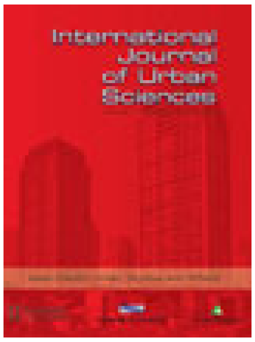

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Safety effectiveness of truck lane restrictions: a case study on Texas urban corridors

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ABSTRACT

Truck lane restrictions (TLRs) have become increasingly popular throughout the United States over the last 20 years due to the improvement in traffic operations and safety, pavement life, and other associated factors. This study examines the safety performance of the TLRs that have been implemented in the North Texas region. TLR prohibit semi- trucks (trucks) from using the left-most freeway lane, or inner lane, except in passing or emergency maneuvers. This study uses 16 sites with TLR in the Dallas-Fort Worth area to conduct an observational before-after study. For safety effectiveness analysis, it is always hard to get three years before and three years after data. For immediate safety effectiveness analysis, sophisticated predictive tools could be used in estimating 'after' year crashes. This study used the Enhanced Interchange Safety Analysis Tool (ISATe) to supplement the limited after year crash data. This study used Empirical Bayes (EB) method due to its consideration of regression-to-mean bias. The findings show that TLRs perform an overall positive safety effectiveness for large truck-involved fatal and injury crashes for six-lane roadways. This study concludes that implementing TLR as a truck-related safety strategy which are cost-effective to implement, may contribute to improving safety on urban freeways.

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Trucks; restricted truck lane; safety effectiveness; crash modification factor (CMF)

1. Introduction

Trucks are mainly used for bulk transportation of goods and materials. The large bodily dimensions of trucks limit their highway operational abilities. The demand of just-in-time delivery in commodity flow has been continued to increase the needs of trucking services that raises safety and operational concerns. In 2013, among the 255.88 million total registered vehicles in the United States, 8.13 million were single-unit trucks (straight trucks), 2.47 million were combination trucks (tractor-trailers), and 0.86 million were buses (FHWA, 2015). In the same year, there were 2,988.3 billion vehicle miles travelled (VMT) by all motor vehicles. Large trucks travelled 9.2% of the total VMT (275.0 billion miles). In 2013, there were 3,541 large truck-involved fatal crashes (11.78% of total fatal crashes). Fatal crash involvement of large trucks is disproportionately higher than VMT. Many states have implemented truck lane restrictions (TLR) to improve mobility

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and safety on freeways. TLR prohibits semi- trucks (trucks) from using left-most freeway lane, or inner lane, except in passing or emergency maneuvers.

The first TLR pilot in Texas was implemented on I-10 East freeway in Houston in September 2000. Based on the experience and the criteria developed for the Houston TLR, North Central Texas Council of Government (NCTCOG) implemented two pilot sections in Dallas-Fort Worth (DFW): I-20 in Dallas and I-30 in Fort Worth in 2005. Since its first implementation in 2000, there have been no comprehensive evaluations of TLR safety effectiveness in Texas. There is limited research on measuring safety effectiveness of TLR on urban freeways. This study aimed to mitigate the current gap by evaluating safety effectiveness of TLR implemented at 16 freeway locations in the Dallas Fort Worth area by using the Empirical Bayes (EB) method. Additionally, this study used the Enhanced Interchange Safety Analysis Tool (ISATe) to estimate after year crash frequencies due to the limitation of availability of three-year after crash data.

2. Literature review

Various studies have been conducted on the safety effectiveness of truck-lane restrictions in other states, and have generally yielded mixed results. Some of these studies have focused on crashes while others have used simulation to obtain safety surrogate measures such as lane change frequency or speed differential. Table 1 provides a summary of the results found in eight published studies. Note that ranges are provided for the magnitude of change in the analysis measure because most of the studies provided results for a range of conditions. Additional details are provided in the following paragraphs.

Gan and Jo conducted a simulation study of truck-lane restrictions, focusing on operational analysis measures (Gan & Jo, 2003). One of their measures included lane changes, which is included in this synthesis as a safety surrogate measure because it has been used by others in this manner. They found that lane change maneuvers will decrease by 2–20% depending on interchange density, a total number of lanes, and number of lanes included in the restriction. Other researchers analysing lane change maneuvers or conflicts include Cate and Urbanik (2004), El-Tantawy, Djavadian, Roorda, and Abdulhai (2009), and Mwakalonge and Moses (2012). These four simulation efforts generally found lane-

Table 1. Summary of safety studies on truck-lane restrictions.

State or province	Year of publication	Analysis type	Analysis measure	Magnitude of change	Reference
FL	2003	Simulation	Lane change maneuvers	−2 to −20%	*2*
TN	2004	Simulation	Lane change maneuvers	−18 to −38%	*3*
TN	2004	Simulation	Speed differential	−3 to +21%	*3*
Ontario, Canada	2009	Simulation	Lane change conflicts	−17 to −21%	*4*
FL	2012	Simulation (arterial street)	Lane change maneuvers	−5 to −9%	*5*
TX	2007	Naïve before-after, with seasonal adjustment	Crashes	−11 to −64%	*6*
FL	2008	Cross-sectional modelling	Crashes	−4%	*7*
TX	2004	Comparison group before-after	Crashes	−7%	*8*
LA	2012	Comparison group before-after	Crashes	−50%	*9*
VA	2009	Empirical Bayes before-after	Crashes	−13 to +28%	*10*

change maneuvers or conflicts decreased in the range of 2–20%, with some reductions as high as 38% in the case of the Cate and Urbanik study (2004). Cate and Urbanik also included speed differential in their analysis, noting that in some simulation scenarios, lane changes decreased but speed differentials between cars and trucks increased, possibly offsetting some of the benefit of reducing lane changes. They further stated that the greatest benefits were observed on freeway sections with uphill grades, while results were practically neutral elsewhere. It should be noted that the study by Mwakalonge and Moses (2012) focused on arterial streets while the rest of the studies listed in Table 1 focused on freeways.

The five crash-based studies listed in Table 1 were conducted by NCTCOG (2009), Kobelo, Patrangenaru, and Mussa (2008), Borchardt, Jasek, and Ballard (2004), Ishak, Wolshon, Sun, Korkut, and Qi (2012), and Fontaine, Bhamidipati, and Dougald (2004). These studies varied in design as listed in the third column of Table 1. NCTCOG (2009) analysed the first two TLRs implemented in the Dallas/Fort Worth area, finding a reduction in crashes of 11% on the I-30 corridor and 64% on the I-20 corridor. They stated that the former finding was not statistically significant but the latter was, at the 90% confidence level. The 4% crash reduction noted by Kobelo et al. (2008) was positive but statistically insignificant. Borchardt et al. (2004) examined TLRs on the I-10 corridor in Houston, Texas, and found an overall 7% reduction in crashes on the treated section while a 3% increase at an untreated section was observed at the same time. The analysis conducted by Ishak et al. (2012) was on the 18-mile elevated bridge section of I-10 over the Atchafalaya Basin in Louisiana. They observed a 50% reduction in crashes; however, it must be noted that in their case, two complementary treatments were implemented: TLRs and differential speed limits (60 mph for passenger cars, 55 mph for trucks). Finally, Fontaine et al. found that TLRs provide a safety benefit (13% crash reduction) in low-volume conditions but a safety dis-benefit (28% crash increase) in high-volume conditions. Their threshold for defining 'high-volume' was 10,000 vehicles/day/lane.

The mixed results observed in the literature suggest that more detailed analysis needs to be conducted on when and how to implement TLRs. Specifically, it is likely that benefits will be more notable on sections with steep, sustained uphill grades, and are likely to vary depending on roadway volume. Additionally, several authors observed that enforcement and compliance need to be considered because non-compliance will decrease the effectiveness of any treatment (Borchardt et al., 2004; Ishak et al., 2012).

3. Methodology

3.1. Site selection

The first TLR in Texas was implemented on IH 10 East freeway in Houston in September 2000.

A 2004 TTI study developed the following criteria to determine corridor feasibility for TLR implementation (TTI, 2013):

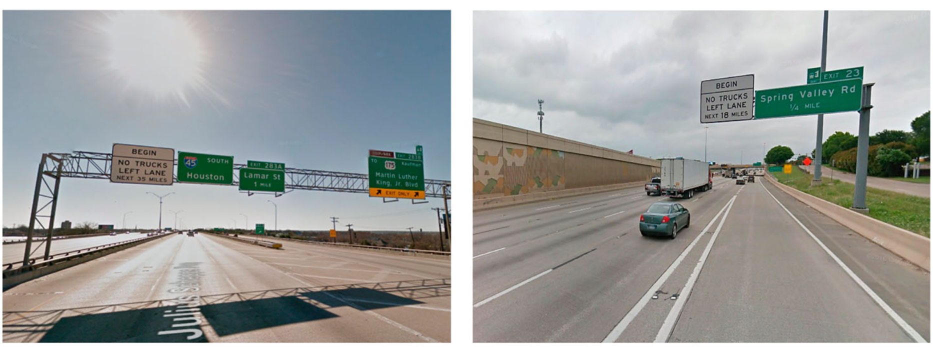
- Criterion 1: Six-mile minimum length of freeway section,
- Criterion 2: Six-lane or wider freeway cross-section,

- Criterion 3: Total truck volume of at least 4% in the mix,
- Criterion 4: At least 5% of total truck traffic using the left (inside) lane, and
- Criterion 5: No left (inside) side ramps within the limits.

Based on the experience and the criteria developed for the Houston TLR, NCTCOG implemented two pilot sections in the Dallas-Fort Worth (DFW) region: I-20 in Dallas and I-30 in Fort Worth in November 2005 which were evaluated in an October 2006 report: Truck Lane Restriction Study: Final Report performed by NCTCOG (2017). The 2006 study determined that the pilot TLR sections should remain in place following the study due to the initial positive improvements in average speed, a decline in crashes, and a reduction in Nitrogen Oxide (NOx) emissions. Subsequently, the July 2009 North Central Texas Truck Lane Restriction Expansion Traffic Study Report was done by NCTCOG in conjunction with the Dallas and Fort Worth Texas Department of Transportation (TxDOT) Districts (NCTCOG, 2009).

The current study described in this paper determined the extent and locations of current TLR routes in DFW and statewide. Figure 1 shows a Google Street view of two example segments. Figure 2 shows a map of the selected 16 TLR sites for this study. Initially, the research team included 19 study sections where TLRs had been implemented. One of the sections was removed because the TLR was never implemented due to on-going construction, Another section was removed due to data quality issues, and the third section was dropped due to the limited availability of after period crash data. Table 2 summarizes the characteristics of the sites selected for this study. It shows that some of the TLRs were only recently implemented. As a result, these TLR sites have limited 'after' year observational data.

Using available data from TxDOT's Crash Record Information System (CRIS), crashes were analysed for each TLR section. However, not all crashes could be located using CRIS's internal reference system (e.g. highway control section, Texas reference markers, etc.) because they had not been geo-located (latitude, longitude) yet. Table 3 shows that on average, 16% of on-system crashes were missing coordinates statewide. Thus, this study developed a method to geo-locate the crashes that were missing coordinates. This helped to ensure that all available reported crash locations were included.



(a) IH 45 (b) US 75

Figure 1. TLR on (a) IH 45, and (b) on US 75.

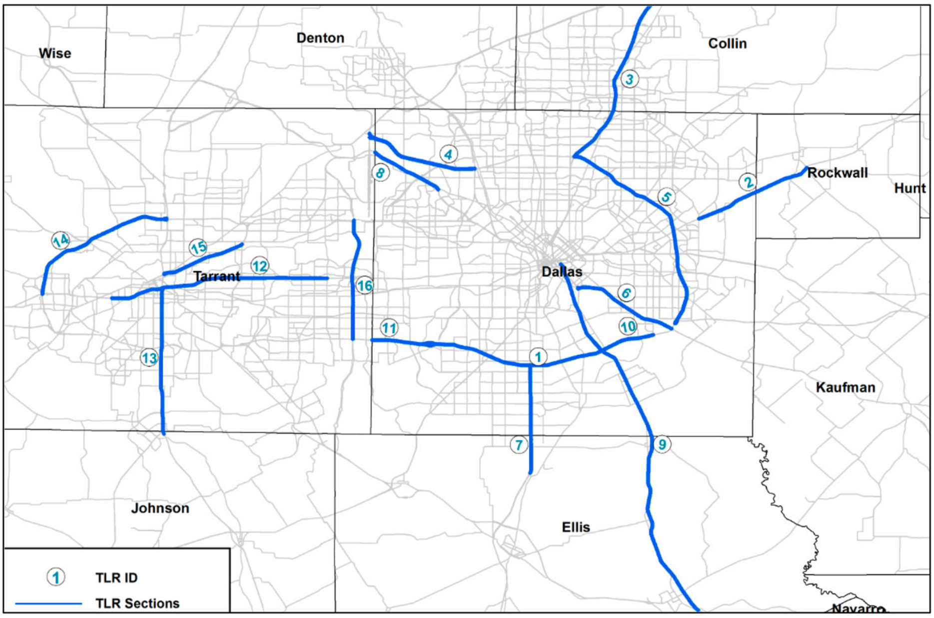


Figure 2. Selected TLR segments.

Table 2. Details of the selected TLRs.

No.	City	Highway	Limits	Length (miles)	Start Date
1	Dallas	IH 20	North Cedar Ridge Drive to IH 45	12.2	11/1/2005
2	Dallas	IH 30	Belt Line to SH 205	9.83	9/21/2015
3	Dallas	US 75	SH 121 south to IH 635	18.00	9/21/2015
4	Dallas	IH 635	Tarrant County Line to IH 35E	8.60	9/21/2015
5	Dallas	IH 635	US 75 to IH 20	19.80	9/21/2015
6	Dallas	US 175	SH 310 to IH 20	8.63	9/21/2015
7	Dallas	IH 35E	US 77 to IH 30	18.0	6/2/2015
8	Dallas	SH 114	Tarrant County Line to SP 348	5.62	9/21/2015
9	Dallas	IH 45	IH 30 to FM 85	38	8/1/2014
10	Dallas	IH 20	IH 45 to St. Augustine Dr.	4.4	8/1/2014
11	Dallas	IH 20	Tarrant County Line to North Cedar Ridge Drive	6.5	8/1/2014
12	Fort Worth	IH 30	Hulen St. (Fort Worth) to Collins St. (Arlington)	18	11/1/2005
13	Fort Worth	IH 35W	IH 30 to SH 174	11.7	1/1/2016
14	Fort Worth	IH 820	IH 30 to IH 35W	11.1	1/1/2016
15	Fort Worth	SH 121	IH 35W to IH 820	6	1/1/2016
16	Fort Worth	SH 360	SH 183 to IH 20	9.1	1/1/2016

Table 3. Number of on-system crashes with and without coordinates in Texas.

Year	With coordinates	Without coordinates	Total number of crashes	Percentage of crashes without coordinates
2011	1,78,464	33,167	2,11,631	16%
2012	1,70,365	35,953	2,06,318	17%
2013	1,90,670	33,619	2,24,289	15%
2014	1,99,851	40,353	2,40,204	17%
2015	2,15,224	39,556	2,54,780	16%

3.2. Before and after observational study

To perform an effective observational study, it was desirable to have at least 12 months of crash data in the 'after' period to conduct a before-after analysis. However, ten of the analysis sections (sections 2, 3, 4, 5, 6, 8, 13, 14, 15, and 16), had fewer than 12 months of 'after' data. There are three approaches that can generally be applied to address the 'after' data gap. All of them have pros and cons as shown in Table 4.

It was decided to use the combined approach for these segments. The ISATe (co-developed by one of the co-authors) was used to compute predicted crash frequencies to provide 12 months of estimated 'after' crash data for analysis (Bonneson, Pratt, Geedipally, & Lord, 2012a; Bonneson et al., 2012b). ISATe provides information about the relationship between roadway geometric design features and safety. It is based on research that quantified the relationship between various design elements (e.g. lane width) or design components (e.g. left-turn bay) and expected average crash frequency. ISATe helps designers make informed judgments about the safety performance of design alternatives. It automates a safety prediction method that consists of various algorithms and equations. It was developed for inclusion as a Part C predictive method for a future edition of the Highway Safety Manual (AASHTO, 2014).

3.3. ISATe analysis

The ISATe analysis task required the following efforts:

1. Each analysis section was divided into freeway segments according to the procedure described in the *ISATe User Manual*. Each segment was required to be homogeneous in its key characteristics such as cross-sectional widths and traffic volume. Segment break points were defined at each location where significant changes occurred or a gore point for an entrance or exit was present.
2. Enter data into the ISATe program to describe the geometric, traffic control, and volume characteristics for each segment.
3. Use ISATe to compute a predicted crash frequency for each identified analysis section.

The locations of segment break points, ramp gore points, and major cross-sectional changes were denoted using placemarks in Google Earth® (as shown in Figure 3) and documented in a keyhole markup language-zipped (kmz) file that contained the coordinates

Table 4. After-data gap approaches.

Approach	Pros	Cons
Extrapolate your limited 'after' data	Immediate analysis/ estimate	May not be accurate because 'before' data does not account for subject treatment or other similar highway characteristics
Combine actual and simulated 'after' data. Data are simulated using ISATe or an SPF	Immediate analysis/ estimate with higher level of confidence	May not fully account for subject treatment
Wait for sufficient 'after' data, at least a year but preferably multiple years	Based on actual observed data	Delayed analysis

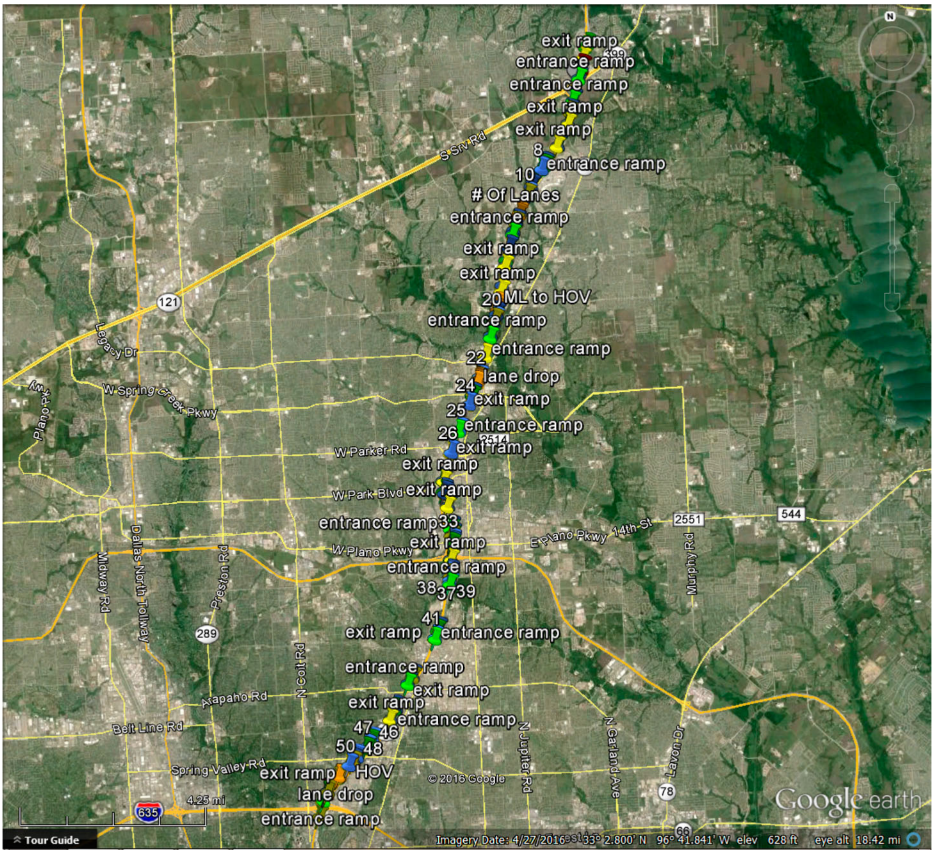


Figure 3. Example of segment break points displayed in Google Earth©.

and labels for the placemarks. Google Earth was also used to obtain measurements of key characteristics for each segment, including the following variables:

- Cross-sectional widths (lane width, shoulder width, median width, etc.).
- Locations of longitudinal barriers.
- Horizontal curve radius and length.
- Locations of ramp gores and weaving sections.

Once the geometric data and traffic volumes were entered into ISATe, the calculation algorithms within the programme were executed. The severity of predicted crashes is recorded as five injury levels (commonly known as the 'KABCO injury scale'): fatality (K), incapacitating injury (A), non-incapacitating injury (B), possible/complaint injury (C), and no injury (O). The fatal injury includes crashes that result in death within 30 days of crash. The incapacitating injury prevents the injured person from normal daily work activities. The non-incapacitating injury includes evidence of significant injury during police reporting. The possible injury indicates complaints of pains or stresses with no physical evidence. No injury crashes, also known as Property Damage Only (PDO), do not involve any injury. The results (using 2014 traffic volumes) are shown in Table 5.

Table 5. Predicted crash frequencies from ISATe for study TLR sections.

Section No.	Crash frequency (crashes/year) by severity				
	K	A	B	C	PDO
2	1.49	3.50	24.98	73.50	239.38
3	5.06	11.30	81.48	322.49	964.36
4	0.70	1.79	12.18	24.94	86.61
5	4.53	11.03	71.97	219.22	697.47
6	0.72	1.82	11.61	20.50	78.10
8	0.74	1.79	12.60	24.64	77.56
13	2.00	5.48	38.39	132.36	420.57
14	1.29	3.43	23.29	53.34	180.78
15	0.88	2.32	16.02	43.78	141.65
16	2.31	5.68	39.67	150.79	510.22

To examine the applicability of ISATe to the freeway system in Dallas-Fort Worth, predicted and observed crash frequencies were compared for eighteen freeway sections. The crash frequencies for severity categories, K, A, B, and C were combined to obtain a fatal-and-injury crash frequency for each section. A comparison of the predicted and observed crash frequencies revealed the following:

- On a section-by-section basis, the ISATe-predicted values differed from the observed values (which represent a sum of CRIS and the TTI geo-located crashes).
- Across the sections, the ISATe prediction agreed closely with observed crash counts for fatal-and-injury crashes. The difference between the two was less than 5% (and less than 1% in an expanded analysis including the years 2012 and 2013 when available).
- Across the sections, ISATe predicted roughly double the number of PDO crashes that were actually observed.
- If the geo-located crashes had not been included in the analysis efforts, ISATe would have appeared to have been over-predicting crashes by a larger margin.

The large difference in predicted and observed PDO crash frequency was likely due to issues with reporting thresholds and practices. Based on the available project resources, only the fatal-and-injury crashes were used in the detailed analysis of TLR safety performance.

The safety prediction models used in ISATe were calibrated using data from the States of Washington, California, and Maine, and the safety effect of TLRs was not explicitly addressed in the modelling efforts due to limited project resources and identification of higher-priority analysis needs (AASHTO, 2014). The topic of truck-lane restrictions was deemed to be ‘low’ importance and ‘high’ level of effort to analyse.

3.4. Empirical Bayes (EB) analysis

The objective of the Empirical Bayes methodology was to estimate the number of crashes that would have occurred at an individual treated site in the after period had a treatment not been implemented. This method accounts for the effect of regression-to-the-mean, changes in traffic volume, and other potential changes in the roadway features during the before and after time periods. In accounting for regression-to-the-mean, the number of crashes expected in the before period without the treatment ($N_{predicted, t, b}$) was a weighted average of information from two sources (AASHTO, 2010):

- The number of crashes observed in the before period at the treated sites ($N_{observed, t, b}$).
- The number of crashes predicted at the treated sites based on reference sites with similar traffic and physical characteristics ($N_{predicted, t, b}$).

Safety Performance Function (SPF) is a statistical model that predicts the mean crash frequency for similar locations with the same characteristics. These characteristics typically include traffic volume and may include other variables such as traffic control and geometric characteristics. The SPF is used to derive the second source of information for the Empirical Bayes estimation – the number of crashes predicted at treated sites based on sites with similar operational and geometric characteristics ($N_{predicted, t, b}$). The calculation method of this current followed the steps used in Hauer's study (Hauer, 1997).

Step 1: Evaluate the predictive values

The predictive models for urban freeway segments can be presented in the following equation:

$$N_{predicted, t, b} = C_L \times (N_{uf, m}) \tag{1}$$

where

$N_{predicted, t, b}$ = predicted crashes (crashes/year)

C_L= Calibration factor (considered as 1 in this study)

$\boldsymbol{N_{uf, m}}$= base crash frequency in urban freeways with 'm' lanes (crashes/year)

The base model for urban freeway with six lanes:

$$N_{uf, 6} = (N_{mv, 6} + N_{sv, 6} + N_{ext, 6} + N_{ent, 6}) \times f_6 \tag{2}$$

where

$N_{uf, 6}$= base fatal and injury crash frequency in urban freeways with six lanes (crashes/year)

$N_{mv, 6}$= multiple vehicle non-ramp fatal and injury crash frequency in urban six-lane freeways (crashes/year)

$N_{sv, 6}$= single vehicle non-ramp fatal and injury crash frequency in urban six-lane freeways (crashes/year)

$N_{ext, 6}$= exit ramp fatal and injury crash frequency in urban six-lane freeways (crashes/year)

$N_{ent, 6}$= entrance vehicle fatal and injury crash frequency in urban six-lane freeways (crashes/year)

f_6= local calibration factor

The SPFs used in this study are based on the Bonneson and Pratt (2009) study.

$$N_{mv, 6} = 0.00352 \times (0.001 \times AADT)^{1.55} \times L \tag{3}$$

$$N_{sv, 6} = 0.119 \times (0.001 \times AADT)^{0.646} \times L \tag{4}$$

$$N_{ent,\,6} = 0.00532 \times (AADT/15000)^{1.33} \times n_{ent} \tag{5}$$

$$N_{ext,\,6} = 0.00064 \times (AADT/15000)^{1.68} \times n_{ext} \tag{6}$$

where

$AADT$ = Annual Average Daily Traffic (vehicle per day or vpd)

L = Length

n_{ent}= number of entrance ramps

n_{ext}= number of exit ramps

The base model for urban freeway with eight lanes:

$$N_{uf,\,8} = (N_{mv,\,8} + N_{sv,\,8} + N_{ext,\,8} + N_{ent,\,8}) \times f_8 \tag{7}$$

where

$N_{uf,\,8}$= base fatal and injury crash frequency in urban freeways with eight lanes (crashes/year)

$N_{mv,\,8}$= multiple vehicle non-ramp fatal and injury crash frequency in urban eight-lane freeways (crashes/year)

$N_{sv,\,8}$= single vehicle non-ramp fatal and injury crash frequency in urban eight-lane freeways (crashes/year)

$N_{ext,\,8}$= exit ramp fatal and injury crash frequency in urban eight-lane freeways (crashes/year)

$N_{ent,\,8}$= entrance vehicle fatal and injury crash frequency in urban eight-lane freeways (crashes/year)

f_8= local calibration factor

The following SPFs are based on the Bonneson and Pratt (2009) study.

$$N_{mv,\,8} = 0.00289 \times (0.001 \times AADT)^{1.55} \times L \tag{8}$$

$$N_{sv,\,8} = 0.113 \times (0.001 \times AADT)^{0.646} \times L \tag{9}$$

$$N_{ent,\,8} = 0.00199 \times (AADT/15000)^{1.33} \times n_{ent} \tag{10}$$

$$N_{ext,\,8} = 0.000482 \times (AADT/15000)^{1.68} \times n_{ext} \tag{11}$$

where

$AADT$ = Annual Average Daily Traffic (vpd)

L = Length

n_{ent}= number of entrance ramps

n_{ext}= number of exit ramps

Step 2: Evaluate the expected values

The empirical Bayes estimate of the expected number of crashes without treatment, $N_{expected,\,t,\,b}$, was computed from the following equation:

$$N_{expected,\,t,\,b} = w \times N_{predicted,\,t,\,b} + (1 - w) \times N_{observed,\,t,\,b} \tag{12}$$

$$w = \frac{1}{1 + k \times \sum_{\substack{all\ study \\ years}} N_{predicted}} \tag{13}$$

where

w = weighted adjustment to be placed on the predictive model estimate; and

k = over-dispersion parameter of the associated SPF used to estimate $N_{predicted}$

It is important to note that with the increment of over-dispersion parameter, k, the weighted adjustment factor decreases; thus, more emphasis is placed on the observed/reported crashes rather than the SPF predicted crash frequency.

The adjusted value of the empirical Bayes estimate, $N_{expected,\ t,\ a}$, is the expected number of crashes in the after period without treatment and is calculated from the following equation:

$$N_{expected,\ t,\ a} = N_{expected,\ t,\ b} \times \frac{N_{predicted,\ t,\ a}}{N_{predicted,\ t,\ b}} \tag{14}$$

The variance of $N_{expected,\ t,\ a}$:

$$Var(N_{expected,\ t,\ a}) = N_{expected,\ t,\ a} \times \frac{N_{predicted,\ t,\ a}}{N_{predicted,\ t,\ b}} \times (1 - w) \tag{15}$$

Step 3: Evaluate the Crash Modification Factor (CMF) and variance of the CMF:

The CMF and its variance can be calculated from the following equations:

$$CMF = \frac{\frac{N_{observed,\ t,\ a}}{N_{expected,\ t,\ a}}}{1 + \frac{Var(N_{expected,\ t,\ a})}{N^2_{expected,\ t,\ a}}} \tag{16}$$

$$Var(CMF) = CMF^2 \frac{\frac{1}{N_{observed,\ t,\ a}} + \frac{Var(N_{expected,\ t,\ a})}{N^2_{expected,\ t,\ a}}}{\left[1 + \frac{Var(N_{expected,\ t,\ a})}{N^2_{expected,\ t,\ a}}\right]^2} \tag{17}$$

Table 6 lists the values of site-specific CMF, standard deviations, and 95% confidence interval (CI) of the CMF from this method. For fatal and injury crashes, four of the sections show positive safety effectiveness (from Table 6). For fatal and injury crashes, four of the TLR sections show positive safety effectiveness. Out of four of those sections, two of them do not contain 1.0 in the 95% confidence interval, which suggests that these two TLR sections had a positive safety effect. Based on the nature of the countermeasure however, it was also required to evaluate the CMFs for large truck-involved crashes. For fatal and injury crashes, ten of the segments show positive safety effectiveness (from Table 7). For fatal and injury crashes that involved large trucks, ten of the TLR sections

Table 6. Crash modification factor (CMF) and 95% confidence interval (CI) of the CMF values for the treatment sites using empirical Bayes (EB) method (fatal and injury crashes).

Segment no.	*CMF*	Standard deviation of the CMF [*sd*(*CMF*)]	95% *CI of CMF*
1	0.74	0.08666	(0.57, 0.91)
2	1.04	0.17338	(0.70, 1.38)
3	1.64	0.09919	(1.45, 1.83)
4	1.86	0.33785	(1.20, 2.52)
5	1.3	0.07635	(1.15, 1.45)
6	1.79	0.30593	(1.19, 2.39)
7	1.33	0.13798	(1.06, 1.6)
8	1.29	0.27163	(0.76, 1.82)
9	1.11	0.13033	(0.86, 1.37)
10	1.35	0.34364	(0.67, 2.02)
11	1.01	0.14803	(0.72, 1.3)
12	0.64	0.06079	(0.52, 0.76)
13	1.34	0.13915	(1.06, 1.61)
14	1.54	0.20688	(1.13, 1.94)
15	0.77	0.17383	(0.43, 1.11)
16	0.98	0.08726	(0.81, 1.15)

Table 7. CMF and 95% CI of the CMF values for the treatment sites using EB method (large truck-involved fatal and injury crashes).

Segment no.	*CMF*	*sd*(*CMF*)	95% *CI of CMF*
1	0.67	0.17161	(0.33, 1.00)
2	0.71	0.30492	(0.11, 1.31)
3	1.40	0.38807	(0.64, 2.16)
4	0.48	0.33165	(0.00, 1.13)
5	1.65	0.38662	(0.89, 2.41)
6	0.72	0.44274	(0.00, 1.59)
7	1.37	0.43374	(0.52, 2.22)
8	0.60	0.36854	(0.00, 1.33)
9	1.24	0.42946	(0.40, 2.08)
10	1.11	0.53473	(0.06, 2.15)
11	1.04	0.43539	(0.19, 1.89)
12	0.61	0.23357	(0.15, 1.07)
13	0.44	0.18893	(0.07, 0.81)
14	0.40	0.28137	(0.00, 0.95)
15	0.44	0.30454	(0.00, 1.04)
16	0.63	0.32743	(0.00, 1.28)

Table 8. CMF and 95% CI of the CMF values for six-lane and eight-lane roadways.

Sites	*CMF*	*sd*(*CMF*)	95% *CI of CMF*
All fatal and injury crashes			
Six-lane roadways	1.05	0.13339	(0.79, 1.31)
Eight-lane roadways	1.32	0.11915	(1.08, 1.55)
Large truck-involved fatal and injury crashes			
Six-lane Roadways	0.68	0.32240	(0.05, 1.28)
Eight-lane Roadways	1.17	0.36623	(0.45, 1.89)

show positive safety effectiveness. While considering the 95% confidence interval, only two sections show positive safety effectiveness.

Table 8 lists the aggregated CMF and 95% of CMF by combining the sections into two broader facility types: (1) six-lane roadways, (2) eight-lane roadways. For all fatal and injury crashes, the CMF for both six-lane and eight-lane roadways were greater than

1. For large truck-involved fatal and injury crashes, the CMF of six-lane roadways was 0.68. It should be noted that large truck related crashes were only 5% and 7% of the fatal and injury (F + I) crashes for six-lane roadways and eight-lane roadways, respectively.

This study was undertaken to evaluate the safety performance of the truck lane restrictions that have been implemented in the North Texas region. The research team analysed 16 TLR sections where this treatment had been implemented. For safety effectiveness analysis, it is always hard to get three years before and three years after data. The current study also has similar limitations. For immediate safety effectiveness analysis, sophisticated predictive tools could be used in estimating 'after' year crashes. This study developed a framework of using ISATe to supplement the limited after year crash data. This framework would be useful for other similar effectiveness measurement.

4. Results and discussion

Overall, TLRs showed positive safety effectiveness for large truck-involved fatal and injury crashes for six-lane roadways, which is the majority of freeways in most urban areas including the Dallas-Fort Worth region. However, these TLRs along with newly implemented ones should be reevaluated in the future to not only expand the after dataset but also increasing the likelihood of observing larger truck crashes on these facility types.

The findings from the empirical Bayes analysis are:

- For fatal and injury crashes, four of the TLR sections show positive safety effectiveness. Out of four of those sections, two of them do not contain 1.0 in the 95% confidence interval, which suggests that these two TLR sections had a positive safety effect.
- The lowest CMF was found for Section 14 (11.1 miles long corridor on Fort Worth). The CMF for this corridor is 0.4, which indicates a 60% reduction of large truck-involved fatal and injury crashes. Section 13 and Section 15 also show very high safety effectiveness. Both of these sections show around 56% large truck-involved fatal and injury crash reduction due to the implementation of the TLRs.
- Some the sections did not show positive safety effectiveness. These sites require more in-depth investigation, which is currently out of scope of the present study. Future studies can reexamine the sites based on the data availability of the after years.
- For fatal and injury crashes that involved large trucks, ten of the TLR sections show positive safety effectiveness. While considering the 95% confidence interval, only two sections show positive safety effectiveness.
- Overall, TLRs show positive safety effectiveness for large truck-involved fatal and injury crashes for six-lane roadways. It should be noted that large truck related crashes were only 5% of these fatal and injury crashes.
- Overall, TLRs show no positive safety effectiveness for eight-lane roadways for large truck-involved fatal and injury crashes. It should be noted that large truck related crashes were only 7% of these fatal and injury crashes.

The TxDOT Dallas and Fort Worth Districts have the majority of current truck lane restriction-designated freeway sections throughout the state so it is critical to have a good understanding of their expected safety effectiveness. It is also worth noting that although large truck related crashes are not frequent, they tend to have higher societal impacts and costs, especially in congested urban areas. Higher costs may be associated with more injuries because they tend to be more severe crashes, have longer durations (which may induce more secondary crashes), more emissions, more vehicular and possible infrastructure damage, lost cargo costs, and higher value of time for truckers.

This study analysed 16 TLR sections in Texas where this treatment had not been implemented. This study used a larger number of study sites. Previous studies in Texas have considered only one or two pilot sites and were based on very limited before and after periods (< 9 months). Another uniqueness of this study is the usage of the enhanced ISATe for supplementing the limited 'after' crash data. Future studies can consider adding more sites for a robust overall CMF for TLR implementation on urban corridors.

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