Truck Accidents at Freeway Ramps: Data Analysis and High-Risk Site Identification

PB98-163744

BRUCE N. JANSON
WAEL AWAD
JUAN ROBLES
Department of Civil Engineering
University of Colorado at Denver

JAKE KONONOV
BRIAN PINKERTON
Colorado Department of Transportation

ABSTRACT

To examine the relationship of ramp design to truck accident rates, this paper presents an analysis of truck accidents in Washington State, plus a comparison to limited data from Colorado and California. We group freeway truck accidents by ramp type, accident type, and by four conflict areas of each merge or diverge ramp. We then compare these groups on the basis of truck accidents per location and per truck-mile of travel. We found that truck accident frequencies and rates were not significantly different by ramp type alone, but were significantly different by conflict area and accident type, both between and within ramp types. We also found that high volume ramps had lower rates of truck accidents per truck-mile of travel. Thus, a ramp's safety risk is related to accident type and conflict area, but not directly to truck volumes, which affects assessments of high-risk locations. Specifically, a ramp with few accidents but a high proportion of rollovers in the merge area may have a deficiency, or a ramp with a low accident rate per truck trip due to high truck volumes may still be a

Professor Bruce N. Janson, Department of Civil Engineering, University of Colorado at Denver, Campus Box 113, PO Box 173364, Denver CO 80217-3364. Email: bjanson@carbon.cudenver.edu.

high-risk site. We describe a straightforward use of the accident data analyzed in this manner to identify accident-prone sites for further investigation.

INTRODUCTION

Nationally, 20% to 30% of freeway truck accidents occur on or near ramps (excluding an additional 10% to 15% that occur at intersections of ramps and surface streets), despite the fact that interchanges account for less than 5% of all freeway lane-miles (Firestine et al 1989). These same percentages hold true for many western states. Of nearly 2,400 truck accidents on Colorado freeways during 1993, 1994, and early 1995, roughly 30% occurred at interchanges, and another 10% occurred at intersections with secondary roads. (We use the term "freeways" in this paper to include all limited access highways; e.g., interstate highways, expressways, turnpikes, and parkways.)

Sullivan (1990) found accidents per vehicle-mile of travel (VMT) to be significantly related to the number of interchange ramps along California freeway sections. In an older study of freeway accidents throughout the United States, Pigman et al (1981) found accidents occurred 33% more often per VMT on freeway sections with bridges or interchanges than on freeway sections without them (see table 1). Both of these findings were for accidents of all vehicle types and severity (fatalities, injuries, and property damage only). However, we also found that truck accident rates were significantly higher on freeway sections in the vicinity of interchanges in our own analysis of truck accident data reported by Goodell-Grivas (1989).

Although most road accidents are precipitated by erroneous driver actions (in both cars and trucks), inadequate interchange designs for large truck operations may contribute to some of them, along with insufficient safety warnings to truck operators at certain locations. Many freeway ramps throughout the United States were designed for older truck configurations and not for longer combination vehicles carrying much greater weights. A study by Ervin et al (1986) found that the American Association of State Highway and Transportation Officials (AASHTO) design standards (at that time) provided a slim margin of safety for operating large trucks through interchanges, although the newer AASHTO (1990) design standards may provide a greater margin of safety for large trucks.

TABLE 1 Accident Rates on Controlled-Access Highway Sections (Pigman 1981)
(Per million vehicle-miles)

	Surrounding area			
Section type	**Rural**	**Suburban**	**Urban**	**Total**
With interchanges	0.57	0.77	3.05	1.22
Without interchanges	0.49	0.61	2.07	0.90

Note: Includes all accidents causing fatalities, injuries, and property damage only.

This paper presents an analysis of truck accidents at freeway ramps in Washington State, plus a comparison to limited data from Colorado and California. We first compare frequencies of truck accidents in four conflict areas of on-ramps and off-ramps by both ramp type and accident type. We briefly summarize findings of truck accident rates per ramp truck volume and ramp truck-mile of travel, which required the estimation of truck percentages at most ramps (see Janson et al 1997). This approach separates the effects of conflict locations, truck volumes, and travel distances. We lastly describe a straightforward use of the data tabulated in this manner to identify accident-prone sites for further investigation.

Although not reported here, we investigated the effects of ramp geometrics (i.e., grade, curvature, and length) on truck accident rates, but did not find any consistent statistical relationships. Traffic accidents are random events with many causal factors such as driver inattention and fatigue, drugs and alcohol, speeding, traffic congestion, lighting, road surface, and weather conditions. The combination of such factors complicates the influence of geometric design features on accident rates as other studies have noted (Miaou et al 1992). Ideally, a study concerned with geometric design effects would limit its analysis to accidents with design as a causal factor. Unfortunately, accident reports do not make that determination, and specific accident factors are not investigated (except for litigation) until an accident-prone site is identified for further analysis.

Difficulties with statistical analyses of truck accidents also arise due to having no information about "non-events." For every accident that does occur, hundreds of "near accidents" are averted by quick and astute driver actions. Thus, characteristics of "near accidents" related to ramp deficiencies are unavailable. A related difficulty is obtaining an adequate measure of exposure, especially at ramps. Few states regularly count ramp volume except where detectors have been installed for ramp control. Where ramp volume is available, truck percentages (let alone truck type classification) are usually not.

This paper does not offer predictive equations of truck accidents based on geometric or traffic characteristics. Instead, we focus on the analysis and use of truck accident data to "flag" accident-prone ramps for further investigation. A well-known difficulty that arises in this context is regression to the mean, whereby some locations (with or without deficiencies) that have relatively few accidents over one period of time may have relatively more accidents over another (Hauer 1997). Deficiencies revealed by a high accident rate over many years may be missed or falsely indicated by the accident rate of fewer years. We revisit this issue later in the paper.

OVERVIEW OF ANALYSIS APPROACH

Taking into account data availability and previous research, our primary objectives in this study were to:

1. Identify requirements of a comprehensive truck accident database to be used for highway improvement studies as part of a state's safety management system.
2. Statistically compare truck accident experiences of four different ramp designs in three states (Colorado, California, and Washington), so as to examine the effects of their design on interchange safety and possibly recommend design improvements.
3. Develop a procedure to identify high-risk locations for remedial action to improve safety using this truck accident database.
4. Include the experiences and observations of truck drivers and fleet managers to identify and assess problem locations, and to develop candidate safety improvements and risk mitigation strategies.

This paper focuses on objectives 1, 2, and 3. Of the states we contacted, we found Washington to have the most comprehensive accident database with which to pursue these objectives. We then created a truck accident database for Washington that included information about "safe travel" through the same interchanges where truck accidents had occurred. We also gathered limited data for Colorado and California to which we make general comparisons. This brief paper highlights the data we compiled and analyzed for Washington, our most complete data source.

Key questions that we investigated regarding truck accidents at ramps were:

1. Do numbers of truck accidents, truck accident rates per truck trip, or truck VMT differ by ramp type, conflict area, or the combination of these two classifications?
2. Do these findings differ significantly by accident type?
3. Do these findings differ significantly by high, medium, or low average daily traffic (ADT) of trucks or all vehicles on the ramps, or in the main freeway lanes due to greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes?
4. Do these findings differ significantly both upstream and downstream of the merge/diverge area?
5. Do these findings differ significantly for different lengths of the accel/decel lanes plus tapers?

To investigate the above questions, we compared accident frequencies and rates by (i) numbers of ramp locations, (ii) ramp truck ADT, and (iii) ramp truck VMT by (a) ramp type, (b) conflict area, and (c) accident type. These multiple comparisons allowed us to examine the separate effects of conflict locations, ramp truck trip, and travel distances. We excluded comparisons per ramp truck trip except in a summary table, but compare accident rates per ramp truck VMT. Comparing truck accidents per ramp truck trip is similar to comparing intersection accidents per "vehicle entered," where types and numbers of conflict points are more important than travel distances. Although ramps involve greater travel distances than intersections, most accidents occur near conflict points, where numbers of vehicles passing may be more critical than VMT, as will be shown by our results.

PREPARATION OF THE WASHINGTON DATABASE

From Washington State Department of Transportation (WSDOT) files, we compiled a database of all truck accidents at all interchanges in Washington over the 27 months from January 1, 1993 to March 31, 1995. All trucks in this study are of at least 10,000 pounds gross vehicle weight. Using each accident's route milepost as a common identifier, we combined data from the following five files into one database: (1) characteristics of truck accidents at interchanges, (2) freeway traffic volumes, (3) ramp traffic volumes, (4) geometric design characteristics, and (5) computer drawings of each interchange with truck accident locations.

Data extracted directly from WSDOT files and coded into our database for each accident were:

1. accident location (route milepost to nearest 1/100 of a mile) and direction of travel;
2. main and secondary route identifiers (perhaps both freeways);
3. accident type (sideswipe, rearend, rollover, other);
4. lane in which accident occurred.

Data that we interpreted from WSDOT files and interchange drawings were:

1. interchange type (diamond, directional, cloverleaf, other);
2. ramp type (diamond, loop, directional, outer connector, other);
3. ramp connection type (freeway-to-freeway, freeway-to-arterial, etc.);
4. conflict area (e.g., ramp, merge/diverge area, upstream, downstream).

Lastly, using a printout of traffic counts and geometric drawings by route milepost, and a supplemental list of 246 ramp counts with truck percentages, we added to our database the additional accident characteristics listed below.

1. length of merge/diverge area from taper to gore (or vice-versa);
2. length of ramp from secondary connection to merge/diverge area;
3. distance of accident upstream from center of merge/diverge area;
4. distance of accident downstream from center of merge/diverge area;
5. main road ADT and truck percentage;
6. secondary road ADT and truck percentage;
7. ramp ADT and truck percentage (if available).

We excluded all accidents at intersections of ramps and secondary roads, but still included all truck accidents on freeway-to-freeway connector ramps. We carefully distinguished accidents on the ramps from accidents on the main freeway lanes near the ramps. We began our classification of ramp types with detailed differences in ramp design, and then simplified our classification to four basic ramp types (diamond, loop, outer connector, and directional), so as to disregard small differences and have sufficient observations in each cross-classification. Depictions of these basic ramp types can be found in many highway engineering textbooks such as Wright (1996).

A paramount concern was to obtain ramp truck ADT for a sufficient number and variety of ramps where truck accidents did not occur so as to not underestimate the truck exposure of any ramp type. There are a total of 2,200 ramps at 465 interchanges in Washington State. We focused our study on 644 ramps at which at least one truck accident occurred during the study period. (A potential bias of this focus is that we disregard the 1,556 ramps at which no truck accidents occurred during this period.) We focused our attention on these ramps for several reasons.

First, the percentage distribution of all ramp types in the state was similar to the 644 ramps in the study, as shown in table 2. The major difference is that diamond ramps used at many lower volume rural interchanges are a larger percentage of total ramps than of the study ramps, and directional ramps used at many higher volume urban interchanges are a larger percentage of study ramps than of total ramps. A second reason for focusing on these 644 ramps is that we could only examine a sample of such ramps in both Colorado and California. Hence, to achieve some limited comparisons between states, we chose a fairly consistent focus in each state.

Third, even to investigate all of the above questions for Washington, we still needed to estimate some data such as ramp lengths and ramp truck

TABLE 2 Distribution of Ramp Types in Washington State

Ramp type	All ramps Number	All ramps Percent	Study ramps Number	Study ramps Percent
Diamond	1,247	56.7	310	48.1
Loop	247	11.2	81	12.6
Outer connector	189	8.6	59	9.2
Directional	407	18.5	152	23.6
Other	110	5.0	42	6.5
Total	2,200	100.0	644	100.0

Note: Study ramps had at least one tnck accident in the study period.

ADT (RTADT) in order to compare truck accident rates per truck-mile of travel as a measure of truck exposure at each ramp. Although RTADT is not generally available, WSDOT was able to provide it for the study period at 246 ramps. This allowed us to estimate RTADT for ramps where the data were not available based on the ramp ADT of all vehicles, as explained later. WSDOT had total ADT for most ramps, but not always for the same study period mentioned above. We requested a special tabulation of total ADT for each of the 644 study ramps for the study period. However, it was beyond the resources of this study to obtain total ADT for all 2,200 ramps via a special collection effort.

It was also beyond the resources of this study for us to identify the length of every ramp in Washington based on geometric drawings, and to distinguish the taper-to-gore distance and the accel/decel lane from the ramp itself. Ideally, this data would be collected in a larger study. However, a primary goal of this study was to develop and demonstrate an analysis procedure of stratifying and comparing ramp truck accidents by ramp type, accident type, and ramp location. Finally, we did control to some extent for the potential bias of not including no-accident ramps, since the study ramps for which we did obtain or estimate RTADT also included many conflict areas where accidents did *not* occur as explained later.

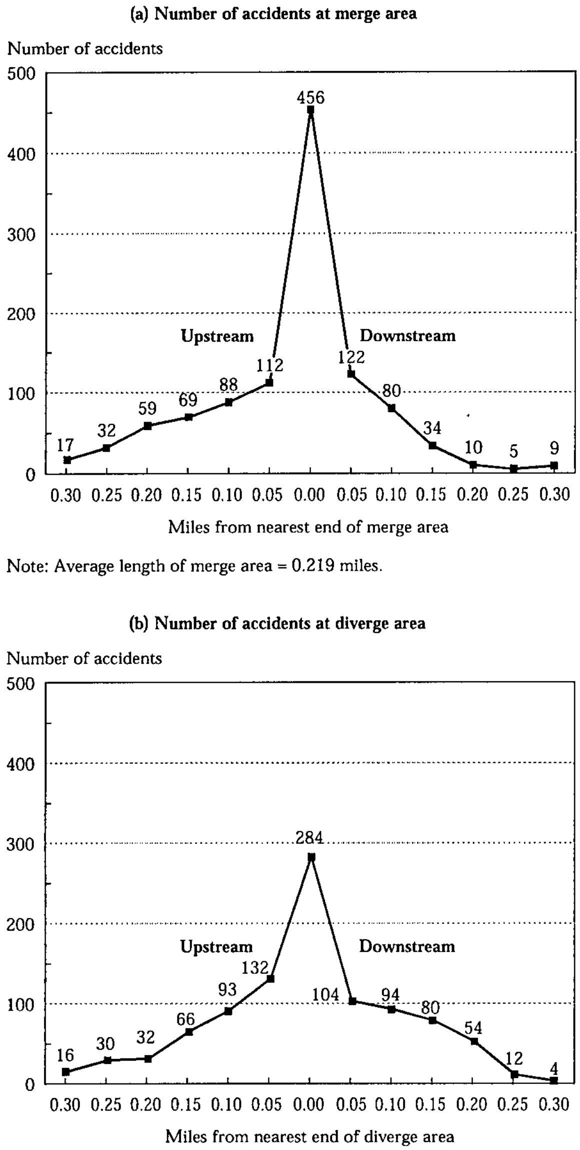
DEFINING THE RAMP INFLUENCE ZONE

In order to identify truck accidents that were possibly affected by ramp design features, we must first define the area boundaries within which such effects are thought to be significant. We defined this influence zone to (i) exclude intersections with arterials, (ii) be mainly confined to accidents either on the ramp, in the accel/decel lane of the ramp, or in the highway lane adjacent to the accel/decel lane of the ramp, and (iii) be within a certain upstream or downstream distance from the ramp, which we define next.

One research question posed above concerned the effects of upstream and downstream distances on truck accident frequencies. Figure 1 shows numbers of truck accidents both upstream and downstream from merge and diverge ramps in Washington State. Figure 1 includes all freeway lanes, although we later restrict our attention to truck accidents in lane 1 nearest the ramp. Upstream distances are measured in 0.05 mile increments from the tip of the merge gore or from the start of the diverge taper. Downstream distances are also measured in 0.05 mile increments from the tip of the diverge gore or from the end of the merge taper. The center of each figure shows the frequency of accidents in the ramp connection area, which is the accel/decel lane plus taper. (Note that the average length of the ramp connection area for merge ramps was 0.219 miles, but only 0.107 miles for diverge ramps.)

We performed a simple test of frequency differences in successive sections of 0.05 miles either upstream or downstream from the ramp connection area for all truck accidents in our database. We found that the truck accident frequencies stopped changing significantly (i.e., leveled off to a similar number per 0.05 mile section) beyond 0.25 miles upstream for both merge and diverge ramps, beyond 0.2 miles downstream for diverge ramps, and beyond 0.15 miles downstream for merge ramps. The shorter downstream distance for merge ramps seems counterintuitive, but when added to the 0.219 mile average length of a merge area, the total length of 0.369 miles exceeds the combined downstream distance of 0.307 miles for diverge ramps (0.107 mile average length of a diverge area plus 0.2 miles). Upstream and downstream accident frequencies by ramp type showed some differences. For example, for both merge and diverge ramps, truck accidents occur most frequently both upstream and downstream of diamond ramps relative to the frequency of accidents in the ramp con-

FIGURE 1 **Washington State Truck Accidents by Distance from Ramp Area**



Note: Average length of diverge area = 0.107 miles.

nection area. In order to compare accident frequencies among ramp types over equal distances, we defined the same influence zone length for all ramp types as follows:

1. 0.25 miles upstream of the tip of a merge ramp gore;
2. 0.25 miles upstream of the start of a diverge ramp taper;
3. 0.15 miles downstream of the end of a merge ramp taper;
4. 0.20 miles downstream of the tip of a diverge ramp gore.

Figure 2 shows these influence zone distances for both merge and diverge ramps. Figure 2 also shows the four conflict areas that we define later. We show average ramp connection lengths in the figure, but we computed truck VMT for each ramp connection area using its RTADT and its gore-to-taper distance as indicated by its geometric drawing.

ESTIMATING TRUCK EXPOSURE MEASURES

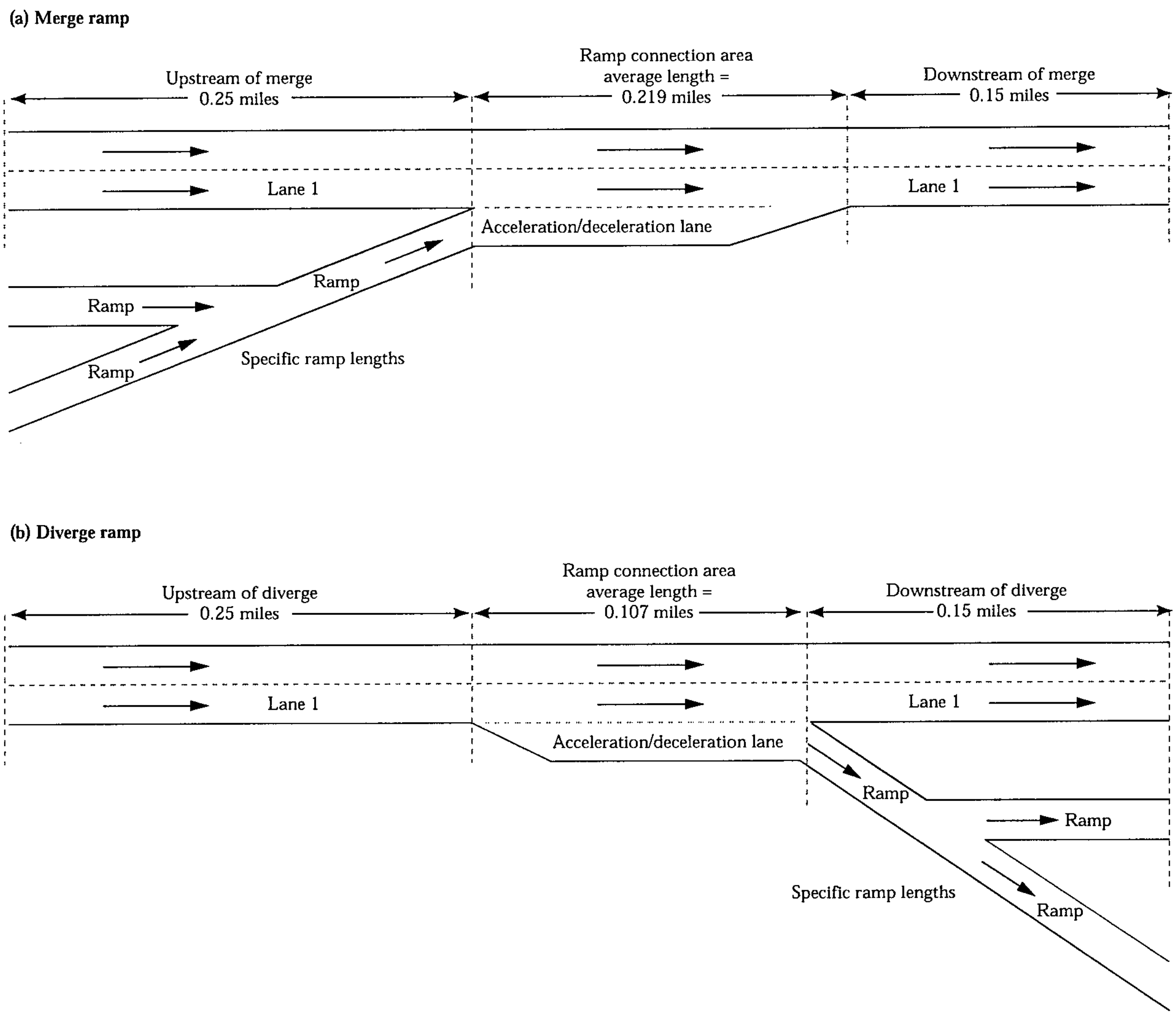
In this section, we compare accident frequencies per location and rates per truck VMT by ramp type, conflict area, and accident type so as to reveal location, volume, and travel distance effects. This required that we estimate ramp truck ADT for ramps where it was not recorded, which we convert to ramp truck VMT for the full study period. WSDOT provided us with ADT and truck percentages at 123 on-ramps and 123 off-ramps. We fitted relationships of RTADT to ramp ADT of all vehicles (RADT) at 84 ramps with at least one truck accident during the study period. Figure 3 shows estimated versus observed RTADT for on-ramps. The figure for off-ramps is very similar. The fitted equations are:

$RTADT = RADT^{0.69}$ for on-ramps
$R^2 = 0.826$, parameter's t-statistic = 131.2
$RTADT = RADT^{0.71}$ for off-ramps
$R^2 = 0.683$, parameter's t-statistic = 106.2

The above equations indicate that RTADT is a decreasing fraction of total ramp ADT as total ramp ADT increases. We fitted several other linear and nonlinear equations to estimate RTADT including (i) a constant, (ii) main road ADT of all vehicles, (iii) truck ADT on the main road, and (iv) secondary road ADT of all vehicles. However, the t-statistics of the other variables were not significant at the 95% confidence level for any of the other models, and the R-squared values were not much improved. Note that two independent data sets (on-ramps versus off-ramps) produced nearly identical fitted parameters (0.69 and 0.71). The fitted equations using all cases (123 on-ramps and 123 off-ramps) also had nearly identical parameters (0.68 and 0.71). Hence, RADT raised to the 0.7 power seems to be a fairly robust predictor for all ramps.

We believe an important predictor of RTADT would be truck ADT on the secondary road, but this data was not available for any interchange

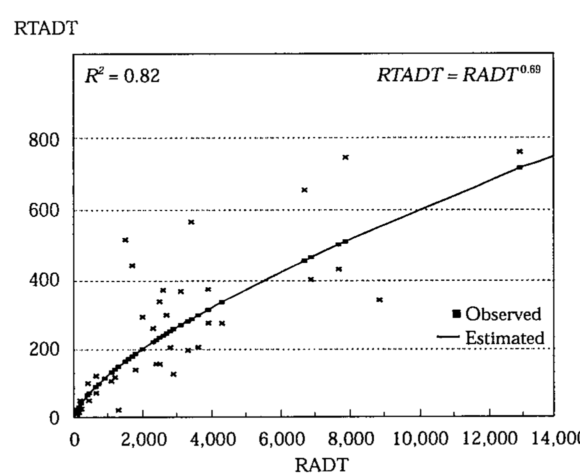
FIGURE 2 Influence Zone Distances in Four Ramp Conflict Areas



location. Certain facilities near an interchange, such as industrial plants, trucking terminals, truck stops, warehouses, and distribution centers will tend to increase RTADT as a proportion of total ADT. Absence of any such facilities, such as an interchange serving mainly residential areas, will tend to decrease RTADT as a proportion of total ADT. Examination of these specific interchange activities would require substantial surveying.

We do not rely heavily on estimated RTADT in this paper, but we emphasize the need for better truck exposure data. Despite their simplicity and lack of accuracy for some specific ramp locations, these equations provide usable estimates of RTADT given the lack of better data. Ideally, state DOTs will sample ADT and truck ADT for a

FIGURE 3 Washington State On-Ramp Truck ADT versus Total On-Ramp ADT



greater proportion of their ramps in the future. Only then will more accurate RTADT be available for truck studies without the need for estimation.

ACCIDENTS PER RAMP IN WASHINGTON STATE

Table 3 shows numbers of ramps and truck accidents per ramp in Washington during the 27 months from January 1, 1993 to March 31, 1995, separated by merge and diverge ramps. The term *ramp* in table 3 refers to the entire ramp area including both the ramp and adjacent freeway lane 1. Part (a) of table 3 shows accidents that occurred on the ramps or in the accel/decel lanes of these ramps, while part (b) shows accidents that occurred on the main line (lane 1) upstream, downstream, or adjacent to these ramps, including shoulder areas. Part (c) shows all accidents combined. Since many ramps had multiple accidents, numbers of accidents by ramp type differ from the numbers of ramps where these accidents occurred. For all 644 ramps combined, 406 (63%) had 1 accident, 141 (22%) had 2 accidents, and the other 97 (15%) had 3 or more accidents, for a total of 1,030 accidents.

Numbers of ramps in parts (a) and (b) of table 3 do not add up to part (c), because many ramps had accidents on both the ramp and main lanes. Numbers of accidents in parts (a) and (b), however, add up to part (c) because every accident is coded to be either on a ramp or on the main line. As explained earlier, we did not record any data for ramps where no accidents occurred. However, these ramps have many conflict areas (i.e., on the ramps, ramp connection areas, upstream areas,

TABLE 3 Washington State Truck Accidents by Ramp Type

Ramp type	Number of on-ramps	Number of off-ramps	Percent of on-ramps	Percent of off-ramps	Number of on-ramp acc	Number of off-ramp acc	Percent of on-ramp acc	Percent of off-ramp acc	Number of acc per on-ramp	Number of acc per off-ramp
(a) Ramp accidents										
Diamond	45	21	37.2	23.1	56	23	33.1	19.0	1.24	1.10
Loop	27	20	22.3	22.0	38	30	22.5	24.8	1.41	1.50
OuterConn	9	10	7.4	11.0	17	12	10.1	9.9	1.89	1.20
Directional	36	34	29.8	37.4	53	48	31.4	39.7	1.47	1.41
Other	4	6	3.3	6.6	5	8	3.0	6.6	1.25	1.33
Total	121	91	100.0	100.0	169	121	100.0	100.0	1.40	1.33
Percent	57.1	42.9			58.3	41.7				
(b) Main line accidents (lane 1)										
Diamond	140	127	57.1	59.3	216	195	54.3	57.0	1.54	1.54
Loop	32	10	13.1	4.7	51	15	12.8	4.4	1.59	1.50
OuterConn	21	22	8.6	10.3	35	36	8.8	10.5	1.67	1.64
Directional	41	49	16.7	22.9	79	89	19.8	26.0	1.93	1.82
Other	11	6	4.5	2.8	17	7	4.3	2.0	1.55	1.17
Total	245	214	100.0	100.0	398	342	100.0	100.0	1.62	1.60
Percent	53.4	46.6			53.8	46.2				
(c) All accidents										
Diamond	168	142	49.6	46.6	272	218	48.0	47.1	1.62	1.54
Loop	53	28	15.6	9.2	89	45	15.7	9.7	1.68	1.61
OuterConn	28	31	8.3	10.2	52	48	9.2	10.4	1.86	1.55
Directional	69	83	20.4	27.2	132	137	23.3	29.6	1.91	1.65
Other	21	21	6.2	6.9	22	15	3.9	3.2	1.05	0.71
Total	339	305	100.0	100.0	567	463	100.0	100.0	1.67	1.52
Percent	52.6	47.4			55.0	45.0				

and downstream areas) where no accidents occurred. Ramps in part (c) minus ramps in part (a) equal ramps where no accidents occurred specifically on the ramps. Ramps in part (c) minus ramps in part (b) equal ramps where no accidents occurred on the main line nearby the ramps. All accidents at intersections of ramps with secondary roads are excluded.

In order to study the effects of ramp geometrics on truck accidents, we separated accidents into four conflict areas, as depicted earlier in figure 2. These four areas are (i) the ramp area away from the main line, (ii) the ramp connection including the accel/decel lane and the adjacent lane 1, (iii) lane 1 upstream of the ramp connection area, and (iv) lane 1 downstream of the ramp connection area. Of the 339 on-ramps and 305 off-ramps listed in table 3(c), only a few merged or diverged on the left side of the freeway.

Average accidents per ramp in table 3 do not account for the volumes and distances of truck travel, but we later examine accident rates per ramp truck trip and per ramp truck VMT. These initial comparisons of average accidents per ramp help to separate out these volume and distance effects. As discussed earlier, there is no "one best" truck exposure measure to use (e.g., RTADT, main line truck ADT, total vehicle ADT). This section compares accident frequencies before introducing an exposure measure. In addition, since truck ADT (both reported and estimated) is not precise, and accident frequencies may be so random or dependent on other factors that no significant relationship to truck ADT is found, an initial inspection of the data without truck ADT is warranted.

Table 4 shows numbers of accidents and average accidents per ramp in the four conflict areas just described. Since numbers of ramps by conflict area include all places where accidents may have occurred even if none did, they generally equal the number of merge or diverge ramps. There are slightly more specific "on-ramps" and "off-ramps" due to collector/distributor connecting ramps for which we did not count upstream and downstream areas. Hence, the average frequencies shown are per all conflict areas regardless of whether any accidents occurred there. Table 4 shows significant differences in the frequencies of accidents per conflict area, which we later examine by ramp and accident type. Accidents occur at significantly lower average frequencies on ramp sections away from freeway lanes (table 4a) than in the upstream, downstream, or ramp connection areas of the freeway (table 4b). Accidents that occur on ramps away from freeway lanes occur more frequently on off-ramps than on on-ramps. Loop off-ramps are a main source of this difference, discussed later in this paper.

Accidents specifically on ramps can occur at junctions of multiple ramps (excluding intersections with arterial roads). Ramp junctions occur most often on directional ramps, and clearly contribute to the frequency of ramp accidents. Among

TABLE 4 Washington State Truck Accidents by Conflict Area

Conflict area	Accidents	Percent	Conflict areas	Accidents per conflict area
(a) On-ramp accidents				
Upstream of merge	151	26.6	331	0.46
Merge ramp	267	47.1	331	0.81
Downstream of merge	74	13.1	331	0.22
On-ramp	75	13.2	339	0.22
Total	567	100.0	1,332	0.43
(b) Off-Ramp Accidents				
Upstream of diverge	119	25.7	294	0.40
Diverge ramp	131	28.3	294	0.45
Downstream of diverge	122	26.3	294	0.41
Off-ramp	91	19.7	305	0.30
Total	463	100.0	1,187	0.39

328 on-ramps containing 94 ramp junctions, 45 truck accidents occurred at junctions (0.644 accidents per junction). Only 40 other truck accidents occurred on the 328 on-ramps (0.122 accidents per ramp). Among 292 off-ramps containing 86 ramp junctions, 25 truck accidents occurred at junctions (0.402 accidents per junction). The 70 other truck accidents on off-ramps occurred away from the junctions (0.240 accidents per ramp). Beyond these comparisons, we did not separately investigate the effects of ramp junctions in this study, and grouped all accidents that occurred on the ramps together, but still separate by merge or diverge ramp.

Table 5 shows a two-way frequency table of accidents by ramp type and conflict area for both merge and diverge ramps. The third line of each cell shows the accident frequency per conflict area, where we see that accidents occur most frequently in ramp connection areas (merge and diverge areas). However, the average frequencies for all on-ramps, all off-ramps, and all ramps combined are not greatly different. Excluding ramp type "other," a two-way analysis of variance showed these average accident frequencies to be significantly different by conflict area at the 95% confidence level, but not by ramp type. This finding suggests the importance of comparing accident histories by conflict area rather than by ramp type alone.

Table 6 shows a two-way frequency table of accidents by conflict area and accident type by aggregating all ramp types together. Note that sideswipe accidents are most prevalent for all ramp types, especially in ramp connection areas. Although not shown here, if separated by ramp type, sideswipe accidents are similarly prevalent at each ramp type, while rollover accidents are most likely to occur at loop off-ramps. Of 50 rollover accidents at all ramps, 19 occurred at loop ramps, of which 11 were at loop off-ramps. Loop ramps are only 12.6% of all study ramps.

Values in the righthand portion of table 6 show the accident frequencies per conflict area. A two-way analysis of variance showed that these average accident frequencies were significantly different by accident type at the 95% confidence level, but not by conflict area, since the values vary highly within conflict areas. One reason the accident frequencies, when grouped by accident type, do not vary significantly by conflict area is that some accident types are so easily affected by driver actions (e.g., a sideswipe may result from the driver attempting to avoid a rearend collision on a short ramp). Thus, frequency variations by conflict area are overshadowed by differences in accident type frequencies. However, two important observations are that sideswipes are most frequent in merge areas, and rollovers are most frequent on ramps themselves.

We next investigate whether stratifying ramps by high, medium, or low ADT of trucks on the ramp shows greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes. In table 7, we grouped conflict areas together by whether RTADT was low, medium, or high. These stratified results, especially from low to middle ADT levels, show accident frequencies on the ramps and in ramp connection areas to increase more consistently with higher ADT than in the upstream or downstream areas, which indicates the effects of traffic volumes on truck accident frequencies on the ramps and in ramp connection areas where most weaving occurs. Results were similar when ramps were stratified by total ADT.

ACCIDENTS PER RAMP TRUCK VMT IN WASHINGTON

This section compares Washington truck accidents per ramp truck VMT (RTVMT). Our final report for this study also makes these comparisons per ramp truck trip. Totals in the rightmost columns of table 8 show numbers of accidents, cumulative RTVMT in millions, and accidents per RTVMT for the four conflict areas. To calculate RTVMT, each RTADT was multiplied by its conflict area length, divided by 1 million, and multiplied by 820 days in the study period (January 1, 1993 to March 31, 1995). We calculated a specific length for each ramp and ramp connection area based on the route milepost data and geometric drawings provided by WSDOT. RTVMT is added once to its sum for each conflict area regardless of whether none or many accidents occurred there.

The upstream and downstream conflict area lengths are the same for each ramp as defined earlier. Hence, the truck VMT of each upstream conflict area equals its RTADT multiplied by 0.25

TABLE 5 Washington State Truck Accidents by Ramp Type and Conflict Area

Conflict Area		Ramp type: Diamond	Loop	OuterConn	Directional	Other	Total accidents	Total conflict areas	Accidents per conflict area
On-ramps									
Merge upstream	Accidents	91	7	15	31	7	151		
	Conflict areas	167	50	25	69	20		331	
	Acc/conf area	0.54	0.14	0.60	0.45	0.35			0.46
Merge area	Accidents	116	50	27	63	11	267		
	Conflict areas	167	50	25	69	20		331	
	Acc/conf area	0.69	1.00	1.08	0.91	0.55			0.81
On-ramp	Accidents	21	17	8	28	1	75		
	Conflict areas	168	53	28	69	21		339	
	Acc/conf area	0.13	0.32	0.29	0.41	0.05			0.22
Merge downstream	Accidents	44	15	2	10	3	74		
	Conflict areas	167	50	25	69	20		331	
	Acc/conf area	0.26	0.30	0.08	0.14	0.15			0.22
On-ramps totals	Accidents	272	89	52	132	22	567		
	Conflict areas	669	203	103	276	81		1,332	
	Acc/conf area	0.41	0.44	0.50	0.48	0.27			0.43
Off-ramps									
Diverge upstream	Accidents	67	4	12	32	4	119		
	Conflict areas	142	24	28	80	20		294	
	Acc/conf area	0.47	0.17	0.43	0.40	0.20			0.40
Diverge area	Accidents	54	16	13	42	6	131		
	Conflict areas	142	24	28	80	20		294	
	Acc/conf area	0.38	0.67	0.46	0.53	0.30			0.45
Off-ramp	Accidents	17	23	10	38	3	91		
	Conflict areas	142	28	31	83	21		305	
	Acc/conf area	0.12	0.82	0.32	0.46	0.14			0.30
Diverge downstream	Accidents	80	2	13	25	2	122		
	Conflict areas	142	24	28	80	20		294	
	Acc/conf area	0.56	0.08	0.46	0.31	0.10			0.41
Off-ramp totals	Accidents	218	45	48	137	15	463		
	Conflict areas	568	100	115	323	81		1,187	
	Acc/conf area	0.38	0.45	0.42	0.42	0.19			0.39
Totals for all ramps	Accidents	490	134	100	269	37	1,030		
	Conflict areas	1,237	303	218	599	162		2,519	
	Acc/conf area	0.40	0.44	0.46	0.45	0.23			0.41

miles. The truck VMT in each downstream conflict area equals its RTADT multiplied by 0.15 miles for merge ramps, and by 0.20 miles for diverge ramps. Since ramp lengths and ramp connection lengths (i.e., the accel/decel lane plus taper) vary between ramps, the RTVMT of a ramp or ramp connection area equals its length multiplied by the RTADT. (The length of a ramp is from where it intersects another road to where it joins the ramp connection area.) We also calculated the length of each ramp-to-ramp connection, and added its VMT to the corresponding accident group or ramp type. While drawings from WSDOT fully showed each ramp connection area, they did not always show the full length of every ramp. Hence, the lengths we calculated for some ramps were more approximate than lengths of the ramp connection areas.

Table 8 shows a two-way frequency table of accidents by ramp type and conflict area. Directional ramps have a significantly lower average

TABLE 6 Washington State Truck Accidents by Conflict Area and Accident Type

Conflict area	Conflict areas	Accident type: Side-swipe	Rear-end	Roll-over	Other	Total accidents	Accidents per conflict area: Side-swipe	Rear-end	Roll-over	Other
On-ramps										
Merge upstream	331	79	43	4	25	151	0.24	0.13	0.012	0.08
Merge area	331	170	75	3	19	267	0.51	0.23	0.009	0.06
On-ramp	339	36	7	18	14	75	0.11	0.02	0.053	0.04
Merge downstream	331	38	16	1	19	74	0.11	0.05	0.003	0.06
On-ramp totals	1,332	323	141	26	77	567	0.24	0.11	0.020	0.06
Off-ramps										
Diverge upstream	294	58	40	1	20	119	0.20	0.14	0.003	0.07
Diverge area	294	72	39	3	17	131	0.24	0.13	0.010	0.06
Off-ramp	305	33	16	20	22	91	0.11	0.05	0.066	0.07
Diverge downstream	294	70	31	0	21	122	0.24	0.11	0.000	0.07
Off-ramp totals	1,187	233	126	24	80	463	0.20	0.11	0.020	0.07
Totals	2,519	556	267	50	157	1,030	0.22	0.11	0.020	0.06

TABLE 7 Washington State Truck Accidents by Conflict Area and Accident Type Stratified by Ramp Truck ADT

Conflict area		Ramp truck ADT < 300: # of loc	Accident type: Sswp	Rend	Rovr	Other	300 ≥ Ramp truck ADT < 800: # of loc	Accident type: Sswp	Rend	Rovr	Other	Ramp truck ADT ≥ 800: # of loc	Accident type: Sswp	Rend	Rovr	Other
On-ramps																
Merge	Accidents	114	22	7	2	12	148	39	25	0	8	69	18	11	2	5
upstream	Acc/loc		0.19	0.06	0.02	0.11		0.26	0.17	0.00	0.05		0.26	0.16	0.03	0.07
Merge area	Accidents	114	39	13	2	5	148	87	40	1	10	69	44	22	0	4
	Acc/loc		0.34	0.11	0.02	0.04		0.59	0.27	0.01	0.07		0.64	0.32	0.00	0.06
On-ramp	Accidents	114	2	1	3	3	156	25	3	10	3	69	9	3	5	8
	Acc/loc		0.02	0.01	0.03	0.03		0.16	0.02	0.06	0.02		0.13	0.04	0.07	0.12
Merge	Accidents	114	15	5	1	9	148	16	10	0	5	69	7	1	0	5
downstream	Acc/loc		0.13	0.04	0.01	0.08		0.11	0.07	0.00	0.03		0.10	0.01	0.00	0.07
On-ramp	Totals	456	78	26	8	29	600	167	78	11	26	276	78	37	7	22
	Acc/loc		0.17	0.06	0.02	0.06		0.28	0.13	0.02	0.04		0.28	0.13	0.03	0.08
Off-ramps																
Diverge	Accidents	80	17	11	1	9	172	36	28	0	9	42	5	1	0	2
upstream	Acc/loc		0.21	0.14	0.01	0.11		0.21	0.16	0.00	0.05		0.12	0.02	0.00	0.05
Diverge area	Accidents	80	12	7	1	8	172	49	25	2	8	42	11	7	0	1
	Acc/loc		0.15	0.09	0.01	0.10		0.28	0.15	0.01	0.05		0.26	0.17	0.00	0.02
Off-ramp	Accidents	83	3	2	5	7	180	21	13	14	12	42	9	1	1	3
	Acc/loc		0.04	0.02	0.06	0.08		0.12	0.07	0.08	0.07		0.21	0.02	0.02	0.07
Diverge	Accidents	80	15	7	0	12	172	50	21	0	8	42	5	3	0	1
downstream	Acc/loc		0.19	0.09	0.00	0.15		0.29	0.12	0.00	0.05		0.12	0.07	0.00	0.02
Off-ramp	Totals	323	47	27	7	36	696	156	87	16	37	168	30	12	1	7
	Acc/loc		0.15	0.08	0.02	0.11		0.22	0.13	0.02	0.05		0.18	0.07	0.01	0.04
All ramps	Totals	779	125	53	15	65	1,296	323	165	27	63	444	108	49	8	29
	Acc/loc		0.16	0.07	0.02	0.08		0.25	0.13	0.02	0.05		0.24	0.11	0.02	0.07

Key: ADT = average daily traffic Sswp = sideswipe Rend = rearend Rovr = rollover Loc = location (conflict area)

TABLE 8 Washington State Truck Accidents per Ramp Truck VMT by Ramp Type and Conflict Area

Conflict area		Ramp type					Total accidents	Total RTVMT (millions)	Accidents per RTVMT
		Diamond	Loop	OuterConn	Directional	Other			
On-ramps									
Merge	Accidents	91	7	15	31	7	151		
upstream	RTVMT (millions)	13.66	4.55	2.89	10.88	3.91		35.9	
	Acc/RTVMT	6.66	1.54	5.19	2.85	1.79			4.2
Merge	Accidents	116	50	27	63	11	267		
area	RTVMT (millions)	11.05	3.17	2.84	6.19	3.79		27.0	
	Acc/RTVMT	10.50	15.76	9.49	10.18	2.91			9.9
On-	Accidents	21	17	8	28	1	75		
ramp	RTVMT (millions)	19.81	6.52	4.37	16.02	8.36		55.1	
	Acc/RTVMT	1.06	2.61	1.83	1.75	0.12			1.4
Merge	Accidents	44	15	2	10	3	74		
downstream	RTVMT (millions)	8.20	2.73	1.73	6.57	2.35		21.6	
	Acc/RTVMT	5.37	5.49	1.15	1.52	1.28			3.4
On-	Accidents	272	89	52	132	22	567		
ramp	RTVMT (millions)	52.72	16.97	11.84	39.66	18.41		139.6	
totals	Acc/RTVMT	5.16	5.24	4.39	3.33	1.20			4.1
Off-ramps									
Diverge	Accidents	67	4	12	32	4	119		
upstream	RTVMT (millions)	10.67	2.01	2.59	10.60	3.87		29.7	
	Acc/RTVMT	6.28	1.99	4.63	3.02	1.03			4.0
Diverge	Accidents	54	16	13	42	6	131		
area	RTVMT (millions)	4.67	0.79	1.24	5.49	2.41		14.6	
	Acc/RTVMT	11.57	20.16	10.49	7.65	2.49			9.0
Off-	Accidents	17	23	10	38	3	91		
ramp	RTVMT (millions)	22.89	2.13	2.92	15.80	8.40		52.1	
	Acc/RTVMT	0.74	10.79	3.43	2.40	0.36			1.7
Diverge	Accidents	80	2	13	25	2	122		
downstream	RTVMT (millions)	8.54	1.61	2.07	8.48	3.09		23.8	
	Acc/RTVMT	9.37	1.24	6.27	2.95	0.65			5.1
Off-	Accidents	218	45	48	137	15	463		
ramp	RTVMT	46.76	6.55	8.82	40.38	17.77		120.3	
totals	Acc/RTVMT	4.66	6.87	5.44	3.39	0.84			3.8
Totals	Accidents	490	134	100	269	37	1030		
for all	RTVMT (millions)	99.49	23.52	20.66	80.04	36.17		259.9	
ramps	Acc/RTVMT	4.93	5.70	4.84	3.36	1.02			4.0

Key: RTVMT (ramp truck vehicle-miles of travel) in millions for the study period = ramp truck average daily traffic × conflict area length × 820 ÷ 1,000,000.
Note: Accident rates are per million RTVMT.

accident rate than the other ramp types, and loop off-ramps have the highest average rate. A two-way analysis of variance showed these accident rates per RTVMT to be significantly different by conflict area at the 95% confidence level, but not by ramp type, which is the same test outcome reported for table 5, not taking RTVMT into account. However, these rates differ by conflict area more than for table 5 (i.e., have a higher test power), since lengths of merge and diverge conflict areas and of the ramps themselves are specific to each ramp. When ramp truck volumes and travel distances are taken into account, accident rates per RTVMT are highest in ramp connection areas by a significant margin. While this may be an expected outcome, the finding supports the need to focus ramp improvement efforts on merge and diverge areas.

A final observation from table 8 is that truck accident rates per RTVMT were relatively higher on loop ramps because these ramps are generally shorter, and relatively lower on directional ramps because these ramps tend to serve higher traffic volumes. This finding supports the need to compare the accident rate at a given ramp with similar ramps serving similar traffic volumes.

Table 9 groups conflict areas together by whether RTADT was low, medium, or high. These stratified results show truck accidents per RTVMT to consistently decrease in all conflict areas with higher RTVMT. While truck accidents per location increase with greater truck exposure (as indicated by table 7), the increase is generally much less than the truck VMT increase.

With regard to the accuracy of the RTADT estimates, these equations showed decreasing truck percentages with increasing total ADT. If RTADT were directly proportional to the ramp ADT of all vehicles, then the rates would have the same relative magnitudes as if total ADT were used as the measure of exposure. In that case, the lower accident rates at higher truck volumes would be even lower relative to those for lower truck volumes as seen in table 9.

Table 10 is a summary of Washington truck accident frequencies and rates by conflict area per ramp truck trip and RTVMT. Note that the average accident rates are all nearly equal for merge and diverge ramps when not divided by conflict area, but very different when separated by conflict area. This finding shows the importance of examining the accident histories of ramps by conflict area rather than of entire ramps, in order to identify possible problem spots.

COMPARISON OF ACCIDENTS PER RAMP IN THREE STATES

Since we were not able to obtain RTADT for Colorado or California, we limit our comparisons in this section to accident frequencies per ramp type. Table 11 lists number of ramps and accidents per ramp type for Colorado, California, and Washington. The data in Colorado and California were for 1991 to 1993, while the data for Washington were for 1993 to early 1995. Since our Washington data were for 27 months but our Colorado and California data were for 36 months, all values were converted to a yearly basis. The accident frequencies for Washington State are the weighted means of the frequencies shown in the last two columns of table 3(c). By coincidence, the mean truck accident frequency per ramp for all ramp types was 0.71 per year in each of these states.

The Colorado and California ramps were selected on the basis of a severity index that weighted the number of fatal, injury, and property damage only truck accidents. We also included some sites with lower severity indices in each sample. Thus, the equal mean frequencies for all ramps examined in each state is reasonable. For brevity, we limit our discussion of table 11, but note that the accident frequencies per directional ramp or per loop ramp are very consistent in all three states.

IDENTIFICATION OF HIGH-RISK SITES

Our findings support the need to compare the accident history of a given ramp with similar ramps serving similar traffic volumes. The average accident frequencies did not differ significantly by ramp type, but there was significant variation by conflict area within ramp types. These differences became greater by ramp type and conflict area when accident rates per ramp truck volumes and ADT were examined. These findings led us to propose a straightforward procedure to "flag" potentially high-risk ramps for closer analysis, which can be easily implemented within emerging safety management systems. In states that collect more complete data, the procedure can be made more sophisticated.

Seven comparisons can be made of the accident frequency at a given ramp by one or more of three attributes (accident type, ramp type, and conflict area) to the accident distribution of other ramps in a state. These comparisons are:

1. by accident type for all ramp types and conflict areas;
2. by ramp type for all accident types and conflict areas;
3. by conflict area for all ramp types and accident types;

TABLE 9 Washington State Truck Accidents per RTVMT by Conflict Area and Accident Type Stratified by RTADT

Conflict area		RTADT < 300					300 ≥ RTADT < 800					RTADT ≥ 800				
		RTVMT	Accident type				RTVMT	Accident type				RTVMT	Accident type			
		(mil)	Sswp	Rend	Rovr	Other	(mil)	Sswp	Rend	Rovr	Other	(mil)	Sswp	Rend	Rovr	Other
On-ramps																
Merge	Accidents	3.8	22	8	2	12	16.2	39	25	0	8	15.9	18	10	2	5
upstream	Acc/RTVMT		5.72	2.08	0.52	3.12		2.41	1.55	0.00	0.49		1.13	0.63	0.13	0.32
Merge area	Accidents	3.2	39	13	2	5	12.5	87	40	1	10	11.3	44	22	0	4
	Acc/RTVMT		12.30	4.10	0.63	1.58		6.95	3.20	0.08	0.80		3.88	1.94	0.00	0.35
On-ramp	Accidents	5.9	3	1	3	3	24.3	25	3	10	3	24.9	8	3	5	8
	Acc/RTVMT		0.51	0.17	0.51	0.51		1.03	0.12	0.41	0.12		0.32	0.12	0.20	0.32
Merge	Accidents	2.3	15	5	1	9	9.7	16	10	0	5	9.6	7	1	0	5
downstream	Acc/RTVMT		6.47	2.16	0.43	3.88		1.65	1.03	0.00	0.52		0.73	0.10	0.00	0.52
On-ramp	Totals	15.2	79	27	8	29	62.7	167	78	11	26	61.7	77	36	7	22
	Acc/RTVMT		5.19	1.77	0.53	1.90		2.66	1.24	0.18	0.41		1.25	0.58	0.11	0.36
Off-ramps																
Diverge	Accidents	3.0	17	11	1	9	17.2	36	28	0	9	9.5	5	1	0	2
upstream	Acc/RTVMT		5.68	3.67	0.33	3.01		2.09	1.63	0.00	0.52		0.52	0.10	0.00	0.21
Diverge area	Accidents	1.3	12	7	1	8	7.6	49	25	2	8	5.7	11	7	0	1
	Acc/RTVMT		9.23	5.39	0.77	6.16		6.46	3.29	0.26	1.05		1.93	1.23	0.00	0.18
Off-ramp	Accidents	3.4	3	2	5	7	33.2	21	13	14	12	15.6	9	1	1	3
	Acc/RTVMT		0.88	0.58	1.46	2.04		0.63	0.39	0.42	0.36		0.58	0.06	0.06	0.19
Diverge	Accidents	2.4	15	7	0	12	13.8	50	21	0	8	7.6	5	3	0	1
downstream	Acc/RTVMT		6.26	2.92	0.00	5.01		3.63	1.52	0.00	0.58		0.66	0.39	0.00	0.13
Off-ramp	Totals	10.1	47	27	7	36	71.8	156	87	16	37	38.4	30	12	1	7
	Acc/RTVMT		4.65	2.67	0.69	3.56		2.17	1.21	0.22	0.52		0.78	0.31	0.03	0.18
All ramps	Totals	25.3	126	54	15	65	134.5	323	165	27	63	100.1	107	48	8	29
	Acc/RTVMT		4.97	2.13	0.59	2.56		2.40	1.23	0.20	0.47		1.07	0.48	0.08	0.29

Key: ADT = average daily traffic Sswp = sideswipe Rend = rearend Rovr = rollover

RTVMT (ramp truck vehicle-miles of travel) in millions for the study period = ramp truck average daily traffic × conflict area length × 820 ÷ 1,000,000.

Note: Accident rates are per million RTVMT.

4. by accident type and ramp type for all conflict areas;
5. by accident type and conflict area for all ramp types;
6. by ramp type and conflict area for all accident types; and
7. by accident type, ramp type, and conflict area.

Each additional attribute by which accidents are grouped reduces the sample size of accidents and ramps to which a given ramp is compared. Moreover, the likelihood (or ease) of obtaining data to classify accidents by these attributes is greatest for accident type, less for ramp type, and least for conflict area. With those considerations, we recommend performing comparisons 1, 2, 4, 6, and 7 (in that order) as numbered above. Comparisons 1, 2, and 4 do not require identifying the conflict area, the least obtainable data. Comparisons 6 and 7 require identifying the conflict area, but these comparisons are not necessary to warrant a site inspection and design evaluation. If a ramp is found to have a high frequency of accidents (1) overall, (2) by accident type, and (4) by accident and ramp type, then it probably warrants closer examination. Accident reports for that ramp would be studied, and accidents classified by conflict area and several other attributes such as vehicle type, weather, lighting, road condition, and driver actions. This information would then be used to determine whether improvements to geometric design, signage, or traffic controls are warranted considering various alternatives and their costs.

Thus, the high-risk site identification procedure is as follows:

1. For a given ramp (all conflict areas combined), compare its frequency of *all accident types* over a multiyear analysis period to the frequency distribution of *all accident types in all conflict areas*

TABLE 10 **Summary of Washington Truck Accident Rates by Conflict Area**

Conflict area	Number of accidents	Number of conflict areas	RTT	RTVMT	Accidents per conflict area	Accidents per RTT	Accidents per RTVMT
On-ramps							
Merge upstream	151	331	143.6	35.9	0.5	1.1	4.2
Merge area	267	331	143.6	27.0	0.8	1.9	9.9
On-ramp	75	339	147.0	55.1	0.2	0.5	1.4
Merge downstream	74	331	143.6	21.6	0.2	0.5	3.4
Total	567	1,332	577.8	139.6	0.4	1.0	4.1
Off-ramps							
Diverge upstream	119	294	119.0	29.7	0.4	1.0	4.0
Diverge area	131	294	119.0	14.6	0.4	1.1	9.0
Off-ramp	91	305	122.7	52.1	0.3	0.7	1.7
Diverge downstream	122	294	119.0	23.8	0.4	1.0	5.1
Total	463	1,187	479.6	120.3	0.4	1.0	3.8
Totals	1,030	2,519	1,057.4	259.9	0.4	1.0	4.0

Key: RTT = ramp truck trips; RTVMT = ramp truck vehicle-miles of travel.

Note: Accident rates are per million RTT and million RTVMT.

at all other ramps of a state. If the accident frequency at a given ramp lies above a given threshold (discussed below), an initial flag is raised.

2. For a given ramp (all conflict areas combined), compare its frequency of *each accident type* over a multiyear analysis period to the frequency distribution of *each accident type in all conflict areas at all other ramps of a state.* If any accident type frequency at a given ramp lies above a given threshold, a second flag is raised.
3. For a given ramp (all conflict areas combined), compare its frequency of *each accident type* over a multiyear analysis period to the frequency distribution of *each accident type in all conflict areas at all similar type ramps within a broadly similar range of RTADT in a state.* If any accident type frequency at a given ramp lies above a given threshold, a third flag is raised.

The first comparison indicates whether the ramp has an unusual overall accident history in comparison to all other statewide ramps, and requires minimal information. The second comparison indicates whether the ramp has an unusual accident history for any particular accident type, knowing that data on conflict area and ramp type may not be available. The third comparison (number 4 in the prior list) indicates whether the ramp has an unusual accident history for any particular accident type in comparison to similar ramps, knowing that data on conflict area may still not be available. Note that RTADT as used here indicates that ramps being compared have similar truck exposure. If all comparisons point to a potential problem, then further evaluation is recommended, leading to comparisons 6 and 7 if conflict area data is available for many other ramps of similar design in the state. If only one or two comparisons indicate a potential problem, then further evaluation may be considered depending on available resources.

As for the appropriate threshold, the 75th percentile is suggested by Basha and Ramsey (1993) as an "initial check" to identify locations that may warrant further investigation. A higher or lower percentile might be considered after experience shows whether this percentile flags too many or too few locations that do or do not warrant further attention. If we assume accidents per year at any ramp to be Poisson distributed (for which the variance equals the mean), then the threshold might be set to the number of accidents for which the average "peer" site would have a probability of 5% of exceeding. Note that the accident distribution among ramp locations on which these thresholds are based should ideally include or control for the prevalence of "no accident" locations.

TABLE 11 Comparison of Yearly Truck Accidents per Ramp in Three States

Ramp type	Ramps	Percent	Accidents per year	Percent	Average accident frequency
Colorado accidents					
Diamond	27	30.3	16	25.9	0.60
Loop	12	13.5	9	14.8	0.78
OuterConn	11	12.4	6	9.0	0.52
Directional	39	43.8	32	50.3	0.81
Other	0	0.0	0	0.0	0.00
Total	89	100.0	63	100.0	0.71
California accidents					
Diamond	19	3.9	20	5.6	1.04
Loop	25	5.1	19	5.4	0.76
OuterConn	23	4.7	11	3.1	0.48
Directional	324	65.9	266	75.8	0.82
Other	101	20.5	35	10.1	0.35
Total	492	100.0	351	100.0	0.71
Washington accidents					
Diamond	310	48.1	218	47.5	0.70
Loop	81	12.6	60	13.0	0.74
OuterConn	59	9.2	44	9.7	0.75
Directional	152	23.6	120	26.1	0.79
Other	42	6.5	16	3.6	0.39
Total	644	100.0	458	100.0	0.71

To reduce regression-to-the-mean effects, Bayesian estimates of accident expectancies can also be developed if there are reliable prediction equations of accidents based on explanatory variables, and if reliable data for these explanatory variables is available (see Higle and Witkowski 1988; Higle and Hecht 1989; Miaou et al 1992; and Hauer 1997). We fitted both regression and neural network models of many foms to this data including geometric features and did not obtain reliable prediction equations of ramp truck accidents (see Awad and Janson 1997). Thresholds based on Poisson distributions of accidents per year may be sufficient, however.

The following is an example of applying the above procedure to the interchange of Interstate 25 and State Highway 34 in Colorado, which serves the cities of Greeley and Loveland. This interchange is a full cloverleaf, with four loop ramps and four outer connectors. The entire interchange had experienced 11 truck accidents in the years 1991 to 1993, of which 6 were overturns and 4 were overturns on the loop ramp leading from westbound SH-34 to southbound I-25.

Four truck accidents on one ramp in a three-year period suggested a problem simply according to the first overall test. Four overturns on one ramp in a three-year period more strongly indicated a problem according to the second test. Finally, even compared with other loop ramps, four truck accidents of any type in a three-year period gave justification for a site inspection and design evaluation. Actions were taken to improve the lane markings and speed warning signs at this interchange, and the interchange continues to be monitored.

CONCLUDING REMARKS

Truck accidents per ramp location or per RTVMT can vary by type of ramp, conflict location, and accident type. Based on the data shown, loop ramps in particular have generally higher accident rates, particularly rollovers. One implication of this finding is that a given loop ramp may have a high accident rate compared to all ramp types, but not comparable to loop ramps. Short of total reconstruction, low-cost measures to reduce the accident rate at a loop ramp to be in line with non-loop ramps may be limited. Thus, evaluations of accident mitigation effectiveness should be done within ramp types.

ACKNOWLEDGMENTS

This study was funded by the Federal Highway Administration, the Colorado Department of Transportation, and the Trucking Research Institute. We thank several state DOT officials in Colorado, California, and Washington for their help in providing requested data. We also thank the officials of the Colorado Motor Carriers Association for providing comments on our final project report on which this paper is based.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 1990. *A Policy on the Geometric Design of Highways and Streets.* Washington, DC.

Awad, W. and B.N. Janson. 1997. Prediction Models for Truck Accidents at Freeway Ramps in Washington State Using Regression and AI Techniques, presented at the 77th Annual Meeting of the Transportation Research Board, Washington, DC.

Basha, P.E. and S.L. Ramsey. 1993. A Methodology for Comparing Accident Rates. *ITE Journal* May. 30–35.

Ervin R., M. Barnes, C. MacAdam, and R. Scott. 1986. *Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges: Final Report to the Federal Highway Administration,* volume 1: FHWA-RD-86-057; volume 2: FHWA-RD-86-058. Washington, DC: U.S. Department of Transportation.

Firestine, M., P. Toeg, and H.W. McGee. 1989. *Improving Truck Safety at Interchanges: Final Report to the Federal Highway Administration,* FHWA-IP-89-024. Washington, DC: U.S. Department of Transportation.

Goodell-Grivas, Inc. 1989. *Examination of Truck Accidents on Urban Freeways: Final Report,* FHWA-RD-89-201. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

Hauer, E. 1997. *Observational Before-After Studies in Road Safety.* New York, NY: Pergamon Press, Elsevier Science.

Higle, J.L. and M.B. Hecht. 1989. A Comparison of Techniques for the Identification of Hazardous Locations. *Transportation Research Record* 1238:10–19.

Higle, J.L. and J.M. Witkowski. 1988. Bayesian Identification of Hazardous Locations. *Transportation Research Record* 1185:24–36.

Janson, B.N., W. Awad, J. Robles, J. Kononov, and B. Pinkerton. 1997. Effects of Geometric Characteristics of Interchanges on Truck Safety: Final Report to the Colorado Department of Transportation.

Miaou, S-P., P.S. Hu, T. Wright, A.K. Rathi, and S.C. Davis. 1992. Relationship Between Truck Accidents and Highway Geometric Design: A Poisson Regression Approach. *Transportation Research Record* 1376:10–18.

Pigman, J.G., K.R. Agent, and C.V. Zeeger. 1981. Interstate Safety Improvement Program. *Transportation Research Record* 808:9–16.

Sullivan, E.C. 1990. Estimating Accident Benefits of Reduced Freeway Congestion. *Journal of Transportation Engineering/ASCE* 116, no. 2:167–180.

Wright P.H. 1996. *Highway Engineering,* sixth edition. New York, NY: John Wiley & Sons, Inc.