Evaluating the Road Safety Effects of Interchange Spacing: A Multidisciplinary Approach

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Abstract

In the course of a Preliminary Design Study for the upgrade of an existing two-lane, two-way highway on the edge of a local mid-size community in Southern Ontario, the ultimate plan evolved into a fully controlled-access highway. Under the proposed scheme, existing intersections with arterial roadways were to be eliminated and all access to and from the facility was to be provided through interchanges.

Roads crossing the facility that did not provide access were to be either grade-separated or terminated on either side of the highway. At one such location, the local community asked that consideration be given to providing a full interchange instead of the proposed flyover. In reviewing this request, concerns were raised with respect to the safety and operations of the proposed controlled access facility if an interchange were to be inserted in the requested location because of the close proximity of the adjacent upstream and downstream interchanges.

This paper provides an overview of an innovative and practical approach to the explicit evaluation of the likely road safety performance impact of the requested interchange. We begin with a brief overview of the overall controlled access facility and the design context of the requested interchange. The analysis framework, which requires the development of a risk commentary along each of 5 independent lines of evidence (Interchange systems design practices; human factors; surrogate safety measures assessment through simulation; road safety engineering considerations; and quantitative operational analysis), is then presented.

In our final analysis, we connect the various lines of evidence through an integrated and qualitative discussion of the commonalities and differences of the various indicators examined. Where lines of evidence “overlap” and point to a common conclusion regarding a particular feature or element of the interchange, that conclusion is strengthened by the independence of the indicators and the multiplicity of their occurrence as well as the independence of the individual investigators pursuing the different approaches to the analysis. The approach results in a set of clear and practical recommendations that are easily understood and appreciated by both technical and non-technical audiences alike.

1.0 Introduction

The safety review described in this paper was commissioned as part of the Highway 40, (Churchill Road to London Line), Preliminary Design Study Planning and Environmental Assessment (EA) being carried out for the Ministry of Transportation of Ontario. While a separate review of this type is not normally required as part of an EA, a request that an interchange be considered at the junction of Wellington Road and Highway 40, raised a number of questions with respect to road safety and human factors impacts that could not be dealt with through the normal course of the EA analysis.

The primary objective of this road safety analysis was the preparation of a comparative road safety analysis of the two options set forward for consideration: no provision of a connection between Highway 40 and Wellington Street; and the provision of a full interchange between Highway 40 and Wellington Street.

A plan of the sequence of interchanges within the study area, and the specific format that was used for the Wellington Street interchange is shown in Figure 1.

2.0 A risk-based lines of evidence approach

2.1 Background

Risk is not always easy to assess. In some instances, we may be able to quantify it, but in many others, we may not. More often that not, we must rely on expert opinion nourished by related knowledge and presented in what is necessarily a subjective form, to provide the basis for our decisions. To deal with this issue, we took a “lines of evidence” approach: the practice of examining a range of factors that we know may be related to collision overall safety performance and assessing these first individually, and then as a whole.

Where lines of evidence “overlap” and point to a common conclusion regarding a particular feature or element of the interchange, that conclusion is strengthened by the independence of the indicators and the multiplicity of their occurrence as well as the independence of the individual investigators pursuing the different approaches to the analysis.

2.2 Detailed discussion

Our risk management framework looked at five distinct aspects of the performance of proposals for the section of Highway 40 under review:

- **Design practices:** Freeways and freeway interchanges represent the most complex elements of any road system. Speeds are elevated, volumes are high, commercial vehicle traffic is often significant, and driver workloads – particularly in interchanges – can be substantial. Because of this inherent complexity, there is a recognition that adherence to best design practices is a critical component of good freeway and interchange design. As proposed plans depart from such practices, the level of risk to road users of being involved in a collision increases.
- **Human factors:** The science of human factors deals with the perception, cognition, and psychomotor skills of human beings, and their resultant abilities to react appropriately as circumstances demand. In the road context, we are dealing with driver workload and reaction skills, and the need to bear these in mind in our design and operational practices. As driver workload increases, or as drivers are presented with atypical or unexpected situations, their ability to deal with the situation can be overcome, and the potential for collisions increases.
- **Surrogate safety measures (simulation):** We cannot always quantitatively estimate road safety outcomes directly. The tradition of using surrogate measures of safety such as speed changes, speed differentials, conflicts, or other similar metrics is well established as a means of providing an early-warning indicator of potential problems in this respect. Microsimulation techniques were used successfully as long ago as 1990[1] to look at using simulation as a means of carrying out such conflict-based studies in the virtual environment of the computer. The results of such work indicate that properly structured and calibrated models can provide a reasonable environment for assessing changes in surrogate measures such as those noted above.
- **Road safety engineering:** Road safety engineering principles tend to combine both human factors considerations and design practices into one “envelope”. Baseline evaluations of the road safety performance or an existing facility can often help designers identify priorities for remedial action. When such evaluations are extended into the future, they can provide valuable pointers to the most cost-effective design level or type of facility that should be implemented.
- **Operational analysis:** Human factors specialists can help us identify driver workload issues. However, techniques such as the operational analysis - a technique described in the 1999 Geometric Design Guide for Canadian Roads[2] - can also provide a valuable indicator of workload which is based on a quantitative assessment of the available times for decision-making between decision points along critical travel paths through an interchange or system of interchanges.

In our study, each of these areas was examined for its linkages to road safety outcomes. The objective of each examination was to identify the particular aspects of each element that appear most likely to influence road safety performance. In our final analysis, we connected the various “lines of evidence”

[1] Fazio, J. Rouphail, NM. “Conflict simulation in INTRAS: Application to weaving area capacity analysis”. Transportation Research Record 1287. Transportation Research Board. Washington. DC. 1990. pp. 96 - 107

[2] Transportation Association of Canada. “Geometric Design Guide for Canadian Roads”. TAC. Ottawa. ON. 1999.

coming from each examination through an integrated and qualitative discussion of the commonalities and differences of the various indicators used.

3.0 Design practices

3.1 Geometric design and safety: the literature

In the literature search carried out for this project, we specifically looked for work that addressed the challenges of foreshortened separation distances between interchanges, the human factors consequences of such design approaches, and the necessary designer's response. A number of common design themes arose that we felt constituted "best practices" which are particularly relevant to the Highway 40 situation.

- **Reduce driver workload:** Be responsive to task demands and driver attributes: drivers may become overloaded when they have to process too many sources of information too quickly. Overloaded drivers may become confused or miss important information sources[3].
- **Information placement:** Eliminate information related error sources, including the placement of devices too close to a choice point.[4]
- **Spread information:** Spread information across difficult areas. This reduces the chance for overload at high processing demand locations.[5]
- **Extend speed change lanes:** the relative safety of entrance and exit terminals is enhanced with geometric designs that provide longer speed change lanes.[6]
- **Ramp sequence spacing:** In general, dimensions that appear in AASHTO and similar guides for the sequencing of ramps consider both design needs and capacity considerations. Based generally on experience the distances not only accommodate ramp exit or entrance geometric criteria, but also tend to take into account driver operational needs in spreading conflict or decision points.[7]
- **Cost effective priorities**: It is not practical or cost-effective to grade separate all intersecting traffic movements. Since interchanges represent the most costly intersection treatment in terms of initial investment, the selection of the highest priority intersection locations and the design of the interchange are critical in providing an effective and efficient highway system.[8]
- **Reduce error potential**: Driver error is the principal contributing factor in most collisions. Where errors are committed because of the nature of the task, the demands of the situation, lack of visibility of the interchange, expectancy violations, or deficiencies in information display, designers can reduce the potential for driver error by eliminating – among other things:[9]
    - Excessive task demands
    - Unusual manoeuvres or task requirements
    - Poor forward sight distance
    - Expectancy violations
    - Too much processing demand

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[3] Lunenfeld, H. "Human Factors Associated With Interchange Design Features". TRR 1385. Transportation Research Board. Washington, DC. 1993. pp. 84 - 89
[4] Ibid.
[5] Ibid
[6] Twomey, JM, Heckman, ML, Hayward, JC, and Zuk, RJ. "Accidents and Safety Associated With Interchanges". TRR 1385. TRB. Washington, DC. 1993. pp 100 – 105.
[7] Leisch, JP. "Operational Considerations for Systems of Interchanges". TRR 1385. TRB. Washington, DC. 1993. pp. 106-111.
[8] Holzmann, FD, Marek, MA. "Interchange Study and Selection Process". TRR 1385. TRB. Washington, DC. pp. 90 – 99.
[9] Lunenfeld, H. 1993. Op. Cit.

3.2 Findings of the design best practices evaluation

Table 1 summarizes our evaluation of the two alternatives against this series of best practices. The comparison is somewhat trivial in that it is simplistic, nonetheless it does reveal some fundamental differences in the character of the two proposals. In general, the presence of the Wellington interchange appears to compromise the ability of designers to accommodate drivers throughout the study area (from Confederation Street to Highway 402), because it limits their flexibility in handling the movement of traffic within the relatively confined limits of this system of interchanges. Driver workload will tend to be substantially higher when the interchange is present, further complicating the driving task and increasing the potential for collisions.

When the Wellington interchange is absent, driver workload is reduced throughout the system, information is spread, and driver decisions are thus also distributed in time and space – allowing them greater freedom to concentrate on other aspects of the driving task. The increased flexibility offered by the lack of a Wellington interchange also provides the designers with some flexibility to further improve the design using a number of different means, including the provision of extended speed change lanes, if justified. In a vehicle fleet environment that is expected to consist of a large number of heavy vehicles (13% to 16% of total traffic), the benefits of such flexibility could be substantial.

4.0 Human factors review

4.1 Human factors and safety: the literature

At the beginning of our work, we carried out an extensive review of the human factors and safety literature dealing with interchange design and more particularly – issues relevant to their separation. This review is summarized below.

4.1.1 Interchanges and Safety: General issues

In an article entitled “Collisions and Safety Associated with Interchanges”, Twomey et al. report accident rates for on and off ramps of various designs (Twomey, Heckman, Hayward, & Zuk, 1992). Data based on Cirillo is shown in Table 2 (Cirillo, 1967; Cirillo, 1968). As can be seen, on-ramps have on average 2/3 of the accident rate of off- ramps.

Collision rates have been shown to increase as interchange spacing decreases. When spacing is close, then the potential exists for conflicts between traffic that is exiting at the downstream off ramp and traffic that is entering upstream. Table 3 shows that as distance from the exit side to the exit ramp nose ahead lengthens, safety improves. Similarly as distance from the entrance side to the exit ramp ahead lengthens, safety also improves.

Twomey et al.[10] give accident rates by interchange unit for both rural and urban interchanges. The urban rates are shown in Table 4. The very high rate of collisions at urban interchange ramps is attributed to the fact that acceleration lanes are frequently short.

A particular concern with close interchange spacings is the use of add-drop lanes[11], wherein the entering lane continues and becomes an exit lane. An NCHRP report[12] provides an assessment of 65 freeway lane drop sites with respect to operational and safety problems. A total of 13 add-drop sites were

[10] Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J. (1992). "Collisions and safety associated with interchanges." Transportation Research Record, 1385, 100-105.

[11] Freeway lane drops can be classified in a variety of types: *outlying drop* located at the perimeter of a metropolitan area, an *add-drop*, usually added at the on-ramp and dropped at the off-ramp, a *drop-add*, generally found at freeway-to-freeway interchanges, a *step-over*, where one lane is dropped and another added, commonly at left-hand exits, and a *lane split*.

[12] Goodwin, D. N. (1976). "Freeway Lane Drops." Rep. No. NCHRP Report 175, Transportation Research Board, National Research Council, Washington, D.C.

identified. Almost half of these were given bad ratings with regard to operations and safety - most because of sight distance problems. The authors note, “If drivers cannot see the lane drop in time to make a smooth transition out of the dropping lane, erratic manoeuvres may result”.

4.1.2 Interchanges and Safety: Driver Performance Issues

4.1.2.1 Driver Workload while Merging

A study of driver physiological workload suggested that the physiological stress associated with merging onto a freeway subsided 4 seconds after merging. Thus a distance equivalent to 4 seconds at the 85th percentile operating speed should be assumed to allow drivers adequate time before presenting them with the next task of reading the guide sign for the upcoming exit. Assuming that some drivers will wait until the end of the acceleration lane to complete their merge, the 4 seconds should be assumed to begin at the end of this lane.

4.1.2.2 Driver Response to Guide Signs

The time required for drivers to extract information from guide signs was studied extensively using an eye movement camera to record the search behaviour of 5 subjects driving on a highway[13]. Subjects’ visual acuities ranged between 20/15 and 20/35. Maximum legibility for subjects travelling at 60 mph (96 km/hr) was 11 to 16 seconds. On average, the first fixation on the sign, once it was legible, occurred 7 to 10 seconds away, and the last, at 1 to 4 seconds away. Based on these values, it would be best to assume that drivers will be engaged in sign reading starting at a distance equivalent to 10 seconds from the sign up to a distance equivalent to 1 second from the sign.

4.1.2.3 Driver Lane Change Distance Requirements

McGee et al. studied driver lane change distance requirements, including the time to search for and recognize gaps[14]. They found that in low volume conditions a single lane change requires 8 seconds, and in high volume, 9.8 seconds. These data were based on observed single lane change times from a freeway study combined with very limited data on gap search and recognition time from 12 young male drivers.

A smaller study involving 5 drivers over the age of 70 on Highway 401 approaching Toronto Airport found an average time of 6 sec (range 4.3 – 9.7 sec) when no traffic was in the adjacent lane when a single lane change was requested to an average of 12.7 sec (range of 5.7 to 36 sec) when there was traffic in the adjacent lane. Given the frequent presence of traffic in an adjacent lane, the use of younger male driver data on search times, and the use of means rather than 85th percentile values for the McGee et al. estimate, a figure higher than 9.8 sec, and closer to 12.7 seconds seems an appropriate estimate for a single lane change on highways.

There is better data available on times for 2 and 3 lane changes. McGee measured time from signal initiation to wheels fully in the destination lane in an on road study of 20 drivers with an average of 22 years driving experience each. In moderate traffic, at 88 km/h, the 85th percentile distance for 2 lane changes was 405 m., equivalent to 16.6 seconds, and for 3 lane changes, 587 m., equivalent to 24 seconds (McGee’s, 1982).

In conclusion, rounded values of 13, 17 and 24 seconds are assumed to be necessary times required for gap search and lane changing, one, two or three lanes, for passenger car drivers once a sign has been read.

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[13] Bhise, V. D. and Rockwell, T. H. (1973). "Development of a driver-information-acquisition based operational tool for the evaluation of highway signs." Presented at the 1973 Annual Meeting of the Highway Research Board, Washington, D.C.
[14] McGee, H. W., Moore, W., Knapp, B. G., and Sanders, J. H. (1978). "Decision sight distance for highway design and traffic control requirements." Rep. No. FHWA-RD-78-78, U.S. Department of Transportation, Washington, D.C.

4.1.2.4 Driver Response to the Interchange Area

Drivers are assisted in identifying the interchange area if it has good sight distance. It has been shown in two studies that a significant proportion of drivers wait until they can see the road layout before changing lanes.

The best data on the amount of sight distance that drivers require is probably the data on decision sight distance collected by McGee et al.[15]. Drivers were observed as they responded to unusual highway features such as lane drops at an exit or a lane split. Despite warning devices of various kinds, in approximately half the approaches, subjects did not start responding until they actually saw the feature in question. Detection and recognition times varied from a minimum of 1.5 to 3.0 seconds depending on the complexity of the change in the roadway. Decision and response initiation, which includes time to search for a gap prior to changing lanes, took 4.2 to 7.0 seconds and lane change required 3 to 4.5 seconds. On the basis of this work a decision sight distance of 11 – 14 seconds is recommended. At 120 km/h, this is equivalent to 367 to 467 m.

When interchanges are spaced less than 2 or 3 km, it is particularly important to provide decision sight distance of 11 – 14 seconds. At 120 km/h, this is equivalent to 367 to 467 m. sight distance.

4.1.3 Minimum Distance Between Interchanges: Literature Summary

Our review of the literature suggested that in order to design the highway so that drivers can deal with one task at a time, the following factors be accounted for:

- Length of acceleration lane (500 m)
- Time for mental workload associated with merging to subside (4 sec, or 133 m. at 120 km/h)
- Time for responding to guide sign (9 sec, or 300 m)
- Time for a single lane change (13 sec, or 433 m.)
- Length of deceleration lane (345 m).

Thus with a single lane change, the bullnose to bullnose distance required for a workload of one task at a time, is 1711 m assuming a design speed of 120km/h. With two lane changes, this increases to 1845 m. and with three, to 2079 m. (see Figure 3). It is interesting to note that the safety data of Cirillo shows a 50% increase in crash rates as interchange spacing goes from 1.6 to 3 km down to 0.8 to 1.4 km.[16] [17]. This finding supports the values determined from the driver performance analysis.

4.2 Analysis of Highway 40 Site

If an interchange is built at Wellington St., three closely spaced interchanges will result – Confederation St. to Wellington St. (1.4 km), Wellington St. to London Line (1.4 km) and London Line to Highway 402 (0.7 km). Consequently the bullnose to bullnose distances will all be less than the recommended minimum separation distance, based on driver behaviour, which is 1.7 km.

It is undesirable to have two closely spaced interchanges, and even more undesirable to have four, and particularly so when the last interchange of the four is a freeway to freeway interchange with high volumes and likely more unfamiliar drivers than at a local exit. The close spacing will result in a requirement to use an add-drop lane and, because of the short distance, continue that lane so that it becomes the exit lane. Exiting drivers will expect the merge lane to be dropped before the exit lane begins, and may be uncertain of when to enter this continuous lane, leaving it too late to do so safely.

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[15] McGee, H. W., Moore, W., Knapp, B. G., and Sanders, J. H. (1978). "Decision sight distance for highway design and traffic control requirements." Rep. No. FHWA-RD-78-78, U.S. Department of Transportation, Washington, D.C.

[16] Cirillo, J. A. (1967). "Interstate System Accident Research Study II. Interim Report, Part I." Highway Research Record, 188, 1-7.

[17] Cirillo, J. A. (1968). "Interstate System Accident Research Study II. Interim Report, Part II." Public Roads, 71-75.

Signing will be a particular challenge in this situation. In rural areas advance signs are generally placed 1 km before the exit bullnose. In urban areas, sequential signing is used, in lieu of advance signing. Figure 3 shows a rough outline of a signing plan for northbound Highway 40. Drivers exiting at London Line will see the advance sign for London Line at a distance that will ensure some of these drivers enter the continuous lane to exit before entering drivers at Wellington St. have a chance to merge with the through traffic. Thus the close spacing of Wellington St. and London Line will set up conflicts between entering and exiting drivers.

An even more difficult situation is created for drivers entering at London Line. If the advance sign for Highway 402 is at the standard distance of 300 m. from the exit bullnose, then entering drivers at London Line will be faced with dealing with this sign as they are trying to merge. The limited viewing distance of about 100 m. will make this even more stressful for unfamiliar drivers, and in particular if those drivers are trying to reach Highway 402.

4.6 Findings of the human factors review

- If an interchange is built at Wellington St., four closely spaced interchanges will result – Confederation St. to Wellington St. (1.4 km), Wellington St. to London Line (1.4 km) and London Line to Highway 402 (0.7 km).
- All of these interchange spacings fall below the minimum distance of 1.7 km, between an on-ramp bullnose and an off-ramp bullnose, recommended on the basis of driver performance analysis, and supported by the safety analysis.
- At Wellington St. entering and exiting drivers will use the same, short continuous lane, and conflicts will likely occur between early entering and late exiting drivers.
- Signing will be challenging because of the need to provide advance information for a freeway-to-freeway interchange, “freeway ends” information for Highway 40, in an area with 4 closely spaced interchanges.

5.0 Simulation analysis

5.1 Basis of the Analysis

The purpose of the simulation analysis was to use micro simulation network modeling tools to help us evaluate the relative road safety performance of the alternatives from the standpoint of a number of surrogate measures of safety:

- The location and the number of lane changes taking place;
- Speed variations on individual through lanes and auxiliary lanes;
- Variation in vehicles headway on individual through lanes and auxiliary lanes;
- Potential conflict areas along the corridor.

Network models were developed using digital mapping and aerial photography of the Highway 40 corridor that accurately represented interchange and intersection locations, curve radii, ramp locations and other key geometric features of the corridor. The evaluation of operations along the corridor resulted in production of the 8 individual network models summarized in Table 5.

5.2 Microsimulation Tools Used

We used the CORSIM microscopic simulation models, operating within the **T**raffic **S**oftware **I**ntegrated **S**ystem (TSIS) environment to model the Highway 40 corridor. The nature of micro simulation techniques allows the representation of individual vehicle movements along the corridor, the evaluation of vehicle interactions at critical locations such as weaving areas and ramp terminals, and the assessment of the overall variation of operations along the corridor.

The corridor model was built using both the FRESIM model (for representing freeway road sections) and the NETSIM model (for urban road networks). FRESIM was used to represent all road and ramp sections along Highway 40. NETSIM was used to model the cross roads at London Line, Wellington Street and Confederation Street, including signalized intersections. In this way, the platoon effect resulting from the signal operations could be represented in traffic moving to Highway 40.

5.3 Results of the Analysis

5.3.1 Lane Changes

8 northbound and 8 southbound road segments represented the critical road sections on Highway 40 between Confederation Street and London Line. Table 6 shows the number of lane changes that occurred on each section of roadway.

The data show that the addition of the interchange at Wellington Street increases overall lane changes by approximately 6.3% in the PM peak hour and 8.4% during the AM peak hour. With an interchange present at Wellington Street, lane changes increase significantly in the vicinity of the interchange and reduce to a lesser extent at Confederation Street and London Line.

5.4.2 Lane Specific Speed Variations and Headways

Using virtual detectors within the simulation model, mean speed and headway information was collected at 100-foot intervals in each lane (including auxiliary lanes) of the models between Confederation Street and London Line.

The following points summarize the key findings resulting from this analysis:

- Speed changes along the corridor are most common and noticeable at interchange on-ramps and tend to have the greatest impact on traffic in the outside through lane.
- Elimination of the Wellington Street interchange increases the magnitude of speed reductions at the London Line and Confederation Street on-ramps by an average of 4.3 km/hr. These increases are accompanied by the elimination of on-ramps and their associated speed reductions at the Wellington Street interchange. Conversely, the addition of the interchange results in minor decreases in the magnitude of speed changes at London Line and Confederation Street, but introduces a significant mean speed reduction of approximately 14.7 km/hr at the Wellington Street interchange.
- Generally, speed reductions occur over a relative short distance. The magnitude of the speed change and the distance over which the change occurs is generally reflected in the magnitude of the change in vehicle headways. In other words, higher volumes of traffic entering the Highway 40 corridor at an on-ramp are reflected in the figures by greater speed reductions and a greater reduction in vehicle headways.
- The speed reductions related to the interchange at Wellington Street introduce a level of turbulence to the systems that can be identified by the increased variability in the speed profiles when the interchange is present. Such speed reductions and turbulence represent collision vectors – essentially increasing the risk of collisions because of the need for speed changes and/or avoidance manoeuvring that these generate.

5.4.3 Visual Conflict Analysis

The previous two analyses identified critical areas of potential conflict along the corridor. We supplemented our findings with visual observations of merging and weaving movement along the corridor. TSIS allows such observations in the context of identifying acceleration, braking, and emergency braking actions by vehicle colour. Lane changes, merging/diverging activities, and weaving are identifiable simply by observation.[18]

While traffic volumes along the corridor are below the capacity of the facility and generally result in adequate gaps to allow merging and weaving movements to take place smoothly, we did note various areas where a significant number of braking actions were occurring within merging and weaving zones. The most significant occurrences of such actions were generally related to a platoon of vehicles entering the Highway 40 corridor after passing through a signalized intersection on the surface street system. Such occurrences do not appear to be significantly worse at the Wellington Street interchange as compared to London Line or Confederation Street, but the presence of the interchange introduces a new potential conflict location. This potential for conflicts is exacerbated by relatively close proximity of the adjacent interchanges, and particularly in the short weaving sections between Confederation Street and Wellington Street in the northbound direction and London Line and Wellington Street in the southbound direction.

5.5 Findings of the Simulation Analysis

The following points summarize the key finding of the simulation analysis.

- The Wellington Street interchange introduces additional side friction between the Confederation Street and London Line interchanges resulting in more turbulent speed profiles along the corridor. This side friction represents a collision vector that increases the probability of crashes in this area.
- The absence of the Wellington Street interchange results in an area of relatively stable traffic flow between London Line and Confederation Street.
- Our analysis did not specifically identify any critical locations with a high potential for conflict, though it did identify a number of locations where operational characteristics appear to indicate the presence of collision vectors as noted earlier, and a consequent increased potential for collisions.
- The addition of the Wellington Street interchange to the corridor results in minor operational improvements at London Line and Confederation Street, but introduces a significant impediment to smooth traffic flow through the corridor.
- The addition of the Wellington Street interchange to the corridor results in a notable increase in overall lane changes in the corridor.

6.0 Road safety engineering considerations

6.1 Background

This current review was preceded by a more detailed examination of the existing Highway 40 facility in respect of both its deficiencies today, and projected needs in the planning horizon year. Part of that review examined the road safety performance of the current road segments and intersections within the study area, and also looked at the implications for road safety performance in the future.

Both of these analyses proved instructive in helping to assess the implications of the level of facility being proposed for Route 40. The key elements of their findings are summarized below.

[18] While "virtual" conflict studies of this type are useful general indicators that reflect the order of magnitude and location of conflicts, they must be interpreted with care, since the car following algorithms widely used in microsimulation models do incorporate limits on closing speeds and distance that may not completely reflect what drivers may do – particularly when closure rates are high, and vehicle separations are very short.

6.2 Implications of the baseline road safety performance analysis

The implications of the baseline studies are interesting:

- In general, the current level of safety performance of the facility is about what would be anticipated given the physical characteristics of the facility and its traffic loading.
- There are no glaring negative inconsistencies in performance of the various intersections and road sections within the study area;
- In at least two road section cases (Churchill Road to Scott Road and Wellington to London Line) it appears that the road safety performance level is substantially better than might normally be expected of similar roads of this type;
- In at least two signalized intersection cases (Confederation Road and Wellington Road intersections with Highway 40) it appears that the road safety performance level is substantially better than might normally be expected of similar intersections of this type;
- While the smoothed collision prediction for the Churchill Road signalized intersection indicated higher than expected collision frequencies, the proportion of fatal and personal injury accidents was lower than is typically the case for similar roads. Property damage collisions are about 51% higher than the “generic” case.
- In general, and from a road safety performance standpoint, the road system in the area is performing at least as well, and in several cases, better than expected.
- In the case of the Churchill Road intersection with Highway 40, the analysis indicated that this location was performing substantially better than what might be expected of a road of this type;
- Even in the planning horizon year (2020) it appears that the Churchill Road/Highway 40 intersection does not warrant a priority investment.

7.0 Quantitative operational analysis

7.1 The basic principles

The latest Transportation Association of Canada (TAC) Geometric Design Guide (1999)[19] has introduced a new concept, called Operational Analysis, in analyzing complex interchange designs. The concept of Operational Analysis is also being considered for inclusion in the current draft version (2003) of the Ministry’s Geometric Design Standards.

Operational Analysis is a tool used to understand & evaluate a complex roadway design and test for ease of operation and route continuity from a driver’s perspective. It is most appropriate for evaluating interchange designs in association with other freeway design elements. The object is to “put oneself in the driver’s seat” and to isolate and analyze one driver route at a time. Obviously, the technique is closely related to human factors, and serves as an excellent means of quantifying driver workload in the context of the physical design of the road. This integrated, path-oriented systems approach can be particularly helpful in detecting unforeseen interactions between design elements as well.

The benefit of applying this technique is that an additional check is performed on a plan or design to confirm that it is operationally “friendly” to a driver prior to the selection of a recommended design. It can also highlight features in an operational setting rather than the traditional method of looking each feature in isolation (i.e. all horizontal sight distances followed by all vertical sight distances followed by signage locations, etc.).

[19] Transportation Association of Canada. “Geometric Design Guide for Canadian Roads”. TAC. Ottawa, ON. 1999

7.2 The analysis

Our operational analysis was carried out on two driver routes for the scenario assuming a Wellington Street Interchange. The interchanges assumed at Confederation Street and London Line/Highway 402 were the same as those assumed in the other line-of-evidence analyses. The two analyzed routes were:

- Highway 40 Northbound from Confederation Street to London Line/Highway 402
- Highway 40 Southbound from Highway 402/London Line to Confederation Street

The assumed future interchange scenario and the examined driver routes are shown in Figure 4.

The results of the quantitative operational analysis (QOA) affirm the findings of the human factors review. This is not surprising, since the nature of QOA is based in human performance in information processing and decision-making. The advantage of the technique is the clear link that is made between driver workload challenges and specific physical features of the design – through the length of a series of decisions. In essence, the technique is an approach that recognizes the “systems” nature of both interchange and freeway design.

7.3 Findings of the quantitative operational analysis

The key findings of the QOA on the option with the interchange present can be summarized as follows:

- Both the northbound and southbound directions suffer from critical deficiencies in certain areas.
- Key deficiencies from a human factors standpoint arise from a number of factors, including the impossibility of providing adequate signing, the provision of marginal and deficient separations between consecutive bullnoses (something that affects not only weaving activities, but also other manoeuvres that drivers must execute, including merge, diverge, and simple lane change moves.
- Driver workload for signing is generally medium to high throughout both the north and southbound directions. When considered in the context of foreshortened weave, merge, diverge, and lane change provisions, the workload can probably be considered to be high to very high. Such situations are generally associated with higher levels of risk for collisions.
- A critical sight distance deficiency exists for both DSD and SSD in the southbound direction in the area of London Line.
- Signing in accordance with accepted human factors practices is impossible on 3 of the 6 road segments where signing was an issue.
- The analysis seems to indicate that the Wellington Street interchange could contribute to a substantive compromise in safety performance levels throughout the length of the study area.

8.0 Synthesis of the lines of evidence

8.1 Risk management index structure

Our reviews in the course of this study were limited to the primary focus of road safety and were based on probabilistic assessments. Thus, in developing our final recommendations, we needed to recognize the fundamental nature of the uncertainty built into our conclusions. The “lines of evidence” approach we used provided independent corroboration of facts and conclusions from different sources – a technique which helps to reduce the uncertainty associated with our assessments.

In building our risk assessment profile, we wanted to assess our previous findings from a risk management standpoint. We did this by assessing the two basic aspects of risk associated with each risk element (or “feature”) identified in the lines of evidence as a critical element meriting some attention:

- The magnitude of the potential impact of the feature;

- The likelihood of that impact being realized;

Readers will quickly recognize the “magnitude” and “probability” elements of the classic risk model.

We implemented our risk assessment – or more properly, risk sensitivity evaluation – through the expedient of a quantitative, but subjectively based technique that required a two-step process:

- The estimate of the magnitude of the potential impact of each risk element and the relevant probability of its associated benefits (in terms of reduced collisions) being realized.
- We then calculated an outcome matrix in which the probability factor was multiplied by each impact measure for each line of evidence and element. This provided an output matrix of numbers that were then averaged horizontally to give a final outcome measure for each risk element. The higher the value of that measure, the greater the degree of risk, since higher values of the final index reflect elements associated with a combination of a greater potential for a negative impact, and a higher likelihood of the impact occurring.

The scales we use as input to this process reflect the underlying probabilistic nature of the problem.

1. The potential magnitude of the impact was estimated on a scale of 0 to 1 with 0 representing the lowest possible impact, and 1 the highest.
2. The likelihood of the event actually occurring was also estimated on a scale of 0 to 1 with 0 representing the lowest possible likelihood, and 1 the highest.

8.2 The candidate risk elements

Each of our lines of evidence assessment developed a list of “features” or risk elements of concern. Summarizing and combining common elements provided us with a final list of impact elements to be evaluated in our risk based process. The final candidate risk elements carried into this analysis were as follows:

- Driver workload: The potential for impacts from excessive driver workload;
- Information placement: The potential for the need to accept substandard information placement (all perspectives);
- Limited ramp spacing: The presence of operational constraints in ramp spacing.
- Driver error potential: The potential for driver errors to occur;
- Atypical features: The presence of non-typical design features;
- Deficient signing: The presence of deficient signing (in terms of driver needs);
- Collision vectors present: The presence of design or operational features or phenomena usually associated with higher risks of collisions;
- Sight distance deficiency: The presence of sight distance deficiencies.

8.3 Analysis outcomes

The two alternatives are compared on the outcome factor – which reflects a combination of the potential impact of various risk factors and the likelihood of their occurrence in each of the schemes. Obviously, the impact factors (i.e. the potential impact of risk factors) are the same for each scheme. The differentiation occurs because of the differences in likelihood that certain outcomes will be realized given that fundamental design aspects of the schemes differ because of the presence or absence of the Wellington Street interchange.

Table 7 provides a direct comparison of the outcome factors for each alternative. This table must be interpreted with great caution, since it is essentially the product of a subjective evaluation. However, it is based on the findings of the independent lines of evidence investigations by independent experts, and every effort was made to ensure that the ratings reasonably reflect the findings of those analyses. In assessing the comparison, it is the relative differences that are instructive, and not the absolute values of the factors themselves.

A lower outcome factor reflects a lower “risk” of the impacts of the various risk elements being realized. In this case, it is evident that the presence of the Wellington Street interchange will likely increase the risks associated with the various elements defined in our assessment matrix. The differences in outcome factors are consistent and relatively large.

9.0 Concluding thoughts

The project documented in this paper attempted to assess the alternative schemes for Highway 40 from the standpoint of their potential road safety and human factors performance. In so doing, we used a multiple lines of evidence approach in our evaluation that we found yielded strongly corroborating results that reflected current well-established thinking and practices with respect to the design of systems of interchanges and their relative spacings.

In closing, we stress the fact that our evaluation approach was based on road safety considerations only. We fully realize that these are not the only criteria upon which final design and planning decisions will be made, but are of the opinion that the techniques used in this work are practical, robust and extensible to similar projects, and provide a sound basis for the explicit evaluation of road safety outcomes which can then be used as input to the larger design decision process.

Figure 1.: Study area and reviewed Wellington Street interchange plan

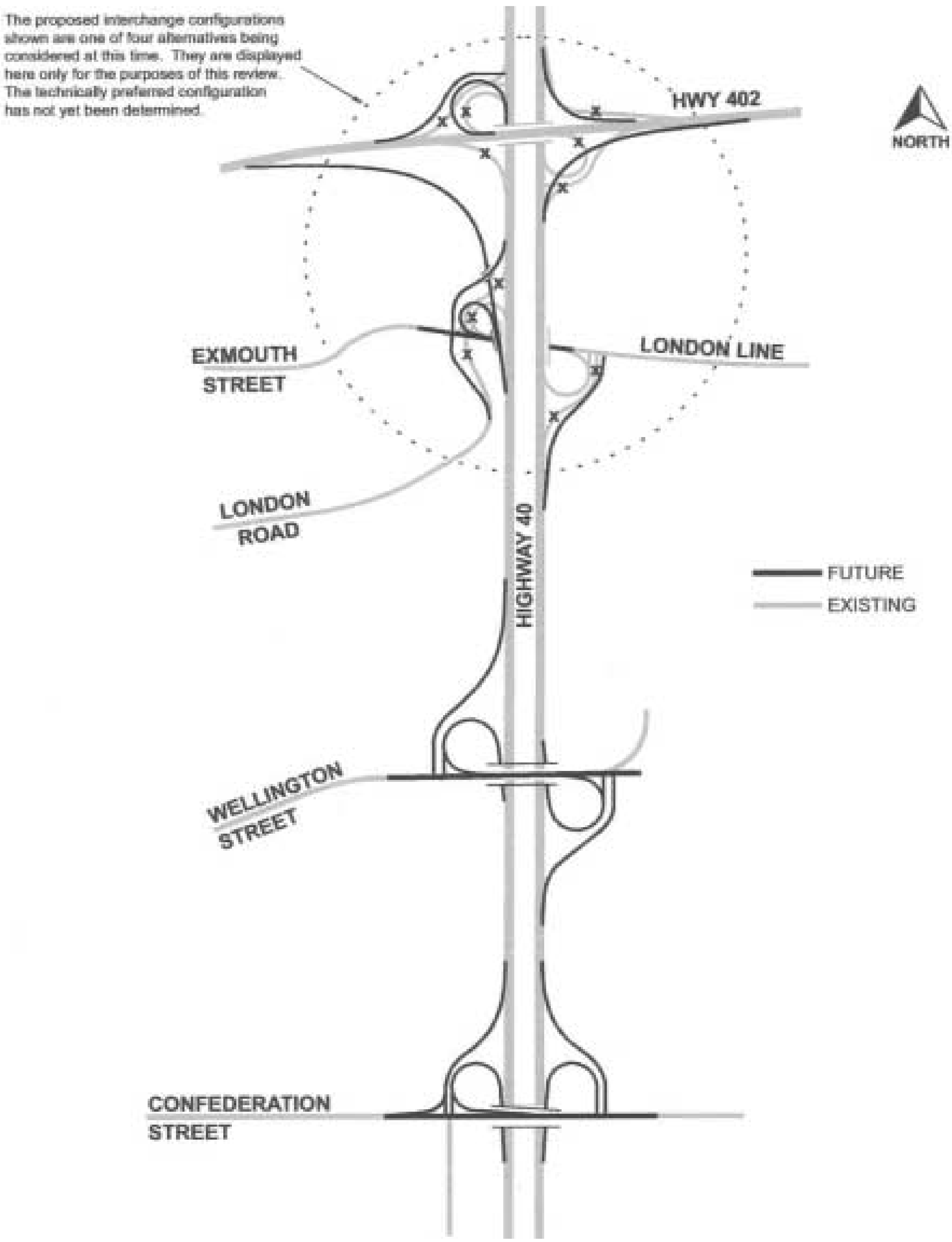
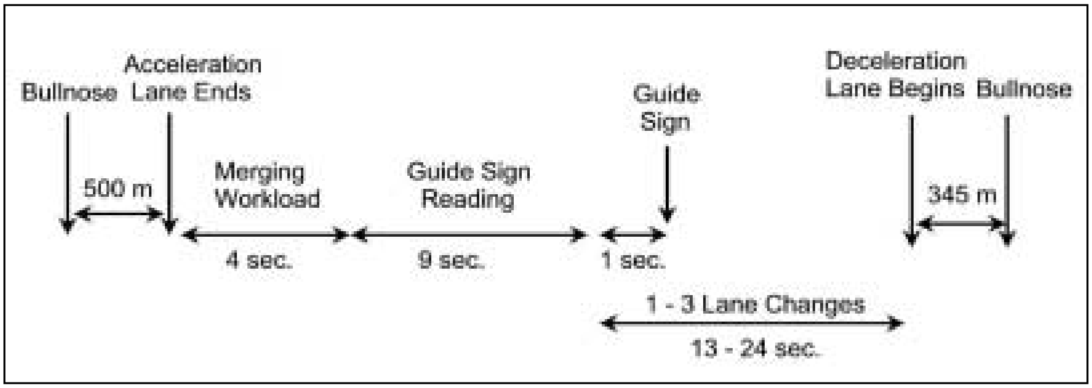
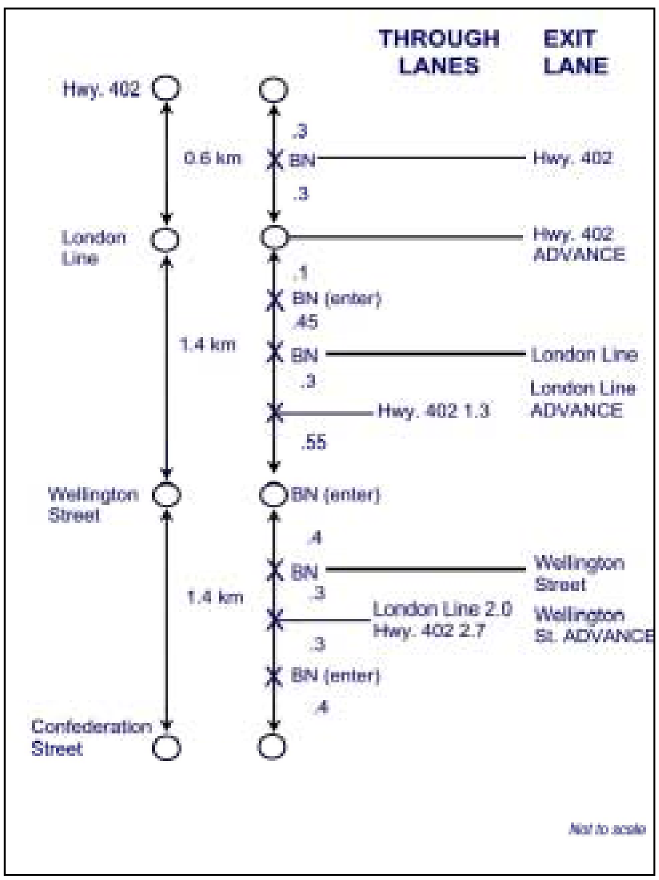


Figure 2: Interchange Spacing: Driver Performance Requirements - Bullnose to Bullnose



N.B. At 120-km/h minimum spacing is 1711 m for 1 lane change, 1845 m for 2 lane changes and 2079 m for 3 lane changes. Speed lane change lengths are shown for design speed of 120 km/h (GDSOH)[20].

Figure 3: Signing plan for Highway 40



[20] Ministry of Transportation of Ontario. "Geometric Design Guide for Ontario Highways". Downsview, ON.

Figure 4: Operational analysis paths and interchange format

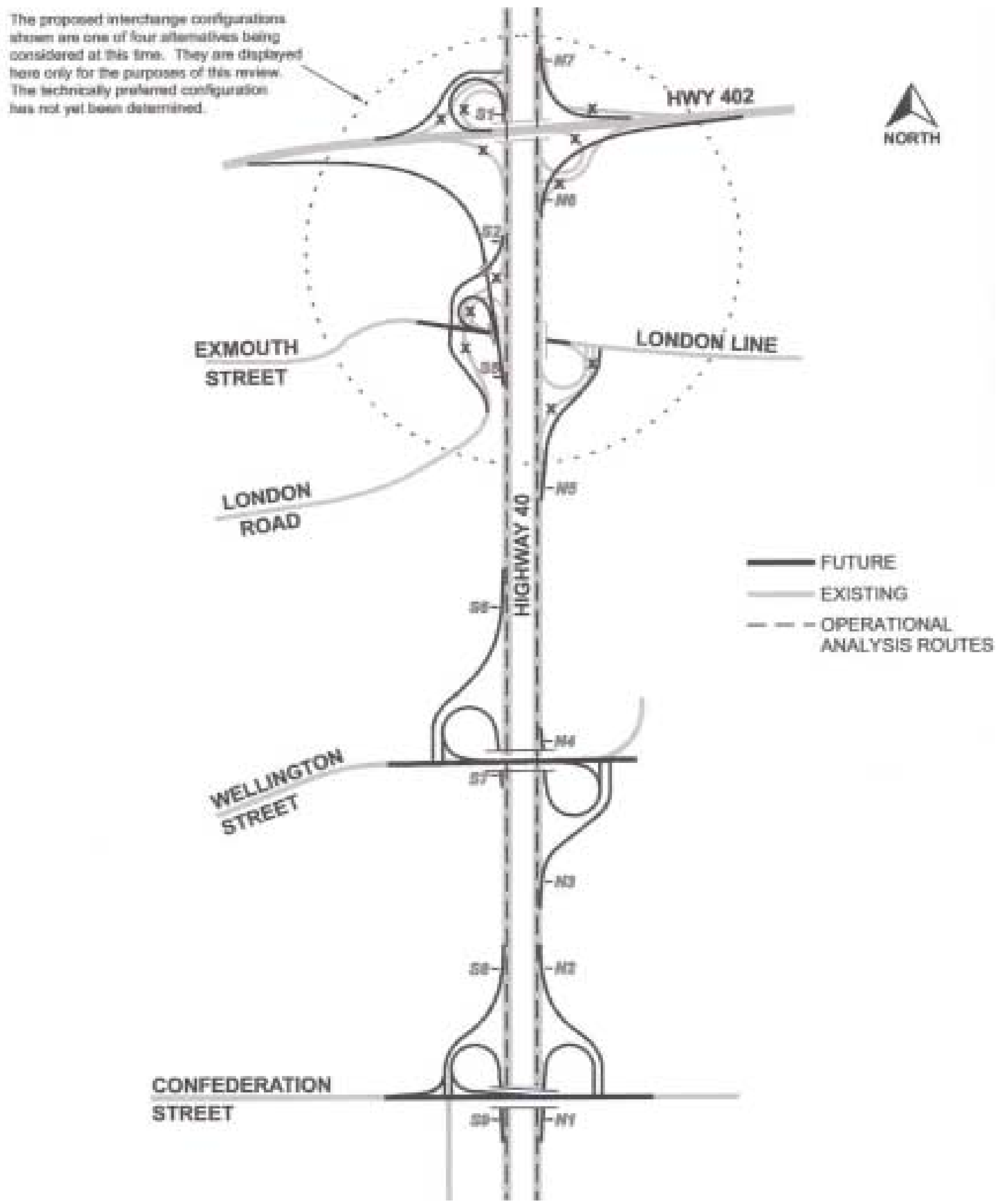


Table 1: Comparative analysis against best practices

Best Practice	Without Wellington IC			With Wellington IC		
	Complies	Moderate compliance	Does not comply	Complies	Moderate compliance	Does not comply
Moderate driver workload		✓				✓
Information placement		✓				✓
Spread information	✓					✓
Extend speed change lanes		✓				✓
Ramp sequence spacing		✓				✓
Cost effective priorities	✓					✓
Reduce error potential		✓				✓

Table 2: Collision rates by type of freeway ramp [21]

Ramp Type	On	Off	On & Off
Diamond Ramps	0.40	0.67	0.53
Cloverleaf Ramps with Collector-Dist Roads[a]	0.45	0.62	0.61
Direct Connections	0.50	0.91	0.67
Cloverleaf Loops with Coll-Dist Roads[a]	0.38	0.40	0.69
Buttonhook Ramps	0.64	0.96	0.80
Loops with Coll-Dist Roads	0.78	0.88	0.83
Cloverleaf Ramps w/o Coll-Dist Roads	0.72	0.95	0.79
Trumpet Roads	0.84	0.85	0.85
Scissor Ramps[b]	0.88	1.48	1.28
Left Side Ramps	0.93	2.19	1.91
Average	0.59	0.95	0.79

NOTE: Collision rates are per million vehicles

[a] Only the On & Off rate includes the collisions occurring on the collector-distributor roads.

[b] A ramp that has opposing traffic crossing the ramp traffic under stop sign control.

[21] Cirillo, J. A. (1967. "Interstate System Accident Research Study II. Interim Report, Part I." Highway Research Record, 188, 1-7. (Adapted)

Table 3 Collision rates by proximity to interchange ahead or behind [22]

EXIT SIDE Distance to exit-ramp nose ahead	Number of Collisions[a]	Collision Rate [b]
Less than .2 miles	722	131
.2 - .4 miles	1,209	127
.5 - .9 miles	786	110
1.0 – 1.9 miles	280	75
2.0 – 3.9 miles	166	63
4.0 – 7.9 miles	19	69
More than 8 miles	No data available	
ENTRANCE SIDE Distance to exit-ramp nose ahead	**Number of Collisions[a]**	**Collision Rate [b]**
Less than .2 miles	426	122
.2 - .4 miles	1,156	125
.5 - .9 miles	1,655	105
1.0 – 1.9 miles	278	84
2.0 – 3.9 miles	151	59
4.0 – 7.9 miles	200	75
More than 8 miles	No data available	

[a] No. of Collisions
[b] Collisions per 100 Million Vehicle-Miles

Table 4 Collision rates by interchange unit

Interchange Unit	Vehicle Miles (100 Mil.)	Number of Collisions[a]	Collision Rate[b]
Deceleration Lane	5.83	1,089	186
Exit Ramp	1.48	546	370
Area between speed change lanes	11.87	1,982	167
Entrance Ramp	1.61	1,159	719
Acceleration Lane	8.40	1,461	174
Acceleration – Deceleration Lane	2.45	555	227
Total	31.64	6,792	214[c]

[a] No. of Collisions
[b] Collisions per 100 Million Vehicle-Miles
[c] Average Accident Rate

[22] Ibid.

Table 5 Network models used for analysis

Wellington Interchange Present	PM Peak Hour	Northbound
		Southbound
	AM Peak Hour	Northbound
		Southbound
Wellington Interchange Not Present	PM Peak Hour	Northbound
		Southbound
	AM Peak Hour	Northbound
		Southbound

Table 6 Summary of lane changes by road segment

Segment	**PM Peak**		**AM Peak**	
	Interchange	**No Interchange**	**Interchange**	**No Interchange**
NB1	183	99	130	60
NB2	1225	1687	670	1036
NB3	166	278	44	140
NB4	247	281	117	143
NB5	2059	739	1067	394
NB6	806	1075	378	642
NB7	732	470	301	281
NB8	1336	1700	664	986
SB1	80	67	179	106
SB2	1707	1672	1899	1580
SB3	978	280	1325	298
SB4	162	306	303	408
SB5	1430	654	1222	805
SB6	1046	1075	1121	1217
SB7	113	164	125	108
SB8	1154	2080	785	1324
Total	**13424**	**12627**	**10330**	**9528**

Table 7 Comparison of outcome factors on each risk element for the two schemes

Risk element	**Outcome Factors**	
	Without Wellington	**With Wellington**
Driver workload	0.25	0.56
Information placement	0.28	0.66
Limited ramp spacing	0.23	0.79
Error potential	0.15	0.63
Atypical features	0.08	0.51
Deficient signing	0.14	0.56
Collision vectors present	0.17	0.63
Sight distance deficiency	0.16	0.74