Investigation of the Economic Feasibility of Exclusive Truck Lanes (ETL)

SYNTHESIS OF SAFETY ANALYSIS IN ETL EVALUATION

DRAFT WHITE PAPER

Prepared for

Office of the Secretary of Transportation
U.S. Department of Transportation
Washington, D.C.

June 23, 2006

Battelle
The Business *of* Innovation

505 King Avenue
Columbus, Ohio 43201

Investigation of the Economic Feasibility of Exclusive Truck Lanes (ETL)

SYNTHESIS OF SAFETY ANALYSIS IN ETL EVALUATION

DRAFT WHITE PAPER

Prepared for

Office of the Secretary of Transportation
U.S. Department of Transportation
Washington, D.C.

June 23, 2006

Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201

Principal Author

Dr. Edward Fekpe

Table of Contents

List of Tables

List of Figures

SUMMARY

Safety and freight mobility efficiency are the main drivers for considering exclusive truck lane (ETL) implementation. The underlying hypothesis is that physically separating heavy trucks from light vehicles will improve highway safety by reducing the number of truck-related crashes. Safety analysis is a critical element in evaluating the feasibility of ETL implementation. This white paper presents a synthesis of potential approaches in evaluating the safety impacts of ETL implementation. The following are concluding remarks and recommendations for future research.

Concluding Remarks

- Historical crash data provide a reliable source for safety analysis, but crash data for mixed traffic lanes do not necessarily reflect ETL situations. In the absence of historical crash data on ETLs, however, simulation becomes an appealing alternative to generate crash data to closely represent real ETL situations. Simulation offers the opportunity to evaluate interactions among vehicles operating under different lane assignment scenarios.

- Simulation generates vehicle conflicts and not crashes. The major challenge is deriving the number of crashes from conflicts data. A multi-criteria approach was developed to help estimate the number of crashes from data on conflict measures generated from simulation. Limitations of the simulation approach are that single-vehicle crashes and severity of crashes could not be derived from conflict data generated from simulation.

- Traffic simulation models such as CORSIM were not originally designed to handle all possible ETL configurations and logic. In order to use any off-the-shelf traffic simulation software application to generate meaningful results for ETL analyses, certain programming modifications are be necessary.

- The statistical approaches include probability models for estimating the safety benefits of implementing on-board technologies designed to reduce crashes and deterministic regression models for estimating the safety benefits of highway improvements. These models were not specifically designed for ETL safety analysis. Moreover, these statistical models were developed from historical crash data from mixed lanes. The regression models for example, were developed with average annual daily traffic (AADT) as the primary independent variable. These models do not consider truck percentage which is a critical element in evaluating the feasibility of ETL implementation.

Recommendations for Further Research

- The suggested thresholds for conflict measures for estimating the number of crashes from vehicle conflict data were based on a limited number of simulation runs. It is recommended that these thresholds be refined with more extensive simulation results.

- Simulation approach is not capable of estimating single-vehicle conflicts hence crashes. Single vehicle crashes are equally important regardless of the analytical approach that is

adopted. Research is needed to develop a methodology for estimating single vehicle crashes. It is conceivable that such a methodology could be statistical, heuristic, simulation or a combination of several fundamental groups of approaches.

- Similar to single vehicle crashes, the simulation approach is not capable of distinguishing among the levels of severity of crashes. Research is needed to determine the severity of crashes from vehicle conflict data. This is important because the cost of a crash depends on the severity of the crash.

- The simulation results assume that all drivers (automobile and truck) observe lane assignments. Furthermore, the simulation approach assumes certain driver behavioral characteristics that may not necessarily be representative of the population of drivers on the roadway. It is possible that these assumptions may not necessarily hold true in reality. It is recommended that research be undertaken to study the driver responses based on which correction factors (where appropriate) can be introduced to the results of simulation runs. Also, research is needed to determine whether or not driver response can be introduced in the vehicle simulation.

1. BACKGROUND

The potential use of exclusive truck lanes (ETLs) in the U.S. as a tool to help improve highway safety and freight mobility efficiency has been investigated through recent research efforts funded by the United States Department of Transportation (USDOT). The underlying hypothesis is that physically separating heavy trucks from light vehicles will improve highway safety by reducing the number of truck-related crashes. In 1990, the Federal Highway Administration (FHWA) sponsored a study to examine the feasibility of ETLs for vehicles by type. This study evaluated exclusive lane use feasibility and resulted in a benefit-cost (B-C) model known as Exclusive Vehicle Facilities (EVFS).

In 2002, FHWA funded a study that updated and improved the B-C model (Battelle, 2002). Several updates were implemented in this study. These updates included information on the number of crashes by vehicle type and crash type from the "1999 Traffic Safety Facts" and other supporting sources including "National Truck Crash Profile, 1998," "1999 Motor Vehicle Crash Data from FARS and GES," and "Truck and Bus Crash Fact Book 1995." While these crash rates are generally reasonable, they were based on crash data from mixed traffic lanes that do not necessarily reflect crash rates for ETLs. This is because there is no existing ETL in the U.S. and therefore no historical crash data on ETLs. Although there are exclusive automobile-only facilities in the U.S., crash data from such facilities are not directly applicable to ETLs. This study also identified potential opportunities for ETL implementation and suggested criteria for selecting feasible sites for ETLs. It was suggested that the traffic criteria to be used to identify potential locations for ETL implementation should be some combination of total traffic volume and the proportion of trucks in the traffic stream. The suggested values were based on results of sensitivity analyses using the updated B-C model. The suggested traffic threshold values are average annual daily traffic (AADT) of 100,000 or more with truck percent of 25 percent or higher.

Important factors in analyzing the benefits of ETLs are the cost of construction and the crash costs. The difficulty in estimating the number of crashes and associated cost is recognized. A notable limitation of the 2002 study is that crash rates were derived from mixed lanes crash data. Crash data from mixed traffic lanes are not fully reflective of ETLs. In an attempt to more fully investigate the prediction of crashes on ETLs and related facilities, three potential approaches were considered to investigate the safety impacts of ETLs:

1. Analyze crash data from existing ETL implementation
2. Use historical data from mixed lanes with assumptions
3. Use a simulation approach to generate conflicts from which to estimate crashes.

Since there are no ETLs or "near" ETLs in the U.S., the first approach was not worth pursuing as a method of crash prediction. With no ETLs in existence, the historical crash data and simulation approaches appear to be more feasible. The use of historical data for mixed lanes has been studied (Battelle, 2002). In 2004, FHWA extended the 2002 study to investigate the simulation approach to estimate the number and cost of crashes on ETLs. The purpose of that project was to update and improve the assessment of benefits and costs associated with the implementation of ETLs as a means of improving highway safety and enhancing freight transportation by highway. The central theme of that project was to use simulation to update the crash data to closely reflect ETL implementation.

The objective of this white paper is to synthesize information on potential approaches to evaluate safety impacts of implementing ETLs. This includes analysis of crash data as a function of several variables and the use of simulation techniques. It is recognized that simulation results are not true representations of real-life situations, particularly in situations involving human factors (e.g., driver behavior). The challenges and limitations of these approaches are also discussed.

2. SUMMARY OF RELEVANT STUDIES

The idea of separating truck and passenger vehicle flow in order to ameliorate congestion and safety as an operational measure is beginning to be examined by many jurisdictions around the country. The concept of truck-car separation can range from lane restrictions to separate truck-only lanes. According to a recent survey (Urban Transportation Monitor, 2004), Federal, state, and local agencies have examined "truck only" routes on some of the nation's busiest corridors for a number of years as a way to reduce traffic congestion, improve the flow of commerce, and increase safety on U.S. highways. Table 1 summarizes the characteristics of ETL initiatives n the U.S.

A detailed review of published literature on safety analysis relating to exclusive truck facilities was included in the 2002 ETL study final report (Battelle, 2002). Little research has been completed that directly addresses ETLs and their impacts on highway safety. This section summarizes a few recent studies that address safety impacts of ETLs.

Hoel and Peek (1999) evaluated the use of lane restrictions to mitigate or reduce conflicts between heavy trucks and light vehicles on Interstate 81 (I-81) in Virginia. A freeway simulation model (FRESIM) was initially applied to hypothetical scenarios and then to three selected segments on I-81. Research results indicated that the effects vary based on factors unique to each site study, such as type of restriction, traffic characteristics, and terrain.

A safety consideration in ETL analysis is interchange design, including exit and entrance ramps, to reduce the risk of truck-car interactions and subsequent crashes. Janson et al. (1998) analyzed truck-involved crashes on freeways in Washington State that are in four conflict areas of merge and diverge ramps. It was found that truck crash frequencies were significantly different by conflict area (off-ramp, on-ramp, merge area, diverge area, upstream, downstream) and type (side-swipe, rear-end, roll-over), and that high-volume ramps have lower rates of truck crashes per truck-mile of travel. Therefore, the safety risk associated with a ramp was related to conflict area and crash type, and not related to truck volume. The findings of the research were used to develop a procedure for identifying high-risk locations for remedial action to improve safety. The tools developed for this analysis could be useful in identifying potential interchange and ramp designs, and modified for use in the safety evaluation of ETLs.

Solomon et al. (1999) analyzed vehicle miles driven and crash data obtained from toll road authorities in Florida, Kansas, New York, Illinois, Indiana, Ohio, and Pennsylvania. It was found that large commercial vehicles were significantly under-involved in single-vehicle crashes on all state toll roads, and commercial vehicles were over-involved in multi-vehicle crashes relative to passenger vehicles (the exceptions being Kansas and Indiana). In Ohio and Pennsylvania, the risk of commercial vehicle involvement in multi-vehicle crashes resulting in serious injury or death was twice that of passenger vehicles. Not surprisingly, the factors

Table 1. Characteristics of Exclusive Truck Lane Initiatives in the U.S.

State	Corridor/Interstate Understudy	Strategies Considered/Cost Projections	Conclusions/Recommendations
California	State Route 60, from I-710 to I-15, a distance of approx. 38 miles	Initially considered sharing existing HOV lanes, and adding both at-grade and above grade lanes. Cost estimate is at least $16 billion.	The study recommended adding truck lanes to the freeway at grade, and adding limited above-grade mixed-flow lanes where right-of-way acquisition would be difficult.
Virginia	I-81	Initial estimate of $6.25-$7.75 billion over 15 years. The funding plan uses $169 million of Virginia DOT's unexpended allocations shown in the current Six-Year Improvement Plan for projects identified in the I-81 corridor.	Separate passenger vehicles and heavy trucks using physical barriers; add truck climbing lanes, as well as longer on- and off-ramps; toll heavy commercial vehicles.
Georgia	I-75, mainly in the Atlanta metropolitan area	State Road and Tollway Authority planning a study in conjunction with HOT study.	Recommendations will not be available for at least a year.
Texas	Trans Texas Corridor parallels I-35, I-37 and I-69 (proposed) from Denison to the Rio Grande Valley, I-69 (proposed) from Texarkana to Houston to Laredo, I-45 from Dallas-Fort Worth to Houston, and I-10 from El Paso to Orange	The 4,000-mile corridor cost would range from $145.2 billion to $183.5 billion. The corridor will include separate tollways for passenger vehicles and trucks, as well as passenger and freight rail and dedicated utility zones. Pavement cost for a four-lane truck roadway is estimated at $3.1 million per centerline mile.	Heavy-duty truck lanes (two in each direction) built first, to be shared initially by both passenger vehicles and trucks. As traffic volumes increase and additional capacity is warranted, separate passenger lanes would be constructed.
Florida	State highway system, both rural and urban locations	All of Florida's interstate system was examined, with further consideration to specific "hot spots" determined by truck crashes, truck volume and percent, and level of service.	Most of Florida's interstate system emerged as suitable for consideration of exclusive truck facilities. "Between City" recommendations include I-95 between Miami and Titusville, I-95 between Daytona and Jacksonville, I-75 between Naples and Ft. Myers, I-41/I-275 between Tampa and Daytona, which includes Orlando. "Within City" recommendations include the port cities of Miami, Jacksonville, and Tampa, which experience high truck volumes.
Washington	Begins in Lewis County, extends north to the Canadian border, containing I-5, running through the Seattle/Everett/Tacoma metropolitan area.	Corridor envisioned as a possible alternative passenger and truck transportation route to the present I-5, which might be financed by tolls and could also be used by rail and utilities. Exclusive truck-only toll lanes will be considered. Estimated cost of at least $41 billion for a four-lane north-south highway across the state from Oregon to Canada.	The state legislature appropriated $500,000 for a study in the state's 2003-2005 transportation budget. Study is still in the conceptual stage. Another alternative is adding a truck-only toll lane to the existing I-5.

Source: The Urban Transportation Monitor, "Consideration of Exclusive Truck Lanes Moves Forward in U.S." Vol. 18 No. 23, pg. 7. December 10, 2004.

influencing whether commercial vehicle crash rates are higher or lower than passenger vehicles are the type of crash, specific toll road, and traffic density.

Garber and Gadiraju (1989) used a simulation model, SIMAN, to evaluate the effect of truck restrictions, such as lane or speed restrictions, on safety. The study analyzed data on crashes in Virginia from 1985 through 1987 by route and city or county. The findings indicate that imposing a differential speed limit in addition to a lane restriction increases the potential for crashes by increasing the interaction between trucks and cars. Overall, no safety benefits were noted in any of the truck strategies tested and the potential for crashes actually increased, particularly on highways with high AADT and a high percentage of trucks.

The various evaluation studies did not reveal a universal approach to evaluate the benefits of ETLs. This was especially true for safety benefits or crash reductions due to ETL implementation. Direct comparison of crash data is the ideal approach to measure highway safety, determine unsafe locations, and evaluate the effectiveness of improvement projects. For ETLs in particular, there are currently no historical crash data for crash analysis. As such, evaluations of even hypothetical options also suffer from lack of sufficient crash data necessary for calibration. To address the problem of lack of data for policy level analysis, traffic simulation is an option.

3. POSSIBLE ETL CONFIGURATIONS

To better understand safety analysis for ETL, it is important to first appreciate the possible ETL configurations that can be practically implemented and evaluated. In estimating the potential benefits of implementing a given scenario, it must not only be compared with the "do nothing" scenario but also with a traditional capacity expansion scenario, i.e., adding mixed-use lanes. Thus the following six options are relevant to ETL safety benefit analysis.

0. *Do nothing* – This is the base case, in which no construction or any other change is made to the physical highway facilities.

1. *Add mixed-vehicle lanes (no special lane use restrictions)* – The first scenario is to increase the number of mixed lanes by constructing additional lanes. No lane restrictions.

2. *Designate existing lanes for mixed, light, and heavy vehicles* – The second scenario is to re-designate the functions of existing lanes. For example, designating one lane of an existing 4-mixed-lane highway as an ETL and the other three lanes remain mixed lanes. In this scenario, no new lanes are added, therefore the total number of lanes remains the same but lane functions have changed.

3. *Add non-barrier separated lanes and designate new and existing lanes for light and heavy vehicles (no mixed lanes i.e., light and heavy vehicle only)* – The third scenario is to increase the total number of lanes (construct additional lanes) and designate at least one lane for the exclusive use of a certain vehicle class.

4. *Add non-barrier separated lanes and designate new and existing lanes for mixed, light and heavy vehicles (allow mixed and heavy vehicle lanes)* – The fourth scenario is to increase the total number of lanes and designate at least one lane for the exclusive use of a certain vehicle class. The difference between this and the scenario 3 is that in this scenario, trucks are allowed to use mixed lanes when the capacity of the designated lane is exceeded, while in the previous scenario, trucks are restricted to use the ETL only.

5. *Add barrier separated lanes and designate new and existing lanes for light and heavy vehicles* – The fifth scenario is to increase the total number of lanes and designate at least one lane for the exclusive use of a certain vehicle class. The additional exclusive lane is barrier separated from the existing lanes and trucks are restricted to use the ETL only.

4. SAFETY ANALYSIS USING HISTORICAL CRASH DATA

The current ETL B-C model computes the number of crashes for light vehicle only lane(s) or heavy vehicle only lane(s) and mixed vehicles lanes using VMT, traffic volume by class of vehicle, and crash rates by severity. The crash rates represent the probability or likelihood of a crash by vehicle type and severity. The crash costs are then estimated by applying the unit crash costs by severity. There are nine different types of vehicle interactions included for a mixed-vehicle facility, as illustrated in the matrix shown in Table 2.

Table 2. Vehicle Interactions for Mixed-Vehicle Traffic Lane

Vehicle Type	Light Vehicle (LV)	Single Unit Truck (SU)	Combination Truck (CV)
0	Single LV (LV_1)	Single SU (SU_1)	Single CV (CV_1)
LV	Multiple LV (LV_2)	SU with LV (SU_3)	CV with LV (CV_3)
SU	LV with SU (LV_3)	Multiple SU (SU_2)	CV with SU (CV_4)
CV	LV with CV (LV_4)	SU with CV (SU_4)	Multiple CV (CV_2)

Source: ETL Final Report, Battelle, 2002

Crash data for mixed lanes, (i.e., the number crashes by vehicle type and crash type) can be obtained from "Traffic Safety Facts" published by the National Highway Traffic Safety (NHTSA). Other supporting sources include "National Truck Crash Profile," "Motor Vehicle Crash Data from Fatality Analysis Reporting Systems (FARS), General Estimates System (GES)," and "Truck and Bus Crash Fact Book."

The advantage of using historical crash data is that it presents the real situation. In using crash data for ETL analyses, however, certain assumptions would be necessary. The underlying assumption is that the certain types of crashes would not be possible with the implementation of certain configurations of ETLs. Furthermore, the number and distribution by type of interaction, vehicle type, and severity would remain about the same. For instance, in the B-C model, the number of possible vehicle interactions for ETLs decreases from nine to seven, including five involving heavy vehicles (SU_1, SU_2, CV_1, CV_2, and SUCV) and two involving light vehicles (LV_1, LV_2). This is because it is assumed that by separating trucks from other vehicles, certain vehicle interactions (LVSU, LVCV) are automatically eliminated because heavy vehicles will be restricted to use ETLs only. However, this method does not capture the changes in interactions between light vehicles because of changed traffic operation. Also, this method does not consider impacts of merge/weave areas where trucks enter and exit ETLs. These are major limitations to the use of historical data for ETL analysis.

5. SIMULATION APPROACH TO SAFETY ANALYSIS FOR ETL

Direct comparison of crash data is the ideal approach to measure highway safety, determine unsafe locations, and evaluate the effectiveness of improvement projects. However, crash reports are frequently incomplete, erroneous, or imprecise. Additionally (and fortunately), crashes occur sporadically and it usually takes a long time to collect sufficient and valid crash data. Small crash sample sizes, often the basis of many crash analysis studies, could lead to inaccurate conclusions. For ETLs in particular, there is currently no historical crash data for crash analysis.

In the absence of historical crash data, the only practical option for purposes of evaluating the economic viability of ETLs is to use simulation techniques to estimate crashes. However, simulation cannot directly measure crashes. Instead, simulation can be used to measure conflicts from which the number of crashes can be estimated. Many of the existing traffic simulation models do not include crash rates or crash measures. These simulation models are intended to simulate traffic operations in a non-crash scenario, i.e., the models assume that no unsafe maneuvers will occur.

As an alternative to crash analyses, various researchers have suggested the use of traffic conflicts. Gettman and Head (2003) define a traffic conflict as a "traffic event involving the interaction of two or more road users, mostly vehicles, where one or both drivers take evasive action such as braking or swerving to avoid a collision." Amundsen and Hyden (1977) defined conflict as an observable situation in which two or more road users approach each other in time and space for such an extent that there is the risk of collision if their movements remain unchanged. For a conflict to happen, the road users must be on a collision course, i.e., the users must be attempting to occupy the same space at the same time. The primary requirement of a traffic conflict is that the action of the one user places the other on a collision path unless evasive action is taken by the other user to avoid it. It is important to note that by definition, this kind of conflict analysis does not account for single-vehicle crashes.

An advantage of the simulation based approach is that it allows the identification of conflicts over the entire network including movements at interchanges and ramps. Conflicts are expected to occur more frequently than crashes, and not all conflicts result in a crash. The challenge, therefore, is to relate the conflicts to the number and severity of crashes.

5.1 Conflict Measures

The goal of analyzing the conflict-crash relationship is to determine conflicts that result in crashes. Before exploring the relationship, it is important to identify the types of conflicts of specific relevance to ETL implementation and also identify the relevant conflict measures. Gettman and Head (2003) investigated the potential for deriving surrogate measures of safety from existing traffic simulation models and categorized conflicts by type of maneuver. The two main types of multiple vehicle crashes relevant to ETLs are:

1. Merging/lane change conflicts, which are always followed by a sudden braking, can happen in two cases. The first case is when the merging vehicle suddenly merges into the open lane. The second case is when a vehicle tries to merge when there is not enough space in the open lane.

2. Rear-end conflicts, which happen in sudden braking without any preceding merging.

In order to identify conflicts, surrogate conflict measures which can be quantified need to be defined. Examples of surrogate conflict measures proposed by various researchers (e.g., Gettman and Head, 2003) include the following.

1. Gap Time (GT) – Time elapsed between completion of encroachment by lane-changing vehicle and the arrival time of the following vehicle at the encroachment location (point where the lane change is completed) if they continue with same speed and path.

2. Time to Collision (TTC) – Expected time for two vehicles to collide if they remain at their present speed and on the same path.

3. Deceleration Rate (DR) – Rate at which a vehicle must decelerate to avoid collision. Since it usually is not constant, the Maximum Deceleration Rate (MDR) is often used to measure the conflict severity.

4. Proportion of Stopping Distance (PSD) – Ratio of distance available to maneuver to the distance remaining to the projected location of collision.

5. Post-Encroachment Time (PET) – Time elapsed between end of encroachment of lane-changing vehicle and the time that the through vehicle actually arrives at the potential point of collision. This measure is similar to GT, but it takes the following driver's reaction (deceleration) into consideration.

6. Failed Lane Change Maneuver – Indication of a missed lane change due to unacceptable gap in traffic flow.

7. Number of Lane Changes – Number of lane changes in segment

8. MaxS, DeltaS – Maximum of speeds of the two vehicles involved in conflict event and Relative speed of two vehicles involved in conflict event

9. Speed Differential between Cars and Trucks – Difference in speeds of cars and trucks

Having defined the quantifiable surrogate conflict measures, the next step is to relate the conflict measures to crashes. The following section discusses the relationships between conflicts and crashes.

5.2 Relating Traffic Conflicts to Crashes

There has been debate regarding the connection between conflict measures and crash prediction (Migletz et al. 1985). However, attempts have been made to estimate the number and possibly the severity of potential crashes given certain categories of conflicts. The underlying premise of the simulation effort is that the probability of crash occurring is a function of a conflict situation.

Based on review of the available literature, it was clear that there is no existing proven relationship between traffic conflicts and crashes that can be directly applied to this study. Glauz et al. (1985) conducted a study to establish a relationship between conflicts and crashes. The data were collected at 46 signalized and un-signalized intersections in the greater Kansas City area. The conclusions are limited to daytime and weekday traffic and to dry pavement conditions. Crash/conflict ratios were determined for several types of collisions for each of the four types of intersections (signalized high volume, signalized medium volume, un-signalized medium volume, and un-signalized low volume). These ratios can be applied to comparable intersections to obtain an expected crash rate of a specific type after the appropriate conflict data are collected. Overall, traffic conflicts of certain types are good surrogates for crashes in that they produce estimates of average crash rates nearly as accurate, and just as precise, as those produced from historical crash data. The study by Glauz et al. (1985) was restricted to analyzing intersection crashes only and recommended conflict data as a surrogate measure of safety when crash data are insufficient.

Brown (1994) evaluated the potential of traffic conflicts for road user safety studies. In this study, traffic conflicts were observed and recorded at intersections over three summer periods, and evaluated against 5-year crash records. The correlation between overall crashes and conflicts were not significant. The crashes were stratified into different categories: left-turn/opposing, left-turn/crossing, rear-end, crossing, weaving, and right turn. Conflict stratification followed the same categories. The stratification yielded statistically more sound results. No explicit relationship was established.

Tarko and Venugopal (1999) conducted a study to evaluate the effectiveness of a safety improvement measure after it had been implemented. They assumed a linear relationship between crashes and conflicts, as shown in Equation (1). The specific value of K was not estimated. This linear relationship was applied in their evaluation of a safety improvement system in Indiana. The zero-intercept assumption implies that no crashes will be expected when no conflicts are expected. It was reported that conflicts were much more frequent than crashes, which implies that not all conflicts result in crashes.

$$E(A) = K * E(Con) \qquad \text{Eqn. (1)}$$

Where:

E(A) = Expected number of crashes
E(Con) = Expected number of conflicts

K = Proportionality constant

This relationship in Equation (1) assumes that given a conflict situation, the probability of a crash occurring can be determined from the conflict measures. It does not provide a mechanism for differentiating between different types of conflicts. As noted earlier, the underlying premise of the simulation effort is that the probability of crash occurring is a function of a conflict situation. Equation 1 above can be generalized to represent the relationship between conflicts and crashes as

$$\text{crashes} = \text{X. conflict measures} \qquad \text{Eqn. (2)}$$

where X can be a probability function, a factor, an expression, or a set of criteria that certain conflict measures must satisfy to be considered a crash. This expression does not assume that the relationship between crashes and conflicts (measures) is necessarily linear.

The challenge however, is to determine the form of the function "X." In the absence of field data, however, assumptions about the form of the function "X" cannot be easily supported. Therefore, extensive simulation runs are necessary to establish its form. This function needs to be validated when actual field data on crashes on ETLs become available.

5.2.1 Conflict Severity

Conflict severity determines the likelihood of crash occurrence. Thus, the number of crashes can be estimated based on the severity of conflicts. It is also important to distinguish the severity of the conflict from the severity of the resulting crash. The primary conflict severity measure that has been proposed is Time-To-Collision (TTC), (Sayed 1994; Hyden 1987; Hayward 1972). As defined above, TTC is the time required by two vehicles to collide if they continue at the present speeds on same paths, without taking any evasive action. As the TTC becomes smaller, the conflict can be considered to be more severe. According to findings by Hayward (1972), conflicts with less than 1.0 second of TTC could be considered near misses. Dissanayake et al. (2004) categorized TTC into three groups: (i) a TTC value greater than 1.50 seconds is considered a low-risk conflict; (ii) a TTC value from 1.00 to 1.50 seconds is a medium risk; and (iii) TTC from 0 to 0.99 seconds is a high risk. Gettman and Head (2003) noted that lower TTC certainly indicates a higher probability of collision but cannot be directly linked to the severity of the collision. Other research efforts (e.g., Darzentas et al. 1980a, 1980b, Cooper et al. 1976) indicate deceleration rate as the primary indicator of severity instead of TTC. Other methods used to evaluate the severity of conflicts include the concepts of Risk of Collision (ROC), Encroachment time (ET), gap time (GT), Deceleration Rate (DR), and Post Encroachment Time (PET).

Gettman and Head (2003) recommended that the magnitude of surrogates TTC, PET, and DR collectively indicate the severity of conflict events, i.e., how likely is it that a collision will result from a conflict such that:

- Lower TTC indicates higher probability of collision
- Lower PET indicates higher probability of collision
- Higher DR indicates higher probability of collision.

MaxS and DeltaS are used to indicate the likely severity of the (potential) resulting crash, if the conflict event had resulted in a crash, instead of a near miss. The research findings clearly indicate that the number of crashes can be derived from data on several conflict measures. In other words, the form of "X" is visualized as a complex combination of the various conflict measures that can be expressed in the form of a multi-criteria function or set of conditions that must be satisfied for a crash to occur. The first step is to identify the relevant conflict measures that can be generated from simulation runs. The second step is to establish the threshold values for the selected conflict measures.

5.2.2 Selected Conflict Measures

The ability to identify conflicts using microsimulation is an ongoing research activity. Gettman and Head (2003) reviewed the various simulation packages available commercially for their capability to generate conflict data outputs. Based on the recommendations of Gettman and Head (2003) and the discussions presented above, Battelle along with the developers of CORSIM identified the capability of the simulation tool to generate the following conflict measures of interest (Battelle, 2006):

1. TTC – Expected time for two vehicles to collide if they remain at their present speed and on the same path. CORSIM is capable of measuring TTC and generating several metrics satisfying given threshold values, e.g., for TTC equal to or less than 4 seconds.

2. PET – Time lapsed between end of encroachment of lane-changing vehicle and the time that the following vehicle actually arrives at the potential point of collision. To compute PET in CORSIM would require additional logic and stored parameters to retain the encroachment point, and then to track and detect when the vehicle crossed the potential point of collision. Normally, the simulation is executed with a 1-second time step. Interpolation logic would have to be used to find when the vehicle arrived at the encroachment point. Logic to compute this parameter may slow execution time considerably. The computation may be better done in a post-processing environment.

3. DR – Rate at which a vehicle must decelerate to avoid collision. The parameters to compute this value are available internally to the simulation and can be made available through the output processor.

4. MaxS – Maximum of speeds of the two vehicles involved in conflict event. This value is currently available within CORSIM.

5. DeltaS – Maximum relative speed of the two vehicles involved in the conflict. This value is currently available from CORSIM.

These conflict measures can be derived either directly from CORSIM or in a post process environment.

5.2.3 Threshold Values for Conflict Measures

Having selected the relevant conflict measures, threshold values must be established. These threshold values define conflicts that are most likely to result in crashes. These thresholds were derived from analysis of results of CORSIM simulation runs. Based on analyses of the simulation results, multi-criteria were determined to represent the function "X" (in Equation 7) to identify conflicts that are most likely to result in crashes as follows (Battelle, 2006):

Number of crashes is given by conflict measures satisfying the following conditions:

A. An initial set of events with TTC <= 2.0 seconds is identified.

B. For events satisfying the first condition, the following criteria must also be met:

   1. Relative speed between leader-follower vehicles (DeltaS) is greater than 20 fps
   2. The maximum speed of the follower vehicle during the event (MaxS) is greater than 60 fps
   3. The separation at minimum TTC is less than 50 feet
   4. The maximum deceleration rate of follower vehicle (DR) is greater than 5 fps^2

All the above conditions must be satisfied for an event to be considered a conflict that is most likely to result in a crash. For each ETL configuration simulated, the expected number of conflict events satisfying these conditions represents the number of crashes.

The suggested threshold values need to be refined through extensive simulation runs and calibrated by comparing the number of estimated crashes based on simulation runs for mixed traffic lanes (no ETLs) with actual historical crash data for mixed lanes. Once convergence is achieved, it can be concluded that the criteria are adequate in estimating crashes from simulation runs. Calibration of the criteria also establishes confidence in their use to estimate crashes from conflict measures.

The following are some important considerations in the analysis and reporting of simulation data

- Simulation must be run several times for each possible ETL configuration to generate sufficient data from which to derive average values that could be representative of the scenario under consideration. At least 10 runs for each scenario is suggested as the minimum.

- In estimating the number of crashes, it is important to distinguish between rear-end collisions and lane-change collisions, and to distinguish among each type of car-truck combination. The simulation should be configured such that these distinctions are made. The estimated number of crashes can then be used in calculating crash rates for use in evaluating the benefits and costs of alternative ETL configurations. Note that the VMT generated from simulation runs should be used in computing crash rates.

- Noting that simulation runs can generate large volumes of data, it is expedient to use a post-processor for analyzing the results to estimate the number of crashes. A post-processor in spreadsheet format is adequate.

- Since only one ETL configuration can be simulated at a time, the number of crashes for each possible scenario should be estimated separately and compared with those of other scenarios.

An example illustrating the application of simulation results in the ETL B-C model is shown in Appendix A of this white paper.

5.3 Commentary on Simulation Approach

This section discusses the challenges, assumptions, and limitations of the simulation approach in safety analysis for ETL implementation. These discussions are based largely on experiences in updating the B-C model for evaluating ETLs that included modifying CORSIM and analyzing data generated from that model.

5.3.1 Advantages, Challenges, and Assumptions

As noted earlier, the use of historical crash data from mixed lanes has limitations for ETL analysis. Simulation, despite its limitation of not fully representing reality, was considered a better alternative to safety analysis in ETL evaluation. Even though simulation can only generate vehicle conflicts and not crashes, it offers the opportunity to evaluate different ETL configurations and scenarios. Furthermore, the simulation allows the estimation of the number of crashes by the various vehicle interactions. The challenge is relating conflicts to crashes.

Redesign and programming of simulation packages is necessary in order to accommodate ETL specifications. Traffic simulation models such as CORSIM are not originally designed to handle all possible ETL configurations and logic. In order to use any off-the-shelf traffic simulation software applications to generate meaningful results for ETL analyses, certain modifications would be necessary. For example, in the recent ETL study for FHWA, CORSIM was modified to accommodate the logic behind the various potential types of ETL configurations. The number and type of vehicle conflicts as well as metrics involving conflicts are the primary measures of effectiveness (MOEs) produced by the simulation and are used to assess the effectiveness and safety (crash prediction) of ETL operations. CORSIM was not designed to collect or report any information regarding vehicle conflicts other than the number of unsafe lane changes. Because CORSIM is a microscopic model that uses a car-following-based algorithm to move vehicles, the collection of conflict metrics is simply a matter of collecting the raw conflict information and then formulating the desired metrics. This modification to CORSIM was necessary for it to be useful for ETL analysis.

Translation of simulation output to depict real-life situations needs careful attention in interpreting the results. Assumptions about the reality or similarities between simulations and real-life situations are important in understanding the results.

The objective of ETL implementation is safety improvement. Until historical data become available to establish this hypothesis as a fact, simulation appears to be the only approach to provide some idea about interactions among vehicles operating under different lane assignment scenarios.

A major assumption in the analyses of results from simulation runs is that all drivers (automobile and truck) observe lane assignments used in the simulation. Furthermore, the simulation runs assume certain driver behavioral characteristics that may not necessarily be representative of the population of drivers on the roadway.

5.3.2 Limitations of Simulation Approach

In addition to the challenges and assumptions presented above, the following are some limitations in the use of simulation techniques for safety analysis for ETL evaluation.

Severity of crashes – Estimation of crash costs requires that crash rates be defined in terms of severity. Three severity levels are required – fatality, injury, and property damage only (PDO). CORSIM does not measure crashes directly and therefore information on the severity of crashes cannot be derived directly from the conflict measures. Gettman and Head (2003) noted that conflict events of severity exceeding the thresholds for TTC, PET, and DR but that are of low severity on the DeltaS and MaxS scales would be crashes that are more likely to be PDO. However, this observation does not provide any guidance to identify the severity of crashes from conflict measures.

Single-vehicle crashes – It is noted that CORSIM cannot estimate single-vehicle conflicts; therefore, results from the simulation runs cannot be used to estimate single-vehicle crashes. This is because CORSIM uses a car-following-based algorithm where two vehicles must be traveling on the same path for a conflict to occur. Safety analysis of ETL includes both single- and multiple-vehicle crashes.

To obtain crude estimates of the number of crashes in each severity category, historical crash databases can be analyzed to determine the percent distribution of crashes by severity and then apply these percentages to the total number of crashes estimated from the conflict-crash relationship. This approach assumes that the percent distribution for mixed lanes is applicable to situations with ETLs.

Until crash data from existing ETLs become available, estimates of single-vehicle crashes can be derived by assuming that the percent of single-vehicle crashes for mixed lanes are identical to roadways with ETLs. With this assumption, the percent of single-vehicle crashes by vehicle class (i.e., LV, SU, and CV) can be derived from historical crash data.

It is recognized that these assumptions may not be entirely true in reality. Nonetheless, they provide the basis for developing estimates for the purposes of the analysis.

6. STATISTICAL APPROACH TO SAFETY BENEFIT ANALYSIS

Two examples of statistical approaches to safety analysis are presented. Each example was designed for a different purpose or application. The relevance of the methodologies in each example to ETL safety analysis are discussed.

6.1 Volpe and NHTSA approach for IVSS program

Volpe and NHSTA have been investigating the development of a safety benefits methodology based on driving behavior. Najm and Burgett (1997) and Najm and De Silva (2000) described the approach to estimate benefits based on encounters with critical driving conflicts. The approach is a general methodology for quantifying safety benefits for three selected crash countermeasure systems for rear-end, lane-change, and single vehicle roadway departure collisions. The part-statistical process is founded on estimating the system effectiveness in eliminating collisions in distinct safety-critical driving conflicts or pre-crash scenarios that are recognizable in national crash databases such as the General Estimates System (GES). This benefit assessment approach was expanded for the Intelligent Vehicle Initiative (IVI) program established by the U.S DOT. The IVI program evaluates the effectiveness of safety systems on trucks (measured in terms of reductions in crashes). The safety benefits methodology outlined above was used in evaluating the IVI field operational tests (FOTs). The methodology simultaneously examines the reduction in either the driving conflicts or in the probability of a crash given a driving conflict occurrence. The benefit estimation equation is presented in Appendix B of this white paper.

6.2 New Safety Analysis Procedures for HERS

In different study (Cambridge Systematics Inc, 1998), regression models were developed to estimate the impacts of highway improvements on highway safety, measured in terms of the number of crashes. The regression models were developed from historical crash data from mixed lane highways. For rural and urban freeways the primary variable for estimating the numbers of crashes is AADT. For other functional highway classes such as two-lane streets, the number traffic signals and other geometric features of highways are included as independent variables. These models may be useful in applications such as Highway Economic Requirements System (HERS) model where the focus is to estimate the total impacts of implementing different highway improvements. The crash estimation models for freeways are presented in Appendix B of this white paper.

6.3 Commentary on Statistical Approach

The statistical approach in the IVI program described above was developed to estimate the safety benefits of implementing on-board technologies designed to reduce crashes. The following limitations make it difficult to adopt this methodology to ETL implementation.

- The benefit equation essentially applies correction factors to the number of crashes derived from historical crash data for mixed traffic lanes. As such, direct applicability to ETLs is questionable.

- The equation is intended to estimate the benefits in terms of crash reduction (i.e., the difference in crashes before and after implementation of the technology or safety improvement). Analyses of costs and benefits of different ETL scenarios require crash rates for the various types of car and truck interactions with and without ETL as inputs. The types of possible vehicle interactions are also determined by the ETL configuration.

- The probability-based approaches were derived based on data from field operational tests which linked driving behavior with crashes. The IVI program for which these methods were developed included on-board data collection and vehicle testing on test-beds to estimate the relationships between conflicts and crashes. A major term of the benefit equation is dependent on on-board data collection. On-board data collection or field testing in cases of ETLs could be costly.

- The prevention ratio term in the equation measures the efficiency of the safety improvement system at preventing crashes after a particular driving conflict has occurred. As noted above, this needs to be measured directly using field testing or using statistical methods such as Monte-Carlo simulation.

The regression models developed for HERS application are not considered suitable for ETL evaluation for the following reasons.

- Truck percentage is a critical element in evaluating the feasibility of ETL implementation. The regression models were developed as a function of average annual daily traffic (AADT), which by itself, is not a sufficient parameter for ETL evaluation. A recent study (Battelle, 2002) identified the traffic criteria for identifying potential locations for ETL implementation to be a combination of total traffic volume (i.e., AADT) and the percent of trucks in the traffic stream.

- Interaction among different vehicle classes was not considered in the development of the models. Physical separation of different vehicle classes (trucks from other vehicles) is the premise behind ETL implementation. As such, it is important that models directed at evaluating the safety impacts of ETLs should consider interaction effects of the different vehicle classes.

- The regression models were designed to estimate the total number of crashes due to highway improvements. While different models were developed for different highway functional classes, they are not vehicle specific. As such, the models cannot be used to evaluate the safety impacts on the individual vehicle classes.

7. CONCLUDING REMARKS

Crash data are critical to evaluating feasibility of ETL implementation. This is because the underlying premise is that physically separating trucks from other vehicles would potentially enhance safety. Historical crash data provide a reliable source for crash rate analysis, but crash data for mixed traffic lanes do not necessarily reflect ETL situations. In the absence of historical crash data on ETLs, however, simulation becomes an appealing alternative to generate crash data to closely represent real ETL situations.

The simulation approach has the advantage of simulating different ETL configurations and scenarios. Simulation approach encounters some challenges and limitations. The major challenge is deriving number of crashes from conflicts data. A multi-criteria approach was developed to help estimate the number of crashes from data on conflict measures generated from simulation. Limitations of the simulation approach are that single-vehicle crashes and severity of crashes could not be derived from conflict data generated from simulation.

8. RECOMMENDATIONS FOR FURTHER RESEARCH

The following areas are identified for future research.

- The suggested thresholds for isolating conflicts that result in crashes were based on a limited number of simulation runs. It is recommended that these thresholds be refined with more extensive simulation results.

- Simulation approach is not capable of estimating single-vehicle conflicts hence crashes. Single vehicle crashes are equally important regardless of the analytical approach that is adopted. Further research is needed to develop a methodology for estimating single vehicle crashes. It is conceivable that such a methodology could be statistical, heuristic, simulation or a combination of several fundamental groups of approaches.

- Similar to single vehicle crashes, simulation technique is not capable of distinguishing among the levels of severity of crashes. Further research into the nature of conflict measures is needed that would allow estimation of the severity of crashes. This is important because the cost of a crash depends on the severity of the crash. Historical crash databases derived from mixed lanes are available but do not necessarily represent ETL crash severity.

- The simulation results assume that all drivers (automobile and truck) observe lane assignments. Furthermore, the simulation approach assumes certain driver behavioral characteristics that may not necessarily be representative of the population of drivers on the roadway. It is possible that these assumptions may not necessarily hold true in reality. It is recommended that some human factor research be undertaken to study the driver responses based on which correction factors (where appropriate) can be introduced to the results of simulation runs.

9. REFERENCES

Amundsen, F. and Hyden, C. 1977. "Proceedings of first workshop on traffic conflicts," Oslo, Institute of Transport Economics.

Battelle (2006) "Investigation of Potential Safety and Other benefits of Exclusive Facilities for Truck." Draft Final Report, being prepared for FHWA Office of Transportation Studies, Washington, D.C. (in press).

Battelle, (2002) "Investigation of Potential Safety and Other benefits of Exclusive Facilities for Trucks," Final Report. Submitted to FHWA Office of Transportation Policy Studies, September 2002.

Brown, G.R. (1994). *Traffic Conflicts for Road User Safety Studies*. Canadian Journal of Civil Engineering, Vol. 21

Cambridge Systematics Inc., (1998) "New Safety Analysis Procedures for HERS". Final report prepared for FHWA, U.S. Department of Transportation, Washington, D.C.,

Center for National Truck Statistics, (1997). *Truck and Bus Crash Fact Book 1995*. Office of Motor Carriers, FHWA, U.S. Department of Transportation, Washington, D.C., Sept. 1997.

Cooper, D. and Ferguson, N. (1976). "A conflict simulation model," Traffic Engineering and Control, Vol. 17, pp. 306-309.

Darzentas, J. et al. (1980a). "Simulation of road traffic conflicts at T-junctions," Simulation, May pp. 155-164.

Darzentas, J. et al. (1980b). "Minimum acceptance gaps and conflict involvement in a single crossing maneuver," Traffic Engineering and Control, Vol. 21, pp 58-62.

Dissanayake, S., Lu, J, and Castillo, N. (2004) *Traffic conflicts to evaluate safety of drive way left Turing alternatives*. 83rd TRB Annual Meeting. Washington, D.C.

Federal Motor Carrier Safety Administration (FMCSA). (1999). National *Truck Crash Profile, 1998*. FMCSA Analysis Division, U.S. Department of Transportation, Washington, D.C.

Garber, N. J. and Gadiraju, R. (1989) *Effects of Truck Strategies on Traffic Flow and Safety on Multilane Highways*. Transportation Research Record 1256.

Gettman, D., and Head, L. (2003) *Surrogate Safety Measures from Traffic Simulation Models,* Paper Presented at 82nd TRB Annual Meeting, Washington D.C.

Glauz, W.D., K.M. Bauer, and K.J. Migletz. (1985) *Expected Traffic Conflict Rates and Their Use in Predicting Accidents.* Transportation Research Record 1026, TRB, Washington, D.C.

Hayward, J. (1972) *Near Miss Determination Through the Use if a Scale of Danger.* Highway Research Record No. 384, Washington, DC, Highway Research Board. pp. 24-33.

Hoel, L. A. and Peek, J. L. (1999) A *Simulation Analysis of Traffic Flow Elements for Restricted Truck Lanes on Interstate Highways in Virginia.* Virginia Transportation Research Council.

Hyden, C. (1987). "The development of a method for traffic safety evaluation: The Swedish conflicts technique." Dept. of Traffic Planning and Engineering, Lund University, Sweden.

Janson, B. N., Awad, W., Robles, R., Kononov, J., and Pinkerton, B. (1998) *Truck Crashes at Freeway Ramps: Data Analysis and High-Risk Site Identification.* Journal of Transportation and Statistics, Bureau of Transportation Statistics, January 1998.

McMillan, N.J., A.C. Christiaen, and G.V. Stark, (2001) *Estimating Safety Benefits for the IVI Generation 0 Field Operational Tests.* Society of Automotive Engineers, Inc...

Migletz, D. et al. (1985). "Relationships Between Traffic Conflicts And Accidents." FHWA-RD-84-042. U.S. DOT FHWA, Washington D.C.

National Highway Traffic Safety Administration (NHTSA). (2000) *Traffic Safety Facts 1999- A Compilation of Motor Vehicle Crash Data from Fatality Analysis Reporting System (FARS) and General Estimates System (GES).* NHTSA, U.S. Department of Transportation, Washington, D.C., December 2000.

Najm, W.G., and Burgett, A.L., (1997) *Benefits Estimation for Selected Collision Avoidance Systems,* 4th World Congress on Intelligent Transportation Systems, Berlin, Germany, October 21-24.

Najm, W.G., and De Silva, M.P. (2000) *Benefits Estimation for Intelligent Vehicle Safety Systems Based on Encounters with Critical Driving Conflicts,* ITS America Tenth Annual Meeting and Exposition, May 1-4, 2000.

Neighbor, M.B. (2002) *GES Driving Conflict Identification for the IVI Generation 0 Field Operational Tests.* Society of Automotive Engineers, Inc.

Sayed T. et al., (1994) *Simulation Of Traffic Conflicts At Unsignalized Intersections.* Accident Analysis and Prevention. Vol. 26, No. 5.

Solomon, M. G., Braver, E. R., and Preusser, D. F. (1999). *Commercial and Passenger Motor Vehicle Crashes on Toll Roads.* Insurance Institute for Highway Safety, May 1999.

Tarko, A.P. and S. Venugopal, (2001). Safety and Capacity Evaluation of the Indiana Lane Merge System, Joint Transportation Research Program.

The Urban Transportation Monitor, (2004) *Consideration of Exclusive Truck Lanes Moves Forward in U.S.* Vol. 18 No. 23, pg. 7. December 10, 2004.

APPENDIX A - APPLICATION OF SIMULATION RESULTS IN ETL SAFETY ANALYSIS

This appendix describes procedures for estimating crash rates based on conflict information from simulation runs for use in the ETL B-C model. The procedures are illustrated with an example.

The site simulated is a typical freeway-to-freeway interchange (Figure A1). This site includes the I-710 and Atlantic Boulevard interchanges on SR-60. Cases simulated include the baseline (i.e., existing) roadway configurations as well as ETL configurations.

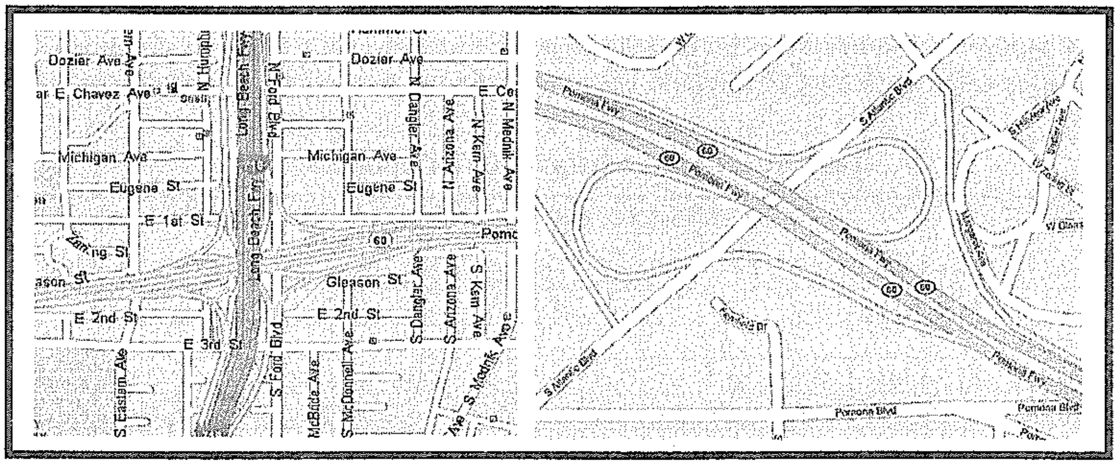

Figure A1. Site Modeled and Simulated

The following are the categories of configurations that were modeled. Note that the truck lanes were modeled only on SR-60.

- **Baseline Case** – This case represents the existing freeway configuration.
- **Baseline + Truck Lanes** – This set of cases models the existing freeway configurations with truck lanes designated on either the right or left side of the freeway
- **Baseline + New Lanes** – This set of cases models 1 or 2 lanes added to the existing freeway configuration. No truck lanes are specified, i.e., adding mixed lanes.
- **Baseline + New Lanes + Truck Lanes** – This set of cases models 1 or 2 lanes added to the existing freeway configuration, with truck lanes designated on either the right or left side of the freeway.
- **Baseline + Barrier-Separated Truck Lanes** – This set of cases models the existing freeway configuration with barrier-separated truck lanes added to the configuration.

The example presented in this paper represents the light-heavy scenario where light vehicles and trucks use separate lanes i.e., trucks were not permitted to use light vehicle lanes and vice versa.

Conflict Rates

Once the conflicts most likely to result in crashes have been identified, conflict rates can be calculated using VMTs generated from the simulation runs. These rates are calculated separately for each ETL configuration simulated. Table A1 is an example of a summary of the results of simulations results showing the average number of conflicts resulting in crashes based on 10 runs as well as the average VMTs for each ETL configuration. The simulation cases include baseline (existing) roadway configurations as well as additional configurations used to analyze the effects of adding lanes and designating lanes as exclusive truck lanes.

For each vehicle class, conflict rates are calculated by dividing the estimated number of conflicts that are likely to result in crashes by the vehicle miles for that vehicle type. By definition of conflicts, as noted earlier, CORSIM does not provide information on single-vehicle conflicts.

Table A1. Conflict Data for ETL Configurations

ETL Configuration	Average Number of Conflicts Per Run*									Aggregates				
	LV-LV	LV-SU	LV-CV	SU-LV	SU-SU	SU-CV	CV-LV	CV-SU	CV-CV	Car-Car	Car-Truck	Truck-Truck	Car-SU	Car-CV
Baseline	178.1	0.2	0.2	2.4	0	0	5.4	0	0.2	178.1	8.2	0.2	2.6	5.6
No New Lanes										0				
Left Lane ETL	194.5	0.1	0.3	2.4	0	0.1	5.4	0	0.1	194.5	8.2	0.2	2.5	5.7
Right Lane ETL	170.5	0.5	0.5	2.5	0	0	5.3	0	0.1	170.5	8.8	0.1	3	5.8
Left 2 Lanes ETL	491.8	0.4	0.4	2.4	0	0	6.4	0	0.1	491.8	9.6	0.1	2.8	6.8
Right 2 Lanes ETL	330.2	0	0	2.2	0	0	5.6	0	0.4	330.2	7.8	0.4	2.2	5.6
One New Lane										0		0		
No Truck Lane	186.3	0	0.7	2.1	0.1	0	9.1	0.1	0.4	186.3	11.9	0.6	2.1	9.8
Left 1 Lane ETL	228.8	0.2	0.3	2	0.1	0	8.3	0	0	228.8	10.8	0.1	2.2	8.6
Right 1 Lane ETL	217.4	0.4	1.2	2.5	0	0.1	11.5	0.1	0.2	217.4	15.6	0.4	2.9	12.7
Barrier Sep - Thru	166.4	0	0.2	1.4	0	0	0.3	0	0	166.4	1.9	0	1.4	0.5
Barrier Sep - Mid	182.8	0.1	0.5	1.6	0	0	9.6	0	0.2	182.8	11.8	0.2	1.7	10.1
Two New Lanes										0				
No Truck Lane	171.7	0.1	0.5	2.6	0	0	6.2	0.2	0.3	171.7	9.4	0.5	2.7	6.7
Left 2 Lanes ETL	240.1	0.3	0.2	3.1	0	0	7	0.1	0.3	240.1	10.6	0.4	3.4	7.2
Right 2 Lanes ETL	219	0.2	1.5	3.6	0	0.1	11.6	0	0.2	219	16.9	0.3	3.8	13.1
Barrier Sep - Thru	159.7	0.1	0.1	2.2	0	0	0.2	0	0	159.7	2.6	0	2.3	0.3
Barrier Sep - Mid	178	0.2	0	2.4	0	0	2.1	0	0	178	4.7	0	2.6	2.1

* - *average number of conflicts that satisfy the conditions for a crash to occur*

Relative Reduction in Conflict Rates

The impact of each ETL configuration on safety can be estimated in terms of the changes in vehicle crashes (in this case, measured by conflicts that are most likely to result in crashes). Based on these changes, the vehicle interactions used in calculating total crashes and crash costs in the current ETL B-C model can be revised. For each ETL configuration simulated, the changes in the number of estimated crashes (i.e., conflicts most likely to result in crashes) relative to the baseline for each type of interaction can be calculated from Eqn. A1 as follows.

$$Change_{ETL} = \left(\frac{CR_{ETL} - CR_{Baseline}}{CR_{Baseline}} \right) \qquad \text{Eqn. A1}$$

where

$Change_{ETL}$ – Change in the conflict rate due to the ETL implementation
$CR_{Baseine}$ – Estimated conflict rate for baseline from CORSIM simulation
CR_{ETL} – Estimated conflict rate for ETL configuration

Essentially, the approach of using the crash estimates from simulation is to calculate the conflict rates from simulation data and then modify actual crash rates from historical data for mixed lanes. This addresses the limitations of the current B-C approach identified in Section 4.0 of this report. The simulation results capture the changes in interactions between light vehicles because of changed traffic operation. Also, the simulation network accounts for the impacts of merge/weave areas where trucks enter/exit ETLs.

Equation A1 estimates the change in conflict rates due to implementation of an ETL compared to the baseline or do nothing case in the simulation. It is assumed that changes in conflicts are proportional to changes in vehicle interaction. This is because the crashes are derived from conflicts that are measures of vehicle interaction. Thus, x% reduction in conflicts for a given vehicle type based on simulation results, for example, would correspond to x% reduction in interactions for that vehicle type. The concept is illustrated with LV crashes for barrier separated ETLs. The interaction rates for LVs for the baseline or do nothing case from historical crash rate are shown in row (a) of Table A2. Rows (b) and (c) show the conflict rates derived from CORSIM simulation for the baseline (simulated) and a barrier separated configuration. Using Equation A1, the changes in conflict rates can be calculated as shown in Table A2. For example, the change in multiple LV conflict rate due to implementing barrier separated ETL is

$$Change_{ETL} = \left(\frac{CR_{ETL} - CR_{Baseline}}{CR_{Baseline}} \right) = \frac{0.00990 - 0.01390}{0.01390} = -0.2912 \qquad \text{Eqn. A2}$$

The changes are similarly calculated for the other possible vehicle interactions involving LV. These changes are then applied to the baseline vehicle interaction rates derived from historical crash data. The results represent the revised or new interaction rates as shown in row (e) of Table A2. For example, the new interaction rate for LV as a result of implementing this ETL configuration is

$$\text{New } LV_2 \text{ Interaction Rate} = 0.6581 + [-0.29 \times 0.6581] = 0.4668 \qquad \text{Eqn. A3}$$

Table A2. Sample Calculation of Changes in Interaction Rates for LV

ETL Configuration	Calculation	Single LV LV$_1$)	Multiple LV (LV$_2$)	LV with SU (LV$_3$)	LV with CV (LV$_4$)
Baseline – No ETL (from historical data)	a	0.2912	0.6581	0.0247	0.026
Baseline – No ETL (from simulation)	b	Not Simulated	0.01390	0.00002	0.00000
Barrier Sep Lane- common entry/exits (from simulation)	c	Not Simulated	0.00990	0.00001	0.00000
Change	d = (c-b)/b	Not Simulated	-0.29	-0.65	0.73*
New Interaction Rates	e = a + (a*d)	0.2912	0.4668	0.0170	0.0210

Note: A negative value indicates a reduction in interaction rates relative to baseline
* - *Rounded*

The analyses for other vehicle interactions and ETL configurations can be similarly calculated as shown in Table A3. Table A4 shows the new interaction rates. Since single vehicle conflicts cannot be simulated, it is assumed that the impact of ETL implementation on single vehicle crashes is negligible. In other words, the analysis assumes that the percent of single vehicle crashes for mixed lanes are identical to roadways with ETLs. This assumption is valid given that ETLs are expected to reduce interactions between different vehicle types.

Table A3. Changes in Vehicle Interaction Rates

ETL Configuration	Single LV (LV_1)	Multiple LV (LV_2)	LV with SU (LV_3)	LV with CV (LV_4)	Single SU (SU1)	Multiple SU (SU_2)	SU with LV (SU_3)	SU with CV (SU_4)	Single CV (CV_1)	Multiple CV (CV_2)	CV with LV (CV_3)	CV with SU (CV_4)
Baseline – Simulation		0.0139	0.0000	0.0000		0.00	0.01	0.00		0.00	0.01	0.00
No New Lanes												
Left 1		0.09	-0.50	0.50		0	0.02	0		-0.48	0.03	0
Right 1		-0.05	1.49	1.49		0	0.17	0		-0.46	0.06	0
Left 2		2.13	1.27	1.27		0	-0.27	0		-0.62	-0.09	0
Right 2		1.04	-1.00	-1.00		0	-0.32	0		0.50	-0.22	0
Add One Lane												
No Truck Lane		-0.23	-1.00	1.57		0	-0.40	0		0.33	0.12	0
Left Lane ETL	No Data from Simulation	-0.07	-0.27	0.09	No Data from Simulation	0	-0.42	0	No Data from Simulation	-1.00	0.08	0
Right Lane ETL		-0.13	0.42	3.26		0	-0.20	0		-0.23	0.63	0
1 Barrier Sep - Thru		-0.35	-1.00	-0.30		0	-0.58	0		-1.00	-0.96	0
lane 1 Barrier Sep- common entry/exits		-0.29	-0.65	0.73		0	-0.55	0		-0.37	0.12	0
Add Two Lanes												
No Truck Lane		-0.30	-0.64	0.82		0	-0.27	0		0.09	-0.17	0
2 Left Lanes ETL		-0.03	0.08	-0.28		0	-0.13	0		0.07	-0.08	0
2 Right Lanes ETL		-0.11	-0.27	4.44		0	-0.02	0		-0.31	0.48	0
2 Barrier Sep - Thru		-0.38	-0.66	-0.66		0	-0.42	0		-1.00	-0.98	0
lane 2 Barrier Sep- common entry/exits		-0.30	-0.30	-1.00		0	-0.38	0		-1.00	-0.76	0

Note: changes in interaction rates are relative to baseline case from simulation

Table A4. New Interaction Rates

ETL Configuration	Single LV (LV_1)	Multiple LV (LV_2)	LV with SU (LV_3)	LV with CV (LV_4)	Single SU (SU1)	Multiple SU (SU_2)	SU with LV (SU_3)	SU with CV (SU_4)	Single CV (CV1)	Multiple CV (CV_2)	CV with LV (CV_3)	CV with SU (CV_4)
Baseline (historical crash data)*	0.2912	0.6581	0.0247	0.0260	0.2831	0.6883	0.0034	0.0252	0.2741	0.6778	0.0231	0.0250
No New Lanes												
Left 1	0.2912	0.7180	0.0123	0.0389	0.2831	0.6883	0.0035	0.0252	0.2741	0.3504	0.0239	0.0250
Right 1	0.2912	0.6274	0.0614	0.0647	0.2831	0.6883	0.0040	0.0252	0.2741	0.3668	0.0246	0.0250
Left 2	0.2912	2.0628	0.0560	0.0590	0.2831	0.6883	0.0025	0.0252	0.2741	0.2592	0.0210	0.0250
Right 2	0.2912	1.3402	0.0000	0.0000	0.2831	0.6883	0.0023	0.0252	0.2741	1.0179	0.0180	0.0250
Add One Lane												
No Truck Lane	0.2912	0.5055	0.0000	0.0668	0.2831	0.6883	0.0020	0.0252	0.2741	0.9013	0.0259	0.0250
Left Lane ETL	0.2912	0.6151	0.0179	0.0284	0.2831	0.6883	0.0020	0.0252	0.2741	0.0000	0.0251	0.0250
Right Lane ETL	0.2912	0.5707	0.0351	0.1108	0.2831	0.6883	0.0027	0.0252	0.2741	0.5195	0.0378	0.0250
1 Barrier Sep - Thru lanes	0.2912	0.4287	0.0000	0.0181	0.2831	0.6883	0.0020	0.0252	0.2741	0.0000	0.0047	0.0250
1 Barrier Sep- common entry/exits	0.2912	0.4668	0.0170	0.0210	0.2831	0.6883	0.0019	0.0252	0.2741	0.4281	0.0439	0.0250
Add Two Lanes												
No Truck Lane	0.2912	0.4608	0.0090	0.0472	0.2831	0.6883	0.0025	0.0252	0.2741	0.7375	0.0193	0.0250
2 Left Lanes ETL	0.2912	0.6369	0.0266	0.0187	0.2831	0.6883	0.0029	0.0252	0.2741	0.7246	0.0214	0.0250
2 Right Lanes ETL	0.2912	0.5874	0.0179	0.1415	0.2831	0.6883	0.0033	0.0252	0.2741	0.4658	0.0342	0.0250
2 Barrier Sep - Thru lanes	0.2912	0.4052	0.0085	0.0089	0.2831	0.6883	0.0020	0.0252	0.2741	0.0000	0.0006	0.0250
2 Barrier Sep- common entry/exits	0.2912	0.4633	0.0174	0.0000	0.2831	0.6883	0.0021	0.0252	0.2741	0.0000	0.0056	0.0250

Number of Crashes

The last step is to use the new interaction rates in Eqn. A4 below to estimate the total number of crashes for both the baseline and the ETL configurations simulated.

$$Crashes = \left(C_{LV}V_{LV}(LV_1 + LV_2\right) + \left(C_{SU}V_{SU}(SU_1 + SU_2\right) + \left(C_{CV}V_{CV}(CV_1 + CV_2\right)$$

$$+ \frac{2(C_{LV}V_{LV}LV_3)(C_{SU}V_{SU}SU_3)}{(V_{LV} + V_{SU})LVSU} + \frac{2(C_{LV}V_{LV}LV_4)(C_{CV}V_{CV}CV_3)}{(V_{LV} + V_{CV})LVCV}$$

$$+ \frac{2(C_{SU}V_{SU}SU_4)(C_{CV}V_{CV}CV_4)}{(V_{SU} + V_{CV})SUCV} \qquad \text{Eqn A4.}$$

Note that the complex terms are expanded versions of the harmonic means of the vehicle miles multiplied by the respective rates. For example, LV-SU crashes are estimated by the fourth term in the above equation and are given as

$$\text{LVSU} = \text{LV with SU per (LV+SU) MVM} = \frac{1}{\left[\frac{1}{(C_{LV}LV_3)} + \frac{1}{(C_{SU}SU_3)}\right]} \qquad \text{Eqn A5}$$

where:

Crashes = total number of crashes of all vehicle types

C_{LV} = total crash rate of light vehicle per million vehicle miles (MVM)
C_{SU} = total crash rate of single-unit vehicle per MVM
C_{CV} = total crash rate of combination vehicle per MVM
V_{LV} = total light vehicle MVM
V_{SU} = total single-unit vehicle MVM
V_{CV} = total combination vehicle MVM

Subscript 1 = crashes where only one vehicle was involved (e.g., LV_1 – crash involving a single light vehicle)
Subscript 2 = crashes where same type of vehicle was involved (but *more* than one vehicle) (e.g., SU_2 – SU and SU crash)
Subscript 3 = crashes in which an LV was involved with a different type of vehicle. However, depending on the vehicle whose crash rate is being calculated this could be LV_3, SU_3, or CV_3.
Subscript 4 = crashes in which a CV was involved with a different type of vehicle. However, depending on the vehicle whose crash rate is being calculated this could be LV_4, SU_4, or CV_4.

Table A5 shows the estimated number of crashes for the various ETL configurations using the approach outlined above. The differences in the total estimated crashes indicate the potential safety impacts due to the ETL configurations.

Table A5. Comparison of Estimated Crashes

ETL Configuration	Estimated Number of Crashes from New Interaction Rates						
	TOTAL	LV–LV	SU–SU	CV–CV	LV and SU	LV and CV	SU and CV
Baseline	724	681	24	14	2	2	1
No New Lanes							
Left 1	762	724	24	9	1	3	1
Right 1	702	659	24	9	4	5	1
Left 2	1729	1688	24	8	4	4	1
Right 2	1214	1170	24	19	0	0	1
Add One Lane							
No Truck Lane	619	571	24	17	0	5	1
Left Lane ETL	683	650	24	4	1	3	1
Right Lane ETL	666	618	24	12	2	8	1
1 Barrier Sep - Thru lanes	547	516	24	4	0	1	1
1 Barrier Sep-common entry/exits	583	544	24	10	1	3	1
Add Two Lanes							
No Truck Lanes	584	539	24	15	1	4	1
2 Left Lanes ETL	709	666	24	15	2	2	1
2 Right Lanes ETL	678	630	24	11	1	10	1
2 Barrier Sep - Thru lanes	530	499	24	4	6	1	1
2 Barrier Sep-common entry/exits	572	541	24	4	1	0	1

APPENDIX B – STATISTICAL MODELS FOR SAFETY ANALYSIS

Volpe and NHTSA Approach for IVSS Program

McMillan et al. (2001)[1] described the safety benefits methodology for evaluating an Intelligent Vehicle Safety System (IVSS) as

Part I, Part II, Part III, Part IV

$$B = \underbrace{N_{wo}}_{\text{Part I}} \times \sum_{i} \underbrace{P_{wo}(S_i|C)}_{\text{Part II}} \times \left\{ 1 - \underbrace{\left[\frac{P_w(C|S_i)}{P_{wo}(C|S_i)} \right]}_{\text{Part III}} X \underbrace{\left[\frac{P_w(S_i)}{P_{wo}(S_i)} \right]}_{\text{Part IV}} \right\} \qquad \text{Eqn. B1}$$

where:

B is the reduction in crashes/crash rates or the benefits of the system.

Each remaining part of the equation is described below

PART I of the equation

N_{wo} represents the total number of crashes or crash rates of a certain type in the system. The source of data for this part of the equation is from the various historical crash databases including GES, FARS etc. Neighbor (2002) conducted a study on the identification of heavy vehicle related conflicts from the National Automotive Sampling System (NASS) General Estimates System (GES). It was determined that the two important types of crashes with implications for ETL are rear-end and lane-change/merge type crashes (about 35% of crashes).

PART II of the equation

$P_{wo}(S_i|C)$ represents the conditional probability that a driving conflict S_i occurred prior to a crash C. This term represents the proportion of crashes of type C in the database which were preceded by a conflict S_i. This was estimated for the IVI program using databases like GES, which identify the cause of the crash. This term is intended to identify how many crashes are preceded by a conflict type. GES also has a Critical Crash Envelope (CCE) system to record pre-crash data. CCE begins at the point where the driver recognizes impending danger or the vehicle is in an imminent path of collision with another vehicle or any other objects. CCE uses five variables to describe the situation before a crash happened:

1. Movement prior to the critical event
2. Critical event
3. Corrective action attempted
4. Pre-crash vehicle control

[1] McMillan, N.J., A.C. Christiaen, and G.V. Stark, (2001) *Estimating Safety Benefits for the IVI Generation 0 Field Operational Tests*. Society of Automotive Engineers, Inc...

5. Pre-crash location.

The first two variables were used by Neighbor (2002) to define driving conflicts, and the Critical Event is considered the most important factor. The Critical Event is the action by the subject vehicle or another vehicle or any other object, without which the subject vehicle would not have been involved in the crash e.g., loss of control due to excessive speed. Seven critical event categories were developed:

1. Loss of control
2. Roadway departure
3. Same lane speed differential – e.g., two vehicles traveling in the same lane and leader suddenly decelerates. This is an important measure for ETLs.
4. Encroachment at a non-junction
5. Encroachment at a junction
6. Initiated by an animal, pedestrian, or other object
7. Other.

Note that pre-crash condition defines a conflict, which is different from the definition of conflict measures derived from simulation described in Section 5 of this report.

PART III of the equation

$\frac{P_w(C|S_i)}{P_{wo}(C|S_i)}$ represents the prevention ratio, which measures the efficiency of the system in preventing crashes after a particular driving conflict has occurred. If the prevention ratio is equal to 1, then the safety benefits are mainly derived from a reduction in the number of conflicts or unsafe situations encountered. In other words, a prevention ratio of 1 indicates that there is no difference between the before and after scenarios. On the other hand, a ratio of less than 1 indicates that the system reduces the probability of a crash given the occurrence of an unsafe situation.

The numerator and denominator represent the probability of a crash given a conflict. For the IVI FOTs, Monte-Carlo simulation was used to estimate this value.

PART IV of the equation

$\frac{P_w(S_i)}{P_{wo}(S_i)}$ represents the exposure ratio, or essentially the reduction in the number of driving conflicts with or without the system. The numerator and the denominator can be measured directly from field operational tests or obtained from simulation.

New Safety Analysis Procedures for HERS

The following equations were developed for estimating the numbers of crashes per 100 million vehicle-miles of travel on rural and urban freeways, urban multi-lane surface streets, and urban expressways lacking full access control.[2] These functional highways have potential for ETL implementation. Different equations were developed for two-lanes and multi-lane roads and streets.

For rural freeways:

$$CRASH = 17.64\ AADT^{0.155}\ \exp[0.0082(12 - LW)] \qquad \text{Eqn. B2}$$

For urban freeways:

$$CRASH = [145.0 - 1.203\ ACR + 0.2580\ ACR^2 - 0.00000524\ ACR^5]\ \exp[0.0082\ (12 - LW)] \qquad \text{Eqn. B3}$$

For urban multi-lane surface streets, and urban expressways:

$$CRASH = a \times AADT^b \times NSIGPM^c \qquad \text{Eqn. B4}$$

Where
AADT – average annual daily traffic
ACR – AADT divided by two-way hourly capacity
LW – lane width, in feet (between 8 and 13)
NSIGPM – number of signals per mile (0.1 to 8)

The coefficients a, b, c are shown below

Type of section	a	b	c
Median	82.6	0.1749	0.2515
Two-way left-turn lane	95.1	0.1498	0.4011
Other	115.8	0.1749	0.2515

[2] Cambridge Systematics Inc., (1998) "New Safety Analysis Procedures for HERS". Final report prepared for FHWA, U.S. Department of Transportation, Washington, D.C.

New Safety Analysis Procedures for HERS

The following equations were developed for estimating the numbers of crashes per 100 million vehicle-miles of travel on rural and urban freeways, urban multi-lane surface streets, and urban expressways lacking full access control.[2] These functional highways have potential for ETL implementation. Different equations were developed for two-lanes and multi-lane roads and streets.

For rural freeways:

$$CRASH = 17.64\ AADT^{0.155}\ \exp[0.0082(12 - LW)] \qquad \text{Eqn. B2}$$

For urban freeways:

$$CRASH = [145.0 - 1.203\ ACR + 0.2580\ ACR^2 - 0.00000524\ ACR^5]\ \exp[0.0082\ (12 - LW)] \qquad \text{Eqn. B3}$$

For urban multi-lane surface streets, and urban expressways:

$$CRASH = a \times AADT^b \times NSIGPM^c \qquad \text{Eqn. B4}$$

Where
AADT – average annual daily traffic
ACR – AADT divided by two-way hourly capacity
LW – lane width, in feet (between 8 and 13)
NSIGPM – number of signals per mile (0.1 to 8)

The coefficients a, b, c are shown below

Type of section	a	b	c
Median	82.6	0.1749	0.2515
Two-way left-turn lane	95.1	0.1498	0.4011
Other	115.8	0.1749	0.2515

[2] Cambridge Systematics Inc., (1998) "New Safety Analysis Procedures for HERS". Final report prepared for FHWA, U.S. Department of Transportation, Washington, D.C.