Moving (More) People Safely:
Examining the Safety Impacts of HOV Lanes

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Abstract

High-occupancy vehicle (HOV) lanes are designed to increase the passenger-carrying capacity of roadways by requiring that all vehicles using the HOV lanes be occupied by a minimum number of passengers (e.g., the driver plus, at least one additional passenger).

HOV lanes, in various forms, have been in use across North America for several decades. However, there is little information available with respect to their impact on the safety performance of the roadways to which they have been added.

Over the past ten years, HOV lanes have been added to several freeway facilities in the Greater Toronto and Hamilton Area (GTHA), and analysis was recently undertaken to examine how the HOV lanes have impacted safety on the treatment sections of those roadways. Predictive collision analysis was used to calculate collision modification factors (CMF) for the addition of buffered, limited-access, concurrent flow HOV lanes to a simple, controlled-access freeway. Related, trends in collision activity have also been identified, as have areas for potential future study.

Based on the CMF development and collision trend analysis, the general conclusion that can be reached is that the addition of buffered, limited-access, concurrent flow HOV lanes to a simple, controlled-access freeway can be expected to result in a moderate (15%) increase in overall collision frequency. The increase in collisions consists almost entirely of additional property damage only (PDO) collisions, particularly rear-end collisions, freeway congestion and several HOV lane design elements appear to be contributing factors.

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Introduction

It's no secret that congestion is a significant obstacle to productivity, and the associated costs have been estimated to reach into the billions of dollars in many of North America's major urban areas. The commonly cited figure for the cost of congestion in the Greater Toronto and Hamilton Area (GTHA) is $6 billion annually (TBOT, 2011), and that reflects only the value of time wasted in traffic. A 2013 study titled *Cars, Congestion and Costs: A New Approach to Evaluating Government Infrastructure Investment* (C. D. Howe Institute, 2013) suggests that the full economic impacts of traffic congestion may be $1.5 to $5 billion per year greater than the commonly cited figure.

High-occupancy vehicle (HOV) lanes are one of the many tools available to transportation practitioners and road authorities in the battle against congestion. In very basic terms, HOV lanes are designed to increase the passenger-carrying capacity of roadways by requiring that all vehicles using the HOV lanes be occupied by a minimum number of passengers (e.g., the driver plus, at least one additional passenger). HOV lanes, in various forms, have been in use across North America for several decades. The fist HOV facility in the US was opened on I-395, in 1969 (TTI, 1998). Over the past ten years, HOV lanes have been added to several freeway facilities in the GTHA. Furthermore, the Province of Ontario has a plan to add over 450 kilometres of new HOV lanes on 400-series highways in the GTHA, and beyond, over the next 25 years (MTO, 2010).

There is little debate about the ability of freeway HOV lanes to increase capacity and a reduce travel times. Under the right conditions, HOV lanes have been proven to provide significant travel time savings and improve travel time reliability, while moving more passengers per lane, and providing an incentive against single-passenger travel. A comprehensive study of HOV lane effectiveness across 12 Districts in California, a state with an extensive freeway HOV network, presented data that suggest average travel time savings of almost 30 seconds per mile (1.6km) in some HOV lanes (May, Leiman, & Billheimer, 2007). Ample research has been conducted and many papers have been written on the operational benefits of HOV facilities. For that reason, the subject of HOV lane operational effectiveness will not be discussed further in this paper. However, there is little information available with respect to the impact that HOV facilities have on the safety performance of the roadways to which they have been added.

The remainder of this paper is dedicated to an investigation of the safety impacts of freeway HOV facilities, including an analysis that was recently undertaken to examine how HOV lanes have impacted safety performance on the treatment sections of two freeways in the GTHA. Predictive collision analysis was used to calculate collision modification factors (CMF) for the addition of buffered, limited-access, concurrent flow HOV lanes to a simple, controlled-access freeway. Related, trends in collision activity have also been identified, as have areas for potential future study.

Literature Review

The first phase in this investigation of the safety impact of HOV lanes was to conduct a thorough literature review. The general conclusion reached following that effort was that there is scarcely little reliable information available about the safety performance of HOV facilities. Despite many jurisdictions having HOV lane monitoring and performance programs, where safety is among the criteria monitored; there have been few published reports dedicated to the safety of HOV facilities. What little information is available on the safety of HOV facilities consists mostly of comparisons of the relative safety performance of various HOV lane design elements or operational strategies.

Even in California, where much of the recent work in the evaluation of HOV facilities appears to have been conducted, there has not been an in depth investigation of how adding HOV lanes to freeways impacts collision frequency or severity. In the 2007 report titled *Determining the Effectiveness of HOV Lanes* (May, Leiman, & Billheimer, 2007), the reports from each of the polled Districts contained a section on safety, and, in virtually every instance, the opinion expressed therein was that "there is not enough evidence to state whether HOV lanes increase or decrease accidents when installed on mainline freeways."

With respect to the relative safety performance of HOV facility design elements and operational strategies, the consensus appears to be as follows:

- Newly constructed HOV lanes (typically with wider shoulders) perform better than retrofitted general purpose (GP) lanes (MTO, 1985);
- Concurrent-flow (same direction) lanes are preferable to contra-flow (or reversible-flow) lanes (Cothron & al., 2004);
- Barrier/buffer-separated HOV lanes provide a safety benefit over directly adjacent (non-separated) HOV lanes (Cothron & al., 2004);
- Continuous access HOV lanes perform better than limited-access HOV lanes, and HOV lane ingress/egress zones in close proximity to on/off-ramps result in a significantly higher collision rate (Jang & al., 2008); and
- Converting HOV lanes to high-occupancy toll (HOT) lanes appears to reduce collisions (Cao, Xu, & Huang, 2012).

HOV lanes in Ontario appear to have been designed with many of the above considerations in mind, and the following statement about HOV lane safety from the Ontario Ministry of Transportation (MTO) website confirms as much:

> *Ontario's HOV lanes have been designed to the highest safety standard, based on over 30 years of experience in other jurisdictions with HOV facilities. Ontario's HOV design includes a buffer separating the HOV lane from the general traffic lane, lane widths to ministry standards and a left shoulder, for optimum safety.*
>
> *Poor safety records of some HOV facilities in other jurisdictions are a result of adding an HOV lane where the existing roadway cannot accommodate a buffer between the HOV lane and general traffic lane, adequate widths for the general traffic and HOV lanes and/or a left shoulder. The result is an increase in the likelihood of collisions and reduced driver manoeuvrability. MTO's HOV lanes have been added to existing highways by widening the highway, rather than converting existing lanes or shoulders* (MTO, 2013).

Despite the significant efforts that have been made to improve the design and operations of HOV lanes, through their monitoring programs, many jurisdictions have reported higher collision rates on freeway sections with HOV lanes than those experienced on sections with only GP lanes. This trend, along with the general lack of information available on the relative safety performance of freeways with and without HOV lanes, is the motivation behind this paper.

Analysis Methodology

An analysis was undertaken to investigate the relative safety performance of freeways with and without HOV lanes. The analysis was conducted in two stages. The first stage involved the development of collision modification factors (CMF) for the implementation of the HOV facilities, while the second stage consisted of a review of collision trends and attributes.

The CMFs were developed to assess the safety performance of the freeways with HOV facilities relative to the expected performance of freeways without HOV facilities in terms of collision frequency. The review of collision trends and attributes was conducted in an attempt to identify design and operational characteristics of the HOV facilities that could be contributing to the change in collision frequency described by the CMF.

CMF Development

The CMF was developed by applying the observational, empirical Bayes (EB) before-after study methodology outlined in *A Guide to Developing Quality Crash Modification Factors* (FHWA, 2010). In basic terms, the applied methodology involves comparing observed collisions at treatment sites to the number of collisions that would have been expected to occur at those same sites had the treatment not been applied. In this case the treatment was the addition of HOV facilities though freeway widening.

By applying the EB methodology, rather than the untreated comparison group method, it is possible to better account for issues related to regression-to-the-mean, and changes in safety due to traffic volumes and time trends, resulting in a more precise estimate of the number of collisions that would have occurred without the treatment. In the EB methodology, the untreated comparison group is replaced by a weighted average of observed collisions at the treatment sites and predicted collision frequencies for the treatment sites, calculated using safety performance functions (SPF).

The specific steps for applying the EB methodology are as follows:

1. Collect observed collision frequencies for the before period (N_{OB}) and for the after period (N_{OA}) for the treated sites;
2. Collect average annual daily traffic (AADT) volumes for the treatment sites for each year of the analysis period;
3. Using applicable SPFs, calculate the predicted number of collisions (without treatment) at the treated sites for the before period (N_{PB});

   SPF for freeway segments (Persaud, Begum, & Lyon, 2009):

   $$\textit{Collisions/year } (N_{PB}) = \alpha(\textit{length})(\textit{AADT})^{\beta} \quad (1)$$

   SPF for freeway interchange mainlines (Parajuli, Lyon, & Persaud, 2006):

   $$\textit{Collisions/year } (N_{PB}) = \alpha(\textit{AADT})^{\beta 1} e^{\beta 2(\textit{length})} \quad (2)$$

   Where the α, β, β1, *and* β2 *are coefficients estimated during the SPF development, that vary based on collision severity and freeway geometry, and "length" is the freeway segment length or interchange area of influence in kilometers.*

4. Using the same SPFs, calculate the predicted number of collisions (without treatment) at the treated sites for the after period (N_{PA});
5. Calculate the *SPF weight*, and use it to estimate the expected number of collisions for the before period (N_{EB});

   $$N_{EB} = \textit{SPFweight}(N_{PB}) + (1-\textit{SPFweight})N_{OB} \quad (3)$$

   $$\textit{Where the SPF weight} = 1/(1+N_P(\phi)) \quad (4)$$

   And ϕ *is the over-dispersion parameter estimated during the SPF development.*

6. Calculate the ratio of N_{PA}/N_{PB} for the treatment sites;
7. Calculate the expected number of collisions for the after period (N_{EA});

   $$N_{EA} = N_{EB}(N_{PA}/N_{PB}) \quad (5)$$

8. Calculate the variance of N_{EA} ($Var(N_{EA})$);

   $$Var(N_{EA}) = N_{EA}(N_{PA}/N_{PB})(1-\textit{SPFweight}) \quad (6)$$

9. Calculate the CMF;

   $$CMF = (N_{OA}/N_{EA})/(1+(Var(N_{EA})/(N_{EA})^2) \quad (7)$$

10. Calculate the standard error for the CMF;

    $$\textit{Standard Error} = ((CMF^2((1/N_{OA})+(Var(N_{EA})/(N_{EA})^2))/(1+Var(N_{EA})/(N_{EA})^2)^2))^{1/2} \quad (8)$$

11. Calculate the 95% confidence interval for the CMF; and

    $$\textit{95\% confidence interval} = CMF \pm 1.96(\textit{Standard Error}) \quad (9)$$

12. Verify the statistical significance of the CMF (i.e., check to see if the 95% confidence interval include the value 1.0).

Steps 1 through 8 of the process described above were followed for each of the treatment sites (freeway segments and interchanges) for two collision severity classifications: fatal and injury (FI) and property damage only (PDO). The treatment site results were then summed for each severity classification, and CMFs were calculated for FI and PDO collisions, separately. Subsequently, all of the results were combined to produce a CMF for “All Collisions.”

The years in which the HOV facilities were under construction were omitted from the analysis, and only years for which a full 12 months of data were available were included in the before and after periods (i.e., no partial years were considered). Additionally, since the durations of the before and after periods used in the study differ by treatment site, the data were converted to average annual values to calculate the CMFs.

Collision Trend Review

The review of collision trends and attributes involved a naive before-after comparison of collision attribute distributions (e.g., the percentage and spatial distributions of collisions by severity, initial impact type, driver actions, road and weather conditions, time of day, day of week, etc.), as well as a comparison of related collision rates.

Similar to what was done for the CMF development, the years in which the HOV facilities were under construction were omitted from the analysis; however, in the case of the collision trend review, all data (including partial years) for the before and after periods were considered.

Collision Modification Factors

Following the methodology presented earlier, CMFs were developed for combined fatal and injury collisions, and property damage only collisions, for buffered, limited-access, concurrent flow HOV lanes added to a simple, controlled-access freeway. The CMF for FI collisions, as well as several of the input and intermediate calculated parameters, are presented in Table 1.

Table 1: Fatal and Injury Collision CMF for Adding Limited-Access HOV Lanes to a Freeway

	Location	Average Annual Observed FI Collisions Before (N_{OB})	Average Annual Observed FI Collisions After (N_{OA})	Average Annual Predicted FI Collisions Before (N_{PB})	Average Annual Predicted FI Collisions After (N_{PA})	Average Annual FI Collisions N_{PA}/N_{PB}	Average Annual Expected FI Collisions Before (N_{EB})	Average Annual Expected FI Collisions After (N_{EA})	Average Annual FI Collisions Variance ($VarN_{EA}$)
Highway A	Interchange 1	1.20	3.00	10.96	12.71	1.16	3.43	3.98	4.56
	Interchange 2	40.00	35.00	20.50	22.79	1.11	37.33	41.49	45.55
	Interchange 3	28.20	28.00	27.91	30.13	1.08	28.15	30.39	32.31
	Freeway Section 1	0.20	0.00	0.45	0.48	1.08	0.41	0.44	0.44
	Interchange 4	22.60	33.00	23.31	26.35	1.13	22.75	25.71	28.62
	Freeway Section 2	5.20	9.00	3.68	4.26	1.16	4.56	5.28	5.53
	Interchange 5	9.20	9.00	11.99	13.30	1.11	9.79	10.87	11.92
	Interchange 6	10.60	4.00	13.32	15.84	1.19	11.48	13.65	15.97
Highway B	Freeway Section 1	2.25	3.33	1.61	2.05	1.27	1.86	2.37	2.91
	Interchange 1	13.50	24.00	18.24	24.01	1.32	14.66	19.31	25.18
	Freeway Section 2	0.25	0.67	1.83	2.35	1.28	1.18	1.51	1.87
	Interchange 2	10.00	16.33	17.13	22.32	1.30	11.89	15.49	20.00
	Interchange 3	5.75	15.00	15.92	19.99	1.26	8.59	10.78	13.09
	Freeway Section 3	1.75	7.67	6.72	8.03	1.20	3.14	3.76	4.45
	Interchange 4	7.75	16.67	13.49	16.05	1.19	9.55	11.36	13.38
	Interchange 5	5.25	7.33	10.63	12.68	1.19	7.23	8.62	10.18
	Interchange 6	0.00	0.33	6.80	8.49	1.25	3.22	4.02	4.97
	Totals	164	212	204	242		179	209	241
	FI Collision CMF		1.01						
	Variance		0.010						
	Standard Error		0.102						
	95% Confidence Interval	0.81	to	1.21					

The CMF presented in Table 1 suggests a very slight (1%) increase in FI collisions following the introduction of the HOV lanes. However, the standard error associated with the CMF is relatively large (0.102), which translates into a 95% confidence interval that ranges from 0.81 to 1.21. Therefore, since the 95% confidence interval includes the value 1.0, the CMF for FI collisions is not statistically significant. The lack of statistical significance means that it is not actually clear whether the treatment increased or decreased FI collision frequency, and it is primarily a function of the limited number of observed FI collisions.

The CMF for PDO collisions, along with the input and intermediate calculated parameters, are presented in Table 2.

Table 2: Property Damage Only Collision CMF for Adding Limited-Access HOV Lanes to a Freeway

	Location	Average Annual Observed PDO Collisions Before (N_{OB})	Average Annual Observed PDO Collisions After (N_{OA})	Average Annual Predicted PDO Collisions Before (N_{PB})	Average Annual Predicted PDO Collisions After (N_{PA})	Average Annual PDO Collisions N_{PA}/N_{PB}	Average Annual Expected PDO Collisions Before (N_{EB})	Average Annual Expected PDO Collisions After (N_{EA})	Average Annual PDO Collisions Variance ($VarN_{EA}$)
Highway A	Interchange 1	5	4	38.31	45.37	1.18	7.72	9.14	10.691
	Interchange 2	129	105	85.83	96.83	1.13	127.35	143.66	160.105
	Interchange 3	89.6	112	123.30	133.95	1.09	91.38	99.27	106.206
	Freeway Section 1	0	0	1.33	1.42	1.07	0.86	0.91	0.884
	Interchange 4	84	114	101.53	115.90	1.14	85.09	97.14	109.206
	Freeway Section 2	14	25	11.58	13.03	1.12	13.57	15.27	15.565
	Interchange 5	31.2	60	46.14	51.97	1.13	32.23	36.30	40.398
	Interchange 6	32.4	38	45.59	54.95	1.21	34.14	41.15	48.846
Highway B	Freeway Section 1	1.75	10.00	5.09	6.19	1.22	2.82	3.43	4.132
	Interchange 1	74	107	77.86	104.80	1.35	74.29	99.99	134.230
	Freeway Section 2	1	5.00	5.87	7.17	1.22	2.42	2.96	3.575
	Interchange 2	54.75	98.33	72.76	96.86	1.33	56.29	74.93	99.489
	Interchange 3	43	98	67.25	85.97	1.28	45.24	57.83	73.209
	Freeway Section 3	5	23.67	22.03	25.45	1.16	6.69	7.73	8.905
	Interchange 4	33.75	81.33	51.98	62.69	1.21	35.89	43.28	52.057
	Interchange 5	33.5	50.67	40.20	48.62	1.21	34.51	41.74	50.343
	Interchange 6	0.25	0.00	13.23	16.82	1.27	4.67	5.94	7.534
	Totals	**632**	**932**	**810**	**968**		**655**	**781**	**925**
	PDO Collision CMF		**1.19**						
	Variance		0.004						
	Standard Error		0.061						
	95% Confidence Interval	1.07	to	1.31					

The CMF presented in Table 2 suggests that the impact of adding HOV lanes is decidedly more pronounced when it comes to PDO collisions. The CMF indicates a 19% increase in PDO collisions, and the standard error of 0.061 results in the CMF being statistically significant at the 95% confidence level. Therefore, it is highly likely that adding HOV lanes to a freeway will result in an increase in PDO collisions of 7% to 31%.

When the FI and PDO collision data were aggregated, it resulted in the CMF for "All Collisions" (FI & PDO) that is presented in Table 3.

Table 3: All Collisions CMF for Adding Limited-Access HOV Lanes to a Freeway

Location	Average Annual Observed FI & PDO Collisions Before (N_{OB})	Average Annual Observed FI & PDO Collisions After (N_{OA})	Average Annual Predicted FI & PDO Collisions Before (N_{PB})	Average Annual Predicted FI & PDO Collisions After (N_{PA})	Average Annual FI & PDO Collisions N_{PA}/N_{PB}	Average Annual Expected FI & PDO Collisions Before (N_{EB})	Average Annual Expected FI & PDO Collisions After (N_{EA})	Average Annual FI & PDO Collisions Variance ($VarN_{EA}$)
Highway A & B Totals	**796**	**1144**	**1014**	**1210**	**1.19**	**834**	**990**	**1166**
Total FI+PDO Collisions CMF		**1.15**						
Variance		0.003						
Standard Error		0.052						
95% Confidence Interval	1.05	to	1.26					

The CMF for All Collisions is a reinforcement of the previous analysis for FI and PDO collisions separately. It shows a lesser increase in collisions associated with the addition of HOV lanes when compared to PDO collisions alone, reflecting the minimal increase in FI collisions, and it is statistically significant at the 95% confidence level. The low standard error (0.052) is a product of the high total number of collisions observed on the treatment highway sections, both before and after the HOV lanes were added.

Based on the results of the CMF development analysis, the general conclusion that can be reached is that the addition of buffered, limited-access, concurrent flow HOV lanes added to a simple, controlled-access freeway can be expected to result in a moderate (15%) increase in overall collision frequency, consisting almost entirely of additional PDO collisions.

Additional Collision Trends

Following from the CMF development analysis, the collision trend analysis was conducted with the goal of trying to better understand the contributing factors that have resulted in the observed change in freeway safety performance with the addition of HOV lanes. Several trends in collision attributes and location were identified, and with few exceptions, the trends were consistent across all of the treatment freeway sections.

Collision Severity

When the distribution of collisions by severity was examined for the before and after periods, it showed a minor increase in the overall proportion of injury collisions, roughly 1% to 3%. This increase is consistent with the CMF of 1.01 that was calculated for combined FI collisions. A very slight decrease (<1%) in the overall proportion of fatal collisions was also observed in the after period.

Further analysis showed that the increases in injury collisions in the after period were largely concentrated in the freeway sections corresponding to the HOV lane ingress/egress zones. In those areas, increased in the proportion of injury collisions of approximately 3% to 7% were observed.

One possible explanation for the observed increase in injury collisions at the ingress/egress zones may be that, under the limited-access configuration, these zones are where the vast majority of interactions occur between HOV and GP lane traffic, and when collisions result, the speed differentials between the two traffic streams cause more severe impacts.

Initial Impact Type

The most pronounced trend identified following the introduction of the HOV lanes was related to the distribution of collisions by initial impact type. Specifically, the overall proportion of rear-end collisions (Figure 1) increased by roughly 8% in the after period, from approximately 47% of all collisions to nearly 55% of all collisions. Some treatment sections experienced increases in rear-end collisions of more than 10%. Corresponding decreases in the proportions of sideswipe and single vehicle collisions were also observed. Combined, rear-end, sideswipe, and single-vehicle collisions make up almost all freeway mainline collisions.

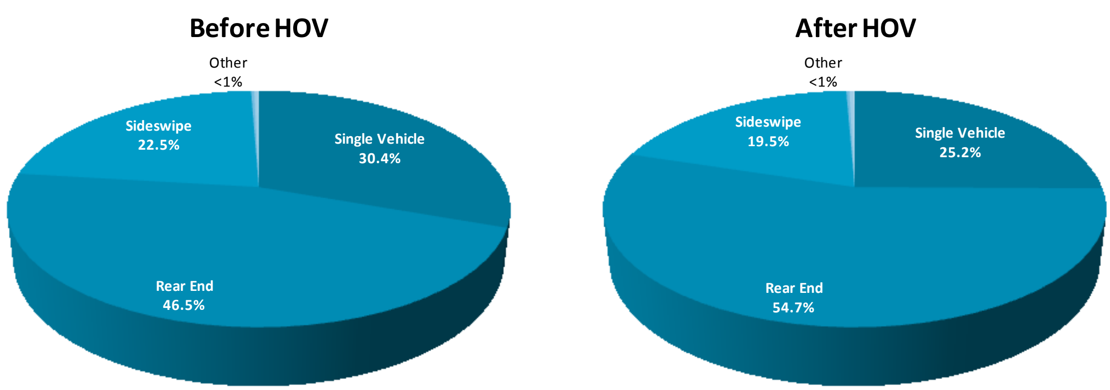

Figure 1: Distribution of Collisions by Initial Impact Type Before and After the Implementation of HOV Lanes

Although increases in the proportion of rear-end collisions were observed during all times of day, the greatest increases occurred during the peak traffic periods, in the peak direction of travel. In some of the treatment sections, in the after period, rear-end collisions represented more than 80% of all collisions. The proportion of rear-end collisions in the off-peak periods maxed-out at 44%.

The observed trends in rear-end collisions, coupled with observed trends in traffic volumes, suggest that the problem is, by and large, a symptom of congestion. The concentration of rear-end collisions in the peak periods, and the fact that the highest rear-end volumes were observed on the most congested freeway sections, support this hypothesis.

Under congested conditions, vehicle headways are very short, and lane changes become challenging, especially if those lane changes have to be made over a relatively short, fixed distance. The location of the HOV lanes, on the far left-hand-side of the freeway, necessitates that drivers make several lane changes to take advantage of HOV lane benefits. Additionally, the limited-access configuration puts pressure on those drivers to make their lane changes within a fixed distance. Therefore, one explanation for the observed increase in rear-end collisions might be that congested conditions, combined with the limited-access HOV configuration is compelling drivers to make more aggressive lane changes or to stop in live traffic lanes.

Location Trends

For analysis purposes, the treatment sections were subdivided into a series of operational zones: ingress/egress zones, weaving and merging zones, and HOV start/end zones. A schematic of the various zones is shown in Figure 2.

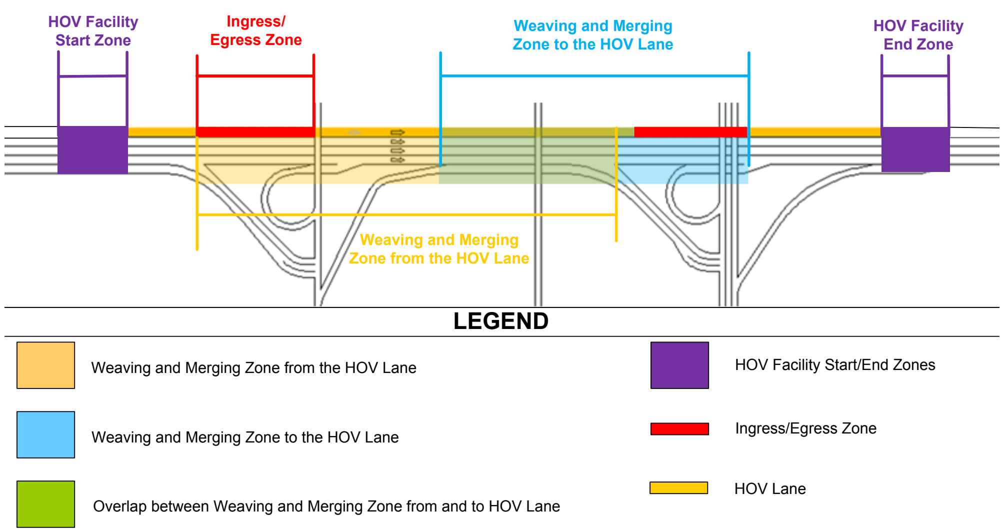

Figure 2: HOV Facility Operational Zones

Collision rate analysis for the treatment sections showed some significant increases in the after period for all of the defined operational zones. The ingress/egress zones, the same zones that experienced an increase in injury collisions, experienced an increase in their collision rates of approximately 0.2 collisions per million vehicle-kilometers. The weaving and merging zones (i.e., the areas from the end of a freeway on-ramp and the end of the first downstream HOV ingress, and from the beginning of and HOV egress to the first downstream off-ramp) experienced the greatest increase in collision rate, 0.5 collisions per million vehicle-kilometers. The HOV start and end zones also saw an increase in collision rates; however, the associated collision frequencies were too low to generate meaningful results.

The identified location trends lead to the same conclusions that were reached based on the collision severity and initial impact type analysis: congestion and HOV facility design appear to be contributing factors in the observed increase in collision frequency following the implementation of the HOV lanes.

Conclusions

Following from the findings and analysis results presented throughout this paper, several conclusions can be drawn:

- Although a considerable effort seems to have been expended on assessing the relative safety performance of various freeway HOV facility design elements and operational strategies, there is a general lack of information available with respect to the overall safety performance of freeways with and without HOV lanes;
- More observational data is required to produce a statistically significant CMF for FI collisions alone; however, the resulting CMF (1.01) suggests that FI collision frequency is largely unaffected by the addition of HOV lanes;
- Adding HOV lanes to a freeway will result in an increase in PDO collisions, with a corresponding CMF of 1.19, and a 95% confidence interval ranging from 1.07 to 1.31;
- Addition of buffered, limited-access, concurrent flow HOV lanes added to a simple, controlled-access freeway can be expected to result in a moderate increase in overall collision frequency (CMF of 1.15), consisting almost entirely of additional PDO collisions;
- An increase (1% - 3%) in injury collisions was observed in the HOV ingress/egress zones, and speed differentials between the HOV and GP lanes may be a contributing factor; and
- A significant increase in rear-end collision activity was identified following the implementation of the HOV facilities (particularly within the weaving and merging zones), and freeway congestion and HOV lane design, specifically the limited-access configuration, appear to be contributing factors.

Despite the fact that the analysis presented in this paper indicates that adding HOV lanes to a freeway facility will increase the collision frequency, further evaluation of the related collision severities and initial impact types suggests that the safety risk associated with that increase is relatively minor.

The findings of this analysis also corroborate the more anecdotal reports from HOV facilities performance monitoring programs (i.e., that collision rates tend to increase with the addition of HOV lanes). However, given the fact that HOV facilities are being expanded across North America, the findings of this analysis also appear to reinforce the implied conclusion that the associated safety risks do not outweigh the operational benefits.

Areas for Recommended Further Study

Based on the findings presented herein, and the general lack of information related to the relative safety performance of freeways with and without HOV facilities, there is ample opportunity for further study of this topic. However, there are two areas of particular interest that spring forward from the current analysis:

- How traffic congestion impacts the safety performance of HOV facilities; and
- How the design of ingress/egress zones on limited-access HOV facilities affects safety performance.

Ultimately, the two concepts may prove to be very much related, given how both may impact drivers' ability to make cautious and controlled lane changes, which could otherwise result in rear-end collisions.

One particular element of limited-access HOV lane design that should be investigated is the length of the ingress/egress zones. The current MTO standard for ingress/egress zone length is 300-450m (MTO, 1985). The specified distance corresponds to the commonly accepted distance required to make a single lane change at freeway operating speeds. However, that requirement relies on the assumption that traffic in the adjacent lanes is travelling at roughly the same speed, and that certain minimum headways are present.

Given the speed differentials that can exist between the traffic in HOV lanes and that in the adjacent GP lanes, the distance required to make a lane change can vary significantly. Congestion is the GP lanes can add to lane change difficulties, and under certain conditions, weaving between the HOV lanes and the interchange ramps can cause congestion across all freeway lanes. Therefore, the spacing of ingress/egress zones can be just as important as their length.

In addition to these areas for further study, there is still much that could be learned by simply repeating the steps the current analysis following a longer period of HOV implementation. Given the short after period that was observed for some of the treatment sections, the statistical significance of the analysis could be improved with more data, particularly with respect to the CMF for FI collisions. Additional CMFs could also be developed, based on the availability of SPFs for specific impact types (e.g., rear-end collisions).

As congestion worsens, more HOV facilities will certainly be constructed, and the opportunity exists to improve upon the current design before significant resources are invested in this new infrastructure; however, it will require more targeted study of the critical design elements.

References

1. C. D. Howe Institute. (2013). *Cars, Congestion and Costs: A New Approach to Evaluating Government Infrastructure Investment.* Toronto: C. D. Howe Institute.
2. Cao, X., Xu, Z., & Huang, A. (2012). *Safety Benefits of Converting HOV Lanes to HOT Lanes: Case Study of the I-394 MnPASS.* Washington, DC: Institute of Transportation Engineers.
3. Cothron, A. S., & al., e. (2004). *Guidance for Future Design of Freeways wtih High-Occupancy Vehicle (HOV) Lanes Base on an Analysis of Crach Data from Dallas, Texas.* College Station: Texas Transportation Institute.
4. FHWA. (2010). *A Guide to Developing Quality Crash Modification Factors.* Washington, DC: U.S. Department of Transportation, Federal Highway Administration.
5. Jang, K., & al., e. (2008). *Safety Evaluation of High-Occupancy Vehicle (HOV) Facilities in California.* Berkeley: Intelemotion - California PATH.
6. May, A. D., Leiman, L., & Billheimer, J. (2007). *Determining the Effectiveness of HOV Lanes.* California PATH Program Institute of Transportation Studies University of California, Berkeley.
7. MTO. (1985). *Geometric Design Standards for Ontario Highways.* Downsview: Queen's Printer for Ontario - MTO Surveys & Design Office.
8. MTO. (2013, November 19). *High Occupancy Vehicle (HOV) Lanes - Frequently Asked Questions*. Retrieved April 24, 2014, from Ontario - Ministry of Transportation: http://www.mto.gov.on.ca/english/traveller/hov/faq.shtml#a11
9. MTO. (2010, June 18). *Summary of the Plan for the 400-Series Highways in the Greater Golden Horseshoe*. Retrieved April 25, 2014, from High Occupancy Vehicle (HOV) Lanes - Summary 2007: http://www.mto.gov.on.ca/english/traveller/hov/summary2007.shtml
10. Parajuli, B., Lyon, C., & Persaud, B. (2006). *Operational Performance Assessment of Freeway Interchanges, Ramps and Ramp Terminals.* St. Catharines: MTO - Highway Infrastructure Innovation Funding Program.
11. Persaud, B., Begum, M., & Lyon, C. (2009). *Operational Performance Assessment of Highway and Freeway Sections.* St. Catharines: MTO - Highway Infrastructure Innovation Funding Program - 2007.
12. TBOT. (2011). *Reaching Top Speed - Infrastructure: Unleashing Ontario's Ability to Grow.* Toronto: Toronto Region Board of Trade (Formerly: Toronto Board of Trade).
13. TTI. (1998). *NCHRP Report 414: HOV Systems Manual.* Washington, DC: Transportation Research Board.