Impact of Truck-Auto Separation on Crash Severity

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Word count: 5493 Texts + 4 Table + 4 Figures = 7493
Abstract: 343
Re-submission Date: November 15, 2014

Paper submitted for Publication in the
Transportation Research Record, Journal of Transportation Research Board after being presented
Transportation Research Board’s 94th Annual Meeting, Washington, D.C., 2015
ABSTRACT
Truck traffic has significant impact on traffic operations and safety. Especially, safety concerns due to truck traffic continue to draw increasing attention of transportation engineers and policy makers who are proposing a number of practical strategies such as lane restrictions and exclusive facilities. The key aspect of all these strategies lies in separating trucks from cars to create more homogeneous traffic conditions. Earlier research demonstrated merits of these strategies whereas very limited findings on their safety impacts have been reported so far. The objective of this study is to examine the impact of truck-auto separation on highway crash severity. Specifically, the safety impact of separation through dual-dual roadways, a system that simultaneously provide separated car-only lanes and mixed traffic flow lanes, is of great interest since this kind of system was barely studied in the past. In order to achieve this goal, a detailed crash data set from a major highway section with dual-dual roadways for several years was examined. Comparative analyses were conducted and a statistical model have been developed. The results of this study show that the deployment of the dual-dual roadways with car-only lanes has statistically significant impact on crash severity. The model results show higher risk of having injury crashes in dual-dual lanes (both inner and outer lanes) compared with regular mix traffic lanes. This finding suggests that other than considering crash frequency as a measure of safety, crash severity should also be considered to fully assess the performance of the truck-auto separation strategies similar to the one studied in this paper. However, other than the impact of the truck-auto separation, these findings can be (partially) changed due to other factors that are not accounted for by the model, such as the actual operational speed when crash occurred, trucks being loaded or empty, etc. In short, due to the unavailability of detailed data, current results need to be considered with great care and should be considered preliminary at best. More research with better and more detailed data is needed to be able to make any final conclusion and recommendation.
INTRODUCTION
Freight transportation by trucks depends heavily on the nation’s roadway system. The annual vehicle distance traveled by trucks reached 2,946,131 million-vehicle-miles in 2011 (1). The existing and projected growth of the number of trucks and commodity moved by trucks on our highway infrastructure are pushing the limits of the national roadway system as it has not been significantly expanded over the many decades. A number of the aging links/routes of the network have already approached or reached capacity and there is a clear need more for maintenance and expansion if this growth in truck demand is going to continue.

Despite the great contributions to the economic development, the tremendous growth in truck transportation on the highway network is a source of real concern in terms of the induced traffic congestion, safety, energy consumption, and environmental impacts. For example, it was estimated that the highway truck bottlenecks account for significant truck hours of delay, totaling upwards of 243 million hours annually (2). Consequently, this causes increased energy consumption as well as emissions. When it comes to traffic safety, 4,143,373 trucks were involved in crashes according to the latest National Transportation Statistics, and among which 333,260 were large trucks. Among the 33,561 fatalities involving passengers and truck occupants, and trucks accounted for about 12 percent of all highway fatalities in 2012, among which large truck occupants were 2.1 percent and 9.6 percent involved large trucks (3). Notably, truck traffic not only contributes to its own safety problems, but also creates dangerous conditions for others (passenger cars, vans, etc.).

The statistics mentioned above have motivated many researchers and agencies (3-6) to establish strategies to reduce the impact of trucks on traffic operations and safety. Typical strategies aimed at improving traffic operations and safety include truck lane restriction, route restriction, exclusive truck facilities (truck-only lanes, designated truckways, etc.), and dual-dual roadways. A key motivation for considering these strategies is to separate trucks from other traffic to realize more homogeneous traffic conditions and safer travel for all users by reducing the potential number of interactions among different types of vehicles (7). A number of early research results highlight the promise of these strategies to improve traffic operations by reducing the potential truck-auto conflicts whereas their potential safety impacts are still not as clear or significant as their operational impacts (7-9). Thus, there is a need to better understand the safety impact of these available strategies.

To complement existing knowledge on the safety effect of these truck traffic oriented strategies, the objective of this study is to examine the impact of truck-auto separation in terms of dual-dual systems on highway crash severity. To accomplish this objective, a rich crash data set from an actual roadway was examined to analyze the severity of each individual crashes and compare the characteristics of crash severity between car-only and mixed traffic roadways with identical geometric and operational conditions.

LITERATURE REVIEW
A considerable number of studies (6, 7, 10-15) discussed the feasibility of implementing truck lane restrictions (i.e. trucks are not allowed in left lane.) and exclusive truck facilities (i.e., roadways for trucks only) to separate truck traffic from autos as a mean to improve highway operations and safety. Some of them briefly discussed the concept/strategies as a countermeasure to increase operational and safety performance of the highways (7, 11, 12), whereas others examined the potential hypothetical configurations (4, 14, 16, 17) and field practices (18-21). Many of them analyzed the configurations of the facilities in terms of type, location, scale, geometric design, etc. A number of factors that have been frequently considered to determine the feasibility of the truck facilities include traffic operation conditions (5, 16), safety performance (8, 22, 23), design plans (24), economic cost (25, 26), etc. Traffic volume, proportion of trucks, level of service, and roadway width were some of the typical elements considered. Many studies (5, 14, 16, 27-29) employed simulation models to measure the effectiveness of various truck traffic management strategies. Others (19, 30) also performed some empirical studies to examine the change in traffic operational performance in terms of travel time saving, congestion release, etc. Despite the overall favorable operational performance findings, the majority of existing studies...
convey an important lesson that the success of the truck traffic management strategies depends critically on a number of localized traffic issues as well as non-traffic factors.

In terms of safety performance, the empirical evidence is still not clear-cut. For instance, Reddy et al. (9) compared the crash data before and after lane use restriction for trucks is implemented and concluded that the restriction led to significant reduction in total crashes and property damage only (PDO) crashes but not in injury crashes. Kobelo et al. (22) assessed the truck lane restriction policy in Florida and found little concrete evidence that the crash occurrence was reduced given the presence of truck lane restrictions. Fontaine (21) examined the truck lane restrictions at 19 actual sites in Virginia, and revealed that only the overall number of fatal and injury crashes was significantly declined. His later study (23) further suggested that traffic volume greatly affected the performance of truck lane restrictions. Specifically, daily traffic volume over 10,000 per lane increased number of crashes over 20% whereas sites with lower volumes had 13% less total crashes and a 32% reduction in fatal and injury crashes. Other than the crash based analysis, some studies (29, 31, 32) also used the simulation models to examine the potential safety gains while implementing truck lane restrictions or exclusive truck facilities. The surrogate safety measures in terms of traffic conflicts were simulated under different scenarios but still a general agreement was not achieved. For example, some of these studies (31, 32) found that truck lane restrictions led to a great reduction in traffic conflicts whereas others (29) highlighted reduction in truck-related conflicts but not car related ones. Different users also showed different perceptions and opinions about the impact of these truck traffic control strategies (33-35).

Other than the lane restrictions and exclusive truck facilities, another approach to separate truck and auto traffic in practice is through a dual-dual roadway system. The dual-dual roadways are a system consisting of parallel, grade-separated lanes with truck traffic excluded from the inner auto-only lanes. The New Jersey (NJ) Turnpike Authority is one of the roadway operators that deployed such a system on the Turnpike (25, 36). A detailed description of the dual-dual system was presented in (24). Lord et al. (37) examined two sections of the dual-dual roadway and found that outer lanes with trucks experienced more crashes. However, the impact of such truck traffic control strategy has not been extensively explored to reach more conclusive results mainly due to the limited practices in filed (8).

TABLE 1 summarizes the major studies that explored the safety performance of various truck traffic control strategies. It can be seen that most of them focused on examining the change in the number of crashes or conflicts on highways with truck lane restrictions or exclusive truck facilities. Understanding the changes in the frequency/rate is only one important aspect needed to assess the effects of these strategies. However, few of them examined the final outcomes of the crashes. In other words, the safety evaluation has to account for not only crash occurrence, but also the severity of these incidents. Separating trucks from autos apparently change the characteristics of the traffic flow and interactions among different types of vehicles.

Although some positive results have been reported on the changes in crash severity changes, limited quantitative analyses have been furnished to draw the reliable conclusions. Thus, additional effort should be made to understand the impact of different truck control strategies on crash severity. As an attempt towards this goal, this paper provides an empirical study using the rich crash data to study the impact of the less studied dual-dual roadways on crash severity. The development of dual-dual roadway systems involves high cost in terms of acquiring additional land, construction, etc. A better understanding of their impact on safety will help policy makers make more informed future decisions.
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Author</th>
<th>Year</th>
<th>Site</th>
<th>Strategies</th>
<th>Evaluation Method</th>
<th>Change of Frequency or Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(38)</td>
<td>Vargas</td>
<td>1992</td>
<td>FL</td>
<td>lane restriction</td>
<td>before/after crash data analysis</td>
<td>truck crashes -38.43%, truck injury: -56.81%</td>
</tr>
<tr>
<td>(18)</td>
<td>Mannering et al.</td>
<td>1993</td>
<td>WA</td>
<td>lane restriction</td>
<td>crash data analysis (before)</td>
<td>less percentage in no-truck lanes</td>
</tr>
<tr>
<td>(9)</td>
<td>Reddy et al.</td>
<td>1999</td>
<td>FL</td>
<td>lane restriction</td>
<td>before/after crash data analysis</td>
<td>no reduction in injury crash</td>
</tr>
<tr>
<td>(39)</td>
<td>Hoel and Peek</td>
<td>1999</td>
<td>VA</td>
<td>lane restriction</td>
<td>simulated lane changes</td>
<td>left lane restrict: lane changes decreased</td>
</tr>
<tr>
<td>(19)</td>
<td>Borchardt</td>
<td>2002</td>
<td>TX</td>
<td>lane restriction</td>
<td>before/after crash data analysis</td>
<td>crash rate reduced 68%</td>
</tr>
<tr>
<td>(31)</td>
<td>Garber &amp; Liu</td>
<td>2007</td>
<td>VA</td>
<td>lane restriction</td>
<td>simulated conflicts</td>
<td>conflicts can be reduced</td>
</tr>
<tr>
<td>(21)</td>
<td>Fontaine</td>
<td>2008</td>
<td>VA</td>
<td>lane restriction</td>
<td>before/after crash data analysis</td>
<td>only fatal &amp; injury crashes declined</td>
</tr>
<tr>
<td>(22)</td>
<td>Kobelo et al.</td>
<td>2008</td>
<td>FL</td>
<td>lane restriction</td>
<td>model prediction</td>
<td>insignificant reduction (4%)</td>
</tr>
<tr>
<td>(23)</td>
<td>Fontaine et al.</td>
<td>2009</td>
<td>VA</td>
<td>lane restriction</td>
<td>crashes: treatment vs. control sites</td>
<td>low-volume decreased; high-vol.: increased</td>
</tr>
<tr>
<td>(40)</td>
<td>Frauenfelder &amp; Espada</td>
<td>2012</td>
<td>AU</td>
<td>lane restriction</td>
<td>simulated lane changes</td>
<td>Truck lane changes reduced</td>
</tr>
<tr>
<td>(41)</td>
<td>Mwakalonge &amp; Moses</td>
<td>2012</td>
<td>FL</td>
<td>lane changes &amp; speed diff.</td>
<td>simulated surrogate safety analysis</td>
<td>right lane restriction: safer</td>
</tr>
<tr>
<td>(42)</td>
<td>Sun et al.</td>
<td>2009</td>
<td>LA</td>
<td>speed limit &amp; lane restrict.</td>
<td>before/after crash data analysis</td>
<td>total crashes: -13%; truck crashes: -77%</td>
</tr>
<tr>
<td>(32)</td>
<td>El-Tantawy et al.</td>
<td>2009</td>
<td>T. O.</td>
<td>lane restriction &amp; dedication</td>
<td>simulated conflicts</td>
<td>conflicts can be reduced</td>
</tr>
<tr>
<td>(29)</td>
<td>Bachmann et al.</td>
<td>2011</td>
<td>T. O.</td>
<td>exclusive truck facilities</td>
<td>simulated conflicts</td>
<td>truck conflict: reduced, car: increased</td>
</tr>
<tr>
<td>(13)</td>
<td>Douglas</td>
<td>2004</td>
<td>NJ</td>
<td>dual-dual roadway</td>
<td>before/after crash data analysis</td>
<td>crash rate reduced</td>
</tr>
<tr>
<td>(37)</td>
<td>Lord et al.</td>
<td>2005</td>
<td>NJ</td>
<td>dual-dual roadway</td>
<td>crash data analysis (after)</td>
<td>overall safer; outer crash rate is higher</td>
</tr>
</tbody>
</table>
DUAL-DUAL ROADWAYS

The New Jersey (NJ) Turnpike (a part of I-95) is used as the study site. Other than the general mixed-flow lanes in each direction, a 32-mile section (see FIGURE 1) between Interchanges 8A and 14 uses a dual-dual roadway concept to serve traffic. The goal of using this roadway configuration is to meet the growing traffic demand by adding more lanes and improve safety by separating truck traffic from light vehicles. This section is identified as the real-world pilot application of the dual-dual roadways in the USA. It is comprised of inner lanes dedicated to cars and outer lanes allocated for trucks/buses as well as cars. The inner lanes and the outer lanes are physically separated from each other. Trucks/buses have to choose the appropriate ramps to access the outer lanes. Light vehicles (cars, vans, etc.) can choose either inner lanes or outer lanes while entering from the toll plazas. As shown in FIGURE 1, the lane configurations between interchanges 8A and 9 is 2-3-3-2 in terms of outer-inner-inner-outer design. Between interchanges 9 and 11, each types of lanes have 3 lanes. Likewise, there are 4 outer lanes and 3 inner lanes in each direction between interchanges 11 and 14. The left-most lane of the outer roadways in north- and south-bounds between Interchange 11 in Woodbridge and Interchange 14 in Newark is reserved as a high occupancy vehicle (HOV) lane. The HOV lane operates on weekdays from 6 a.m. to 9 a.m. in the northbound direction and 4 p.m. to 7 p.m. in the southbound direction. Vehicles carrying three or more occupants can use the HOV lanes. In addition, hybrid vehicles and alternative fuel vehicles are also encouraged to use the HOV lanes. The speed limits along these sections are usually 55 mph or 65 mph. Depending on actual traffic/weather, the dynamic message signs are used to advise the prevailing traffic conditions (incidents, adverse weather, etc.) and speed limits.

There was very limited experience on deploying the dual-dual roadway system. In the early days, Douglas (13) explored the change of crashes to provide some preliminary information on the safety performance of the NJ Turnpike dual-dual roadway system. He compared the total crash rates five years (1965 to 1969) before completion of the dual-dual roadway system and five years (1994 to 1998) after the implementation of the system. The results show that the annual crash rate was reduced over 18 percent. Compared to the other segments of the NJ Turnpike without dual-dual separation, the crash rates for the inner lanes and outer lanes in each year are 26 to 61 percent less. In a ten-year (1994 to 2003) follow-up study, it was found that the crash rates in each year on the dual-dual roadways were 28 to 40 percent less than those without separation. The injury crash rates were observed to be 20 to 34 percent lower along the
dual-dual roadways whereas no consistent findings on the fatal crash rate changes. Arguably, the lower crashes rates along the dual-dual roadways were attributed to the increased roadway capacity and the more homogenous traffic. Nevertheless, more detailed analysis on the crash records and other relevant factors were suggested to investigate how much of the benefits of crash reduction were contributed by the dual-dual separation.

The crash data collected in this study ranges from January 1, 1995 and June 10, 2006 from the New Jersey Turnpike Authority. The raw data were archived in a text file with codes representing information on crash time, location, severity, vehicle, driver, etc. To facilitate analysis and interpretation, the raw data were processed. A master file and a detailed file were extracted to provide the overview and details of the crashes, respectively. The raw data were decoded by referring to the lookup table that defines each variable.

Other than crash data, hourly traffic volume data from the Remote Microwave Traffic Sensors (RTMS) located at milepost 74.6 (between interchanges 8A and 9) were obtained in February, May and August in 2011. The volume, occupancy, and speed of each lane at that location were collected. These data were used to help understand the distribution of traffic in outer and inner lanes. Other than the sensors at this site, there were no other available sensors located between interchanges 9 and 14. Thus, the available sensor data collected between interchanges 8A and 9 are only used for the case study but some differences of volume composition between the interchanges 9 and 14 should be expected. The traffic proportions of outer versus inner lanes are shown in TABLE 2. It can be seen that the average hourly traffic volume in an inner lane is consistently higher than that in an outer lane in both directions.

### TABLE 2 Average Hourly Traffic Volume Distribution in Each Lane in Each Direction

<table>
<thead>
<tr>
<th>Direction</th>
<th>Southbound</th>
<th>Northbound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer (2 lanes)</td>
<td>Inner (3 lanes)</td>
</tr>
<tr>
<td>February</td>
<td>15.1%</td>
<td>23.2%</td>
</tr>
<tr>
<td>May</td>
<td>14.3%</td>
<td>23.8%</td>
</tr>
<tr>
<td>August</td>
<td>12.9%</td>
<td>24.8%</td>
</tr>
</tbody>
</table>

**DESCRIPTIVE ANALYSIS**

A total of 78,751 crashes involving 145,278 vehicles occurred on the NJ Turnpike from January 1, 1995 to June 10, 2006. The numbers of crashes occurring in the inner lanes (for cars only) and the outer lanes (car-truck mixed) are 6,792 and 6,458, respectively. The remaining ones occurred in other regular sections without dual-dual configuration. Since the average traffic volume in the inner lane is much higher than the outer lane (about 20% to 92% more as shown in TABLE 2) and the total numbers of crashes in both types of lanes were similar, the separation of trucks from cars led to the reduction of crash rates in inner (car-only) lane. This confirmed the findings of previous research (13, 37).

FIGURE 2 (a) shows the proportion of crashes that involved trucks/buses in each type of roadway configurations. The results illustrate that the proportion of truck/bus involved crashes in the outer lane is 50.9% whereas it is only 37.7% on other sections. Notably, there were still 4.4% crashes involving trucks/buses in the inner (car-only) lanes. Statistically, the Pearson's Chi-squared test ($\chi^2 = 53.691$, $df = 2$ and $p-value < 0.001$) confirms that there is statistically significant difference between the proportions of truck-involved crashes for each type of lanes. The higher proportion of truck/bus involved crashes in outer lane should be attributed to the higher proportion of truck volume when they were separated from the car-only lanes. Despite being dedicated to cars, the inner lanes still experienced truck and bus-involved crashes, perhaps due to the inappropriate selection of the inner lanes by some heavy vehicles. In addition, some truck might be directed to use the inner lanes during special events (i.e., closure of outer lanes due to incidents). Last but not least, there might be accuracy issues with the crash records, for instance, police on the scene might be making a mistake in recording this data as inner lane
although it might be an outer lane. Despite these possible reasons, a careful study has to be conducted to investigate why there were some truck involved crashes in the car-only lanes.

**FIGURE 2. The proportion of crashes on each type of roadways**

![Proportion of crashes by vehicle type and severity](image)

FIGURE 2 (b) illustrates the severity of crashes on each type of roadway configurations. Note that three crashes occurred on other regular sections that were excluded from this analysis due to the missing information about crash severity. For those crashes that occurred in the outer lanes, inner lanes and the other regular sections, the proportions of injury crashes (including fatal crashes) are 24.3%, 31.9%, and 20.3%, respectively. The Pearson's Chi-squared test ($\chi^2 = 515.481$, $df = 4$ and $p-value < 0.001$) statistically confirms the difference of being severe crashes among the three types of roadways (lanes). A further analysis was performed to examine how many of the injury crashes on each roadway were associated with truck. The results show that more proportion of injury crashes in outer lanes involved trucks than other regular mixed-flow lanes. More specifically, 50.4% of injury crashes in outer lanes involved cars only, 16.3% involved trucks only, and 33.3% involved both cars and trucks. In contrast, 73.3% injury crashes are car-only crashes, 6.5% injury crashes are truck-only crashes and 20.2% involved in both types of vehicles in other regular mixed flow lanes. The underlying mechanism should be further investigated with detailed volume with truck proportions.

**FIGURE 3** shows the temporal distribution of injury crash occurrences on each type of roadway sections. In general, more injury crashes occurred in the peak periods. The hourly proportion of injury crashes on these roadway sections are similar. The major differences are observed in early morning hours before 7 a.m. The hourly proportions of injury crash for inner lanes were consistently higher (about 1% more). This might be attributed to the higher exposure in inner lanes during these periods. Nevertheless, detailed traffic data should be used to verify this hypothesis.
One of the primary goals for separating trucks from cars is to reduce interactions of different types of vehicles and increase overall safety. The dual-dual separation of trucks and cars deemed to change the original mixture of traffic flow as those operated on other sections. For example, the average speed of the car-only lanes is expected to be higher after excluding slow-moving truck traffic. Therefore, it is of great interest to see whether the modified traffic characteristics lead to different patterns of crashes. Specifically, the number of vehicles involved in each crash and the final types of crashes were examined. FIGURE 4 (a) shows the number of vehicles involved in crashes on each type of roadways. It can be seen that the proportion of 2-vehicle crashes is higher on other regular sections whereas the number of single-vehicle crashes in both outer and inner lanes are higher. The proportions of two-vehicle crashes were 57.1% in outer lanes, 50.5% in inner lanes, and 65.0% in other regular lanes. A possible reason of higher proportion of two-vehicle crashes occurred in the outer lanes might be attributed to more interactions between vehicles, particularly, the truck-car interactions. However, further effort should be devoted to examine the underlying mechanisms.
FIGURE 4 (b) illustrates the crash types in each category of sections. For all three types of roadways, rear-end crashes accounted for about 40% of crashes. The proportion of sideswipe crashes were higher on the dual-dual sections. Compared to regular sections, the proportion of collisions with fixed object in outer lanes and inner lanes were approximately half of that in the regular sections.

QUANTIFYING THE RISK OF A SEVERE CRASH
One of the goals of this study is to examine the impact of separating trucks from cars on crash severity. Each crash in the police crash report was categorized as fatal crash, personal injury crash, and property damage only (PDO) crash. As the number of fatal crashes was relatively small, these crashes were combined with the personal injuries and denoted as injury crashes. Thus, crash severity can be denoted as a binary outcome (injury vs. non-injury) of a crash on the highway, where \( y = 1 \) for the injury crash and \( y = 0 \) for the non-injury crash. Naturally, such a binary nature facilitates the use of a logistic regression model to examine the influence of various factors on the probability of a crash being an injury crash, where \( \pi(x) \) is the probability of a crash being classified as an injury crash and \( 1 - \pi(x) \) is the probability of a crash being non-injury. The binary logistic regression model identifies the relationship between the log odds of the dichotomous outcome and various risk contributing factors. Mathematically, it can be written as in equation (1):

\[
\logit[\pi(x)] = \log\left(\frac{\pi(x)}{1-\pi(x)}\right) = \alpha + X\beta \tag{1}
\]

Based on equation (1), the probability that an injury crash will occur on the highway can be described by the logistic distribution shown in equation (2):

\[
P(y=1|X) = \pi(x) = \frac{\exp(\alpha + X\beta)}{1 + \exp(\alpha + X\beta)} \tag{2}
\]

where \( \pi(x) \) is the conditional probability of the form \( P(y=1|X) \); \( X \) is the vector of explanatory variables (risk factors) that could be continuous or dichotomous; \( \beta \) is the corresponding vector of the coefficients; and \( \alpha \) is the intercept parameter. A maximum-likelihood estimation technique was used to determine these parameters in the regression model. A chi-square test was used to test the overall significance of the logistic regression model. The significance of individual risk factors within the model was evaluated using the Wald chi-square statistic. Moreover, the unique contribution of the \( j^{th} \) risk factor on crash severity can be expressed by the odds ratio (OR), which is defined as:

\[
OR = \exp(\beta_j) \tag{3}
\]

with the 95% confidence interval (CI) of \( \left[ \exp(\beta_j - 1.96\text{SD}_{\beta_j}), \exp(\beta_j + 1.96\text{SD}_{\beta_j}) \right] \), where \( \text{SD}_{\beta_j} \) is the standard error of the coefficient \( \beta_j \). OR measures the ratio of the predicted odds for a one-unit increase in the predictor variable \( x_j \) when other variables in the model are held fixed.

To develop injury severity models for different units of analysis, it is necessary to preselect contributory attributes. In this study, we determined the contributory attributes in two steps. The first step was to review all possible attributes available in the crash records of NJ Turnpike and refer to key attributes that are frequently used in the literature. The second step is to select attributes that are thought to have major influence on crash severity under local conditions and also available in the crash records. Following these two steps, attributes including time of day, weather condition, lighting condition, pavement condition, collision type, type of vehicles involved in the crashes, number of vehicles involved, and the location of the crashes were initially hypothesized to have some association with severity levels. These variables reflect the impact of temporal characteristics, environmental conditions, crash characteristics, vehicle characteristics on crash severity. More importantly, the “location” variable represents inner lanes, outer lanes, and other mixed flow lanes. The description and the code for each...
variable is presented in TABLE 3. These variables are binary or dummy indicators representing the existence of a given condition.

Chi-square statistics are used to screen the potential correlation between the attributes and the severity. A variable is considered a risk factor if the Pearson chi-square test provides a $p$ value less than the level of significance (0.1). Several factors were excluded, as they were found to be statistically insignificant. Eventually, the 16 variables listed in TABLE 3 were considered potential risk factors and were incorporated into the following model analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severity</td>
<td>Severity</td>
<td>property damage only crash (= 0); injury crash or fatal crash (=1)</td>
</tr>
<tr>
<td>Time of day</td>
<td>Time</td>
<td>06:00–20:00 (= 0) vs. other periods (= 1)</td>
</tr>
<tr>
<td>Lighting condition</td>
<td>Light</td>
<td>good light condition (= 0) vs. poor light condition (= 1)</td>
</tr>
<tr>
<td>Weather condition</td>
<td>Weather</td>
<td>clear weather (= 0) vs. adverse weather (=1)</td>
</tr>
<tr>
<td>Pavement condition</td>
<td>Pavement</td>
<td>dry (= 0) vs. wet (= 1)</td>
</tr>
<tr>
<td>Vehicle types involved</td>
<td>PassCar</td>
<td>passenger car (i.e. car, &amp; pickup) involved (= 1); = 0 other vehicle (= 0)</td>
</tr>
<tr>
<td></td>
<td>Motorcycle</td>
<td>motorcycle vehicle (= 1); other vehicle (= 0)</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>truck or bus involved (= 1); other vehicle (= 0)</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>VehNum</td>
<td>Total number of vehicles involved in crash</td>
</tr>
<tr>
<td>Collision type</td>
<td>ReadEnd</td>
<td>= 0 if rear-end collision</td>
</tr>
<tr>
<td></td>
<td>Sideswipe</td>
<td>= 1 if sideswipe collision</td>
</tr>
<tr>
<td></td>
<td>Runoff</td>
<td>= 2 if ran off road</td>
</tr>
<tr>
<td></td>
<td>NonFixed</td>
<td>= 3 if collided with nonfixed object (animal, pedestrian, etc.)</td>
</tr>
<tr>
<td></td>
<td>Fixed</td>
<td>= 4 if collided with fixed object (curb, barrier, etc.)</td>
</tr>
<tr>
<td></td>
<td>UTurn</td>
<td>= 5 if U-turn collision</td>
</tr>
<tr>
<td></td>
<td>Overturn</td>
<td>= 6 if overturned on road</td>
</tr>
<tr>
<td>Location</td>
<td>Location</td>
<td>= 0 if other mixed flow lanes (denoted as OtherLane) for section without dual-dual design; =1 if outer lanes; =2 if inner lanes</td>
</tr>
</tbody>
</table>

MODELING RESULTS AND DISCUSSION
The binary logistic regressions were fitted using the Generalized Linear Model in R. The estimated parameters for the severity models for crash-level analysis are presented in TABLE 4. The overall model fit was tested by examining whether the full model with those independent variables fit significantly better than a null model with just an intercept. The chi-squared test was performed. The test statistic was the difference between the residual deviance for the model with independent variables and the null model with degrees of freedom ($df$) equal to the number of predictor variables in the full model. For the crash-level analysis, the chi-squared statistic $\chi^2 = 5528.518$ with 14 degrees of freedom and an associated $p$ value less than 0.001 indicates that the overall explanatory variables of the model have significant influence on the crash severity given a significance level of 0.05.

The significance of individual variables within each model was tested using the Wald chi-squared statistic. Of the variables used for the crash-level severity analysis, 14 were found to be statistically significant. The corresponding estimated coefficients, standard errors, $z$ values, and $p$ values for each variable for different units of analysis are listed in TABLE 4. It should be noted that the estimated coefficients are not directly interpretable; therefore, the odd ratios (OR) were derived. The OR in the table is interpreted as a comparison of the injury risk associated with each level of a variable with the selected
reference. It helps us determine the variables that significantly affect the probability of a crash being an injury crash. The interpretations of these results are presented in the following subsections.

### TABLE 4 Crash Severity Modeling Results

| Variable        | Estimate | Std. Error | z value | Pr(>|z|) | Odds Ratio (OR) | 95% CI of OR |
|-----------------|----------|------------|---------|---------|-----------------|--------------|
| Intercept       | -2.989   | 0.067      | -44.586 | < 2e-16 | -               |              |
| Time            | 0.310    | 0.022      | 14.337  | < 2e-16 | 1.363           | (1.307, 1.422)|
| Weather         | -0.159   | 0.023      | -6.906  | 4.98E-12| 0.853           | (0.815, 0.892)|
| PassCar         | 0.098    | 0.041      | 2.41    | 0.0159  | 1.103           | (1.019, 1.195)|
| Motorcycle      | 2.421    | 0.148      | 16.332  | < 2e-16 | 11.253          | (8.464, 15.145)|
| HeavyVeh        | -0.350   | 0.025      | -13.99  | < 2e-16 | 0.705           | (0.671, 0.740)|
| VehNum          | 0.832    | 0.022      | 37.298  | < 2e-16 | 2.297           | (2.199, 2.400)|
| RearEnd (base)  | -         | -          | -       | -       | -               |              |
| Sideswipe       | -0.627   | 0.024      | -25.764 | < 2e-16 | 0.534           | (0.509, 0.560)|
| Runoff          | 1.171    | 0.053      | 22.076  | < 2e-16 | 3.225           | (2.906, 3.578)|
| NonFixed        | -0.355   | 0.062      | -5.695  | 1.24E-08| 0.701           | (0.620, 0.791)|
| Fixed           | 0.980    | 0.037      | 26.613  | < 2e-16 | 2.664           | (2.479, 2.864)|
| UTurn           | 0.330    | 0.150      | 2.208   | 0.0272  | 1.391           | (1.031, 1.855)|
| Overturn        | 2.458    | 0.092      | 26.637  | < 2e-16 | 11.681          | (9.753, 14.006)|
| OtherLane (base)| -        | -          | -       | -       | -               |              |
| Outer           | 0.299    | 0.032      | 9.285   | < 2e-16 | 1.349           | (1.266, 1.436)|
| Inner           | 0.403    | 0.029      | 13.759  | < 2e-16 | 1.496           | (1.412, 1.584)|

Note: “OtherLane (base)” means the sections that have no dual-dual configuration.

TABLE 4 summarizes the results and the model coefficients imply that the likelihood of an injury crash occurring at nighttime is 1.363 times higher than that of daytime. The higher injury risk may be attributed to the reduced driver alertness, visibility and lighting glare. As many researchers have shown, this study found that the crashes occurred under adverse weather conditions are less severe as the OR is less than one. This is expected that drivers are usually driving with more cautions and lower speeds under adverse weather conditions. Another interesting find is that the crashes involved passenger cars increased were more likely to be an injury crash whereas the ones involved heavy vehicles (i.e., truck) were less severe. The OR associated with the variable “heavy vehicle involved in a crash” is 0.705, implying that the injury propensity of a crash involving heavy vehicle is about 30 percent lower. Arguably, this is because that a passenger car usually has more persons (driver and passengers) being exposed to the crash. A truck often involved less number of people. Nevertheless, if a motorcycle was involved in the crash, the likelihood of being injured is 11.253 times higher. This outcome was expected, as these vulnerable users are less protected than car and truck users, and if a crash occurred, they were more likely to be injured due to the vulnerability (less protected) of road users (43). The more number of vehicles involved, the more likely the crash is an injury crash. Regarding the effect of the collision types, it was found that the sideswipe collisions and the non-fixed object collisions were not prone to result in injury crashes as against the rear-end crashes. Notably, the other crashes due to vehicles run off road, collide with fixed object, U-turn, and overturn on road all led to higher risk of injury.

Both the outer and inner lanes (car-only lanes) configured as dual-dual roadways have higher risk of injury crashes compared to regular lanes in other sections of the highway. The ORs are 1.349 and 1.496 for the outer lanes and the inner lanes, respectively. In other words, crashes that occurred on these separated roadways are 34.9% and 49.6% more likely to be injury crashes than that of regular mixed-flow lanes. The OR of the inner lanes is about 10% more. However, other than the impact of the truck
separation, the increase in injury risk can be (partially) due to other factors that are not accounted for by
the model, such as the actual speed when crash occurred, trucks being loaded or empty, etc. This finding
is consistent with the proportion test results given in the previous section as well as the limited findings
presented in a paper by Lord (37). The changes of crash severity deserves additional discussion under
different traffic configurations. For the outer lanes, the proportion of trucks is higher. The risk of a car
colliding with a truck is higher than the regular mixed-flow lanes. A crash which occurs in the inner lane
tends to involve more passengers when all of the involved vehicles are cars or other vulnerable vehicles
such as motorcycles. For instance, 50.4% of injury crashes in outer lanes involved cars only, 16.3%
involved trucks only, and 33.3% involved both cars and trucks. In contrast, 73.3% injury crashes are car-
only crashes (particularly attributed to larger volume of cars), 6.5% injury crashes are truck-only crashes
and 20.2% involved in both types of vehicles in other regular mixed flow lanes. Despite the reduced crash
rate, results suggest that there is a need to assess the safety performance of dual-dual configuration not
only by considering crash frequency, but also using the outcome of crashes. The underlying mechanism
of the higher risk of severe crashes should be further explored with more detailed data (i.e., speed and
truck proportion, safety system changes, and road geometry features).

CONCLUSIONS
The growing freight transportation activity in the nation’s transportation network leads to a number of
challenges in traffic operation and safety issues. Researchers and practitioners have been exploring
various remedial countermeasures to tackle these problems. As such, different truck traffic control
strategies have been proposed as a mean to reduce their operational and safety impacts. A wide range of
research results in the favor of these strategies based on their operational performance. However, there are
still very limited consensus on their safety impact. Despite some empirical findings on crash reduction,
very few of them specifically examined the outcomes of the crashes. Thus, this study attempts to raise
awareness about the importance of understanding their safety effects not only in terms of crash reduction
but also in terms of the severity of the crashes.

This study specifically examined the impact of separating trucks from autos by means of a dual-
dual roadway. A simple analysis on the change in crash rate is also performed. Particularly, it aims to
examine the changes in crash severity induced by the dual-dual systems. A detailed crash data set
collected over 11 years from a highway has been investigated. This facility is one of the busiest highways
in the country and has a 32-mile dual-dual roadway system as well as an ongoing program for its further
expansion. The dual-dual roadway consists of parallel inner lanes for autos only and outer lanes for mixed
traffic. This configuration provides a great opportunity to compare the changes of crash severity due to
separation of cars from trucks. Comparative analysis results showed that the proportions of severe crashes
occurred in different types of lanes were different. Surprisingly, the proportions of injury crashes occurred
along the dual-dual roadways were higher compared with other sections of the highway. In the meantime,
inner lanes reserved for autos only had the highest proportion of injury crashes. Further, a statistical
model that captured crash severity has been developed. The results also confirmed that crashes on the
dual-dual roadways were more likely to be injury crashes. This can be due to the fact that the sections
without dual-dual system might have lower operational speed and the possibility of a severe crash is less
for congested roadways. In addition, the traffic behavior in the dual-dual system might be different, for
instance, there might be more speeding and lane changing. Nevertheless, due to the unavailability of
detailed data, current results need to be considered with great care and should be considered preliminary
at best. More research with better and more detailed data is needed to be able to make any final
conclusions.

There are few important research questions that need mentioning and which warrant further
study. The present study only examined crash data. Thus, the underlying mechanisms of slightly higher
proportion of injury crashes occurred on the dual-dual configuration compared with regular configuration
deserves more investigation. One important need is to compare the operating speeds between the lanes
since higher speed could be a critical factor for injury crashes. Time of day and directionality can be
indicators of the effect of congestion on crash severity. These are additional factors that need to be
investigated as future research. Additional analysis of the role of traffic composition also needs further investigation. More importantly, the crash data used for this study covers a long duration of time, and numerous and dramatic changes in the availability of vehicle safety systems and features in the car fleet have occurred during this time period. The effects of these safety systems on crash outcome may be confounded with the dual-dual system impact. With more relevant data, their impact on crash severity should be considered.

**ACKNOWLEDGEMENTS**

The authors appreciate the New Jersey Department of Transportation and New Jersey Turnpike Authority for providing data used in this study. The contents of this paper only reflect views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents of the paper do not necessarily reflect the official views or policies of the any agencies. The authors thank for the insightful comments and suggestions from all the anonymous reviewers that helped improve the paper.

**REFERENCES**


