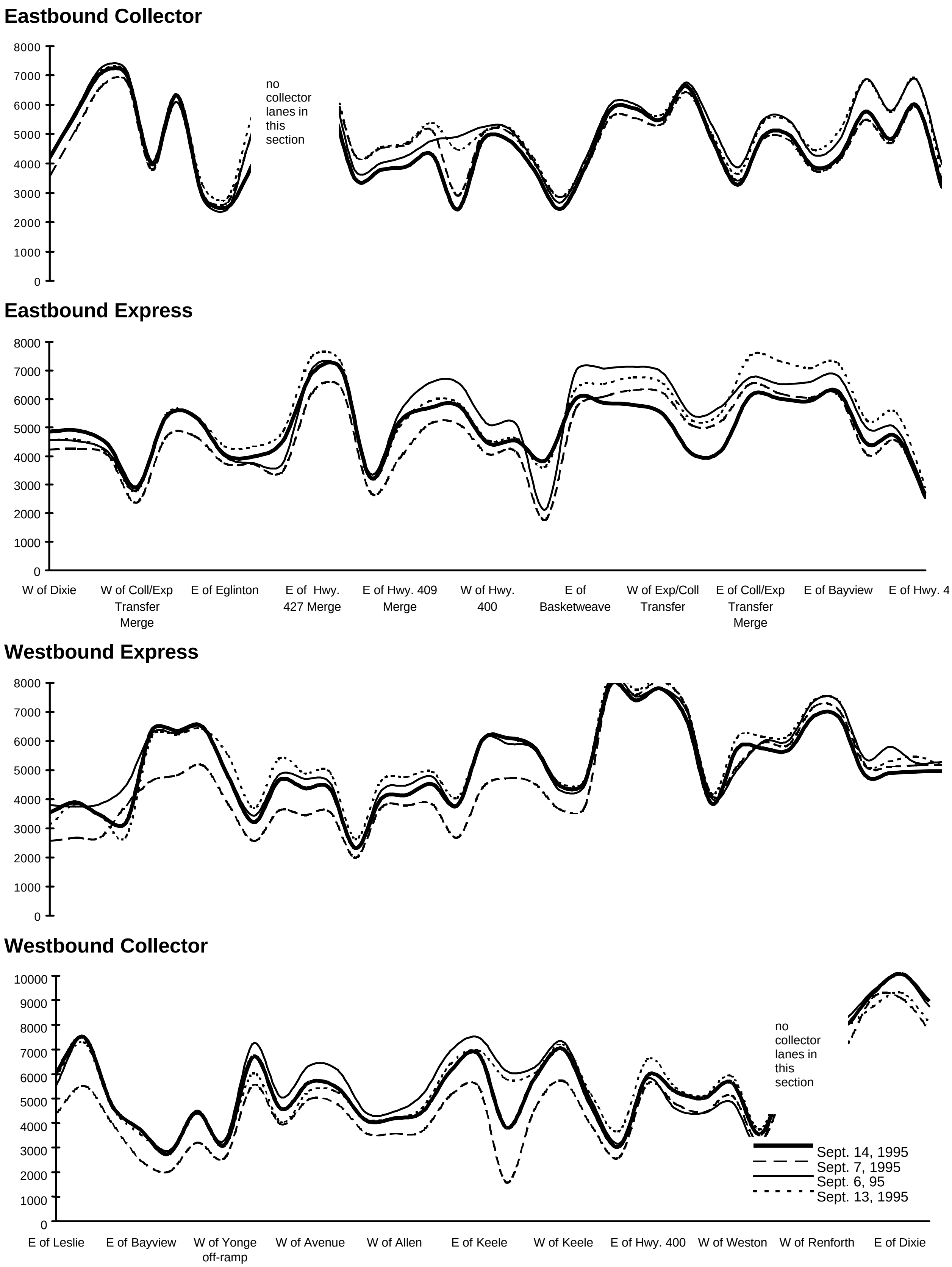


Figure 10b: Daily Variation of Observed Volumes (vph) – 4:30 p.m.



6.0 QUANTIFICATION OF BENEFITS

Initial INTEGRATION model runs were made for each of the individual improvements identified in the early stages of the study. Although it was not expected that each one of these improvements by itself would offer significant congestion relief, these runs assisted the project team in understanding the impact of each improvement on traffic. Specifically, these runs helped identify how bottlenecks could shift between locations (depending on the deficiency addressed by each improvement) and what improvements to combine with one another.

Individual improvements were simulated in 3-hour model runs (3:30 p.m. to 6:30 p.m.), considered sufficient to load the network to congestion levels of traffic for observation of the initial network impacts. It should be noted, however, that due to the dynamic nature of this model, the results of a 3-hour simulation run are not directly comparable with those of a 6-hour run. Therefore, no comparison should be attempted between the results of the 3-hour and 6-hour model runs. A 3-hour base run was used as a basis for comparative assessment of the individual improvements.

Individual model runs were made by modifying the network nodes and links to reflect the improved geometry. Traffic demand was then applied in a 3-hour run (3:30 p.m. to 6:30 p.m.) and the output compared to the 3-hour base run.

The performance of individual improvements and their effect on overall highway operations were assessed on the basis of visual observations during the model runs as well as on a comparison of speed and flow contours between the base model run and the model run for the subject improvement. In assessing speed and flow contours, the objective was to identify whether the improvement caused speeds to increase or decrease locally and system-wide, to what extent, and how the vehicle throughput was affected. This allowed the analysts to determine whether traffic operations were in the free flow, congested or at capacity area of the speed / flow curve and compare the conditions with and without the improvement.

Combinations of potential improvements were generated on the basis of the results of the evaluation of the performance of the individual improvements coupled with engineering judgment as to how these results might be affected by combining certain improvements.

Six-hour model runs (2:00 p.m. to 8:00 p.m.) were performed for the various improvement combinations. The results were assessed in a manner similar to that for the individual improvements. However, the elapsed computer time for each of these runs was quite long (typically over 20 hours) and complete visual observations were not as practical to obtain as with the shorter simulation runs. Therefore, more emphasis was placed on the analysis of base measures of performance such as speeds, volumes and travel times through a time series of relevant plots. Tables 4 and 5 summarize average travel times from the model runs for individual improvements and combinations of them. Average travel times and volumes were used to establish total user benefits or costs, which were then incorporated into the overall benefit / cost analysis.

Table 4: Results of 3-Hour Model Runs for Individual Improvements

Improvement	Travel Time (min) Express	Travel Time (min) Collector	Comments / Observations during Simulation of PM Peak Hour
Westbound – Existing Conditions (simulated)	15.5	11.6	
1: add a lane from Hwy 427 off-ramp to Renforth	12.9	8.5	WB Hwy 401 very congested from merge to Dixon/Martingrove; some congestion on WB express and collector upstream of merge through to Weston interchange
2: add a lane through Dixon/Martingrove interchange area, and an additional lane to Carlingview ("must exit")	13.5	11.6	opens up collector through merge with WB express to about Dixon/Martingrove and then it is congested to the Hwy 427 exit; additional lane to Carlingview ("must exit") has almost no impact; not much relief to WB collector upstream of Hwy 409 exit
3a: add an express lane from the basket-weave to the express-collector merge	14.2	10.8	improves WB express (and collector) significantly through merge with WB collector; some congestion before the diverge to Hwy 427 exit and on WB collector from Weston to Hwy 409 / Islington exit
3b: add a collector lane from Hwy 409 exit to the express-collector merge	14.1	9.7	almost no congestion on WB collector through Weston/Islington, little congestion at merge and then quite congested through Martingrove to Hwy 427; additional lane to Carlingview ("must exit") has almost no impact
4: add an express lane from the basketweave to Hwy 409	16.6	13.5	attracts more traffic to the WB express (basketweave to Hwy 409 and the express/collector merge) and balances congestion between express and collector; additional lane not heavily utilized by traffic exiting at Hwy 409; not much congestion on either express or collector upstream of merge, but very congested around Dixon
5: switch express-collector transfer at Allen Rd. to collector-express.	16.1	12.9	reduces express lane congestion upstream of change
6: add a collector lane from Hwy 400 to Islington	16.7	14.5	some relief on WB collector between Hwy 400 and Weston through to Islington exit; in general, very positive impact on both WB express and collector up to about their merge
Eastbound – Existing Conditions (simulated)	16.6	13.3	(does not fully replicate congested conditions in eastbound express)
7: add a lane from Eglinton on-ramp through Dixon Rd. on-ramp	15.5	14.3	the bottleneck between Eglinton and Hwy 427 is removed but there is increased weaving between Dixon/Martingrove and the express/collector diverge
8: add a lane through Dixon/Martingrove	16.5	16.0	creates some weaving downstream of the improvement as traffic tries to sort itself before the express/collector diverge (i.e. it moves the bottleneck from the Hwy 427 merge with Hwy 401 to past Dixon/Martingrove)
9: add an express lane from express-collector diverge to Hwy 400 off-ramp	20.4	13.3	improves EB express but creates congestion around the Highway 400 area (to the basketweave), which in turn causes traffic to try to use the EB collector; creates weaving-related congestion between Dixon/Martingrove and express/collector diverge, and then around the Islington and Weston interchanges
10: add an express lane from Hwy 409 to Hwy 400	16.6	16.4	no congestion on EB express (Highway 409 to Highway 400); some weaving on EB collector between Weston and Hwy 400
11: add a lane from Weston Rd. to Hwy 400	16.5	16.0	almost no congestion on EB collector through Weston interchange
12: add a collector lane from Allen Rd. to Avenue Rd.	16.4	12.4	improves conditions between Allen Rd. and Avenue Rd., as well as to the east of this section; however, there is still congestion at the transfer to the east of this section;

note: travel time from Yonge to Renforth in express lanes, and from Yonge to express/collector diverge in collector lanes

Table 5: Results of 6-Hour Model Runs for Combined Improvements

Improvement	Travel Time (min) Express	Travel Time (min) Collector	Comments / Observations during Simulation of PM Peak Hour
Westbound –Existing Conditions (simulated)	19.6	24.1	
WB1: add a lane from Islington to Hwy 427	14.7	10.7	conditions improve from the express-collector merge to Dixon Rd. but speeds remain low around Hwy 427
WB2: add an express lane from the basket-weave to Islington, continued as an additional lane to Hwy 427; switch transfer at Allen Rd.	14.3	8.5	conditions in the collector lanes improve with the switch of the transfer; the current bottleneck at the basket-weave in the express lanes is eliminated, and speeds increase through to Islington and Dixon; the bottleneck at the Hwy 427 off-ramp continues to be a problem
WB3: add an express lane from the basket-weave, continued to Hwy 427; switch transfer at Allen Rd.; add a ramp from Hwy 400 southbound to the westbound express lanes	14.0	8.5	conditions in the collector lanes improve with the switch of the transfer; traffic conditions at the express-collector merge are improved; in the express lanes, conditions improve substantially from the basketweave to Islington; however, traffic continues to slow down around Hwy 427
WB4: add a collector lane from Hwy 400 to the express-collector merge, continued as an additional lane from Islington to Hwy 427	15.4	8.4	the bottleneck that currently occurs in the collector lanes just west of Hwy 400 is eliminated; speeds from Hwy 400 to the express-collector merge increase substantially; conditions improve from the express-collector merge to Dixon Rd. but speeds remain low around Hwy 427
WB4R: add a collector lane from Hwy 400 to express-collector merge, continued as an additional lane to Hwy 427; switch the transfer at Allen Rd.	13.5	7.7	in the collector lanes, conditions improve with the switch of the transfer; traffic conditions at the express-collector merge are improved; the current bottleneck in the collector lanes just west of Hwy 400 is eliminated; speeds from Hwy 400 to the express-collector merge increase substantially; conditions improve from the express-collector merge to Dixon Rd. but speeds remain low around Hwy 427
WB5: add an express lane from the basketweave to Islington; switch transfer at Allen Rd; add Hwy 400 ramp; continue express/collector system to Hwy 427	10.1	11.2	traffic moving at close to free flow speed throughout
WB6: add a collector lane from Hwy 400 to the express-collector merge, expand the express/collector system to Hwy 427	10.7	11.2	traffic moving at close to free flow speed throughout
WB7: add an express lane from the basket-weave to Islington, continued to Hwy 427	16.2	12.6	the slow downs which currently occur at the basketweave and at the express-collector merge are improved; slow downs still occur around Hwy 427
Eastbound –Existing Conditions (simulated)	24.8	25.2	
EB1: add a lane from Allen Rd. to Avenue Rd	24.6	24.3	conditions improve from Allen Rd. to Avenue Rd.
EB2: add a lane from Eglinton to Dixon / Martingrove; add a collector lane from Allen Rd. on-ramp to Avenue Rd	23.4	24.3	localized improvement
EB3: add a lane from Eglinton to Dixon / Martingrove; add an express lane from Hwy 409 to Hwy 400; add a collector lane from Allen Rd. to Avenue Rd.	17.2	17.5	conditions in the express lanes from Eglinton to Dixon/Martingrove and form Hwy 409 to Hwy 400 are slightly improved; speeds in the collector lanes between Allen Rd. and Avenue Rd. increase substantially and speeds to the west of this section are also improved
EB4: extend express/collector system; add a collector lane from Allen Rd. to Avenue Rd.	17.3	17.2	results similar to EB3; express/collector system has little effect as the widening included in EB3 was sufficient to relieve congestion in that area

Operational improvements were selected for the preferred plan primarily on the basis of benefit / cost analysis. Improvements were also coordinated with adjacent pavement rehabilitation and timed to provide relief of bottlenecks in a downstream-to-upstream direction. The proposed improvements (WB4R in the westbound direction and EB3 in the eastbound direction), comprised of selected widenings/lane additions and reconfiguration of entries, exits and transfers, have the potential to improve lane continuity on a system-wide basis. Specifically, with the proposed improvements in place, there would be one more continuous lane in each direction (i.e. lane on which a vehicle can traverse the entire stretch of the study area without changing lane) than under existing conditions. Also, the proposed improvements have the potential to reduce travel time by as much as 68% on the westbound collector and approximately 31% on the westbound express and eastbound express and collector.

7.0 SOME VALUABLE LESSONS LEARNED

Application of the process described in this paper was quite successful in the subject study and at the same time quite educational for the traffic analysts involved in it. Not only did traffic micro-simulation contribute to the development, evaluation and selection of improvements, but it also contributed to a better understanding of the advantages and, most importantly, the challenges of the process.

The process showed that the results of micro-simulation could be quite different from those of conventional analysis techniques, and sometimes most revealing when the effects that certain local improvements may have on other parts of the network and system-wide are considered. This is especially true for traffic operations under congested conditions which HCM techniques and other static/macroscopic analysis models are unable to address.

Micro-simulation is usually more data- and effort-intensive than other analysis techniques and, therefore, the up-front cost of such an application is also higher. However, this up-front investment pays significant dividends when the results show that conventional techniques would have failed to properly address the requirements of the analysis and could have resulted in expensive and inappropriate solutions. It is, therefore, very important to know not only how-to, but also when-to and what-to-do prior to adopting micro-simulation as an analysis tool. Extensive traffic engineering expertise and experience is required in order to achieve this level of judgement. Unfortunately, it appears that often inexperienced users believe that it is easy and straightforward to interpret the results of such model.

Although in this particular application, only a limited number of measures of effectiveness / performance (e.g. speeds, travel times, volumes) were used for analysis and evaluation purposes, micro-simulation models typically offer a fairly wide selection of measures of effectiveness outputs. These can be used to undertake comprehensive and rather sophisticated analyses based on fully quantifiable parameters. For example, average network speed, total vehicle-kilometers and vehicle-hours, total and average network stops, as well as fuel consumption and emission statistics are only a few of the measures of effectiveness that can be used to quantify user costs and benefits, air quality characteristics, system-wide efficiency and other evaluation parameters in projects involving physical and operational improvements, Intelligent Transportation Systems deployment, traffic management schemes, etc.

INTEGRATION and other similar micro-simulation software packages permit a range of driver behaviour patterns and decision-making criteria to be simulated. Parameters control the percentage of drivers who make microscopic route choice decisions compared to those who make macroscopic route choice decisions, and the frequency with which drivers update their knowledge of downstream network congestion for use in routing decisions. Informed selection and control of these parameters is important to the success of the modelling exercise.

In general, the issue of model calibration is key to the overall modelling process and users of its results should have realistic expectations before they adopt micro-simulation as tool for their analysis purposes. In this particular study, while a perfect correlation between simulation and reality was not achieved, the results were reasonable and the model fulfilled its purpose.

The Highway 401 model was expected to stretch the limits of INTEGRATION, as it was a detailed analysis of a highly complex network. In the course of the project, some software peculiarities relating to either the functionality of the model or its graphical interface and interaction with the user were uncovered. Many of these were related to the level of complexity and the degree of congestion in this particular application. Some of these peculiarities of the software as well as their consequences and, where possible, potential ways to avoid them are discussed in the following.

For calculation purposes, the length of each link is explicitly stored as a link attribute. However, INTEGRATION's graphic display shows all links as straight lines between two nodes defined by cartesian coordinates. While this approximation is suitable for most traffic links in a road network, it is not suitable for the graphical presentation of loops at highway interchanges. Where these occurred in the model, two or three dummy nodes were added to the loop to give it a more normal appearance (a triangle or quadrilateral rather than a point). These dummy nodes and links added to the complexity of the model without contributing to its quality.

Also in the area of user control and interaction, INTEGRATION does not store intermediate data during the model run in any form that can be controlled by the user. There are two significant consequences of this. First, all runs begin with zero vehicles on all links and vehicles are introduced one by one from their origin points as provided by the O-D matrix. There is no way that the user can save run time by storing the link volumes part way through a run and then reloading the network with these stored traffic conditions. Second, there is no ability to re-play a saved simulation run, except by capturing the screen (as a video image) during a model run. This is not a particularly useful feature since the user cannot zoom or pan the image either during the model run or while it is replaying. Neither of these consequences would be significant, if the model run times were short. However, the elapsed computer time for most of the runs in this application was in the order of 20 to 25 hours.

From a model functionality perspective, calibration of the O-D matrix was considered to be a weak link in the development of the simulation model because of the large number of unknowns (the total number of possible O-D pairs in the matrix) and the relatively small amount of reliable input data. In particular, although there were many loop detectors in the highway lanes, ramp counts and turning movements were not considered to be sufficiently reliable to produce a high quality O-D matrix.

Queens O-D's optimization routine provides two options for its objective function: i) least relative error (minimizes the percentage of predicted value deviation from observed value); and, ii) least squared error (minimizes the square of predicted value deviation from observed value). Both of these objective functions generally provide acceptable results when applied to networks having link flows of similar magnitude. However, for this network, in which a wide range of link volumes existed, a hybrid objective function, may produce a better result. As well, O-D seed data from a planning model and more reliable ramp and arterial road traffic count data could be used to improve the effectiveness of the O-D matrix estimation procedure.

The model allowed 'shifting' of vehicles into express lanes when collector lanes were free and vice-versa, due to the state of network and estimated paths at discrete times. This caused unrealistic assignment of traffic and unstable travel times. A certain degree of this behaviour is accurate; the problem is that it occurred to an extreme degree. Careful consideration of micro vs. macro route choice for various drivers, along with more frequent updates would be necessary in order to rectify this behaviour. This required many calibration runs after all other parameters were settled.

At the project outset, it appeared that eastbound and westbound traffic would be independent. However, a 'spillover' effect from one direction to the other was observed in a number of occasions. In fact, vehicles travelling in certain direction would backtrack for one or two interchanges in the other direction in order to find an interchange that would allow them to take a faster route. For example, an improvement in the eastbound direction often resulted in vehicles exiting the westbound express lanes, going eastbound for 2 interchanges to take advantage of better flow conditions and re-entering the westbound collector lanes. A way around it would be to model the eastbound and westbound directions using separate networks. This would also speed up run times, but would not permit proper assessment of impacts on/from signalized ramp terminals.

Inappropriate use of interchanges for U-turns was also observed (e.g. entering the network at Yonge, going EB to Leslie, across interchange, re-entering WB to go to Highway 400, all to avoid congestion in the vicinity of the WB on-ramp at Yonge). This chokes up interchanges and causes spillovers onto the highway. Again, a certain degree of this is realistic, but it occurs to an extreme degree, especially as the network gets congested. A way around it would be to artificially extend the length of cross-interchange links. However, this must be used sparingly and carefully as it sometimes causes north-south trips across the interchange to get onto the highway, turn around at the next interchange and come back at the opposite side of the original interchange. This situation (as well as the previous one) could be addressed more appropriately through programming by ‘flagging’ vehicles by their general direction of travel and not permitting them to make route choices that cause them to go in the opposite direction.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This project confirmed the authors’ general view that micro-simulation offers significant advantages over other analysis techniques both from a technical and client benefit perspective. It has more flexible analysis capabilities than HCM and other traditional analysis techniques and can quantify a wider range of measures of effectiveness. It can address non-standard facility configurations and allows cost effective and efficient analysis of complex traffic facilities. Micro-simulation is also a most promising technique to assess Intelligent Transportation Systems initiatives and incorporate human factor considerations in the analysis of traffic systems. It can save time and money in the design, construction and operation of a traffic facility and provides realistic assessment of potential benefits that may arise from specific infrastructure capital investing. Finally, it makes it easier to convey the findings of an analysis to a lay person using the graphical animation feature that most micro-simulation programs have available.

With respect to this particular application, micro-simulation was central to the success of the Highway 401 Strategic Improvement Study because the model’s visual output allowed even experienced traffic analysts to develop a better understanding of traffic operations under both the existing network and with the improvements considered in the study. Most importantly, its statistical output enabled the traffic engineers to make credible estimates of time savings associated with various improvements for use in formal benefit / cost analysis of the improvements options. Finally, this modelling exercise increased the awareness of study participants about the advantages of using micro-simulation as an analysis tool, as well as its challenges and shortcomings.

The findings of the study, the lessons learned in the process and our overall experience with micro-simulation models and INTEGRATION in particular, suggest that, in the future, significant effort should be made to address the limitations of the software uncovered in this application in order to improve its credibility and user-friendliness.

Future applications should use the leanest network possible to represent the area to be modelled and also use computers with the highest performance possible. As well, they should use the best possible traffic data, including trip origin-destination survey results and/or relevant output from planning models, and allow adequate time to calibrate the model parameters that describe driver behaviour.

Finally, model development and operation should be directed by a traffic engineer with particular experience in traffic simulation modelling, including an understanding of both traffic behaviour and system performance. Both graphical and statistical output should be used to understand the modelling results, and a critical evaluation of the findings should be performed prior to adopting the results.

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Note

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