# A mechanistic approach for evaluating the safety impacts of left-turn lane offsets

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## ABSTRACT

The introduction of positive offsets for left-turn lanes is a low-cost countermeasure for improving road safety at signalized intersections. Positive left-turn lane offsets provide better line-of-sight of the opposing. The costs range from a low of $200/approach to a high of $15,000/approach. Researchers have reviewed the safety benefits using empirical Bayesian before-and-after studies and have found that there exists positive safety impacts through the reduction of rear-end and angled crashes. However, these studies did not assess whether the presence of the countermeasure and its interaction with various traffic factors, such as left-turn movement volumes and truck percentages, had statistically significant effects due to the lack of available.

A more mechanistic methodology is needed to assess the safety benefits this countermeasure. Microscopic simulation models provide a basis for this mechanistic approach since they are govern by underlying psycho-physical driver behavioural models. The integration of simulation and surrogate safety performance measures, such as time-to-collision, allows for the assessment of safety benefits in-lieu of observational crash data. A factorial experiment was used to assess the statistical significance of main effects and interaction effects. It was found that the main effects of the countermeasure, major AADT, minor AADT, and left-turn lane volumes had statistically significant impacts on total, merging, rear-end, and lane-change conflicts. The presences of the countermeasure improved safety for all types of conflicts. This study provided practitioners insight that specific traffic-related factors must be considered when evaluating the implementation of positive left-turn lane offsets.

## INTRODUCTION

In typical intersections the left-turn lanes are directly opposite of one another, which imposes restrictions on the sight distances for the “left-turn lane” driver leading to difficulties in assessing acceptable gaps on the opposing approach; this is especially more pronounced for older drivers who have greater difficulties in judging gaps *(1).* When these intersections have permissive left-turns then the uncertainty in gaps may lead to collisions between left-turning vehicles and the vehicles on the opposing approach. AASHTO’s policy *(2)* on geometric design suggested the use of positive left-turn lane offsets to improve sight distances when medians are greater than 5.5 meters (18 feet). This geometric design change is achieved by adding a strip of paint on the right side of the left-turn lane. The painted strip ranges from 0.15 meter (0.5 feet) to 0.91 meter (3 feet) in width based on AASHTO’s guidelines. Researchers [*(3),(4)*] have found that the wider the offset the greater the increase in the available sight distance. Easa and Muhammad (5) determined that the desired offset for passenger cars is 0.6 meters. While for trucks the desired offset is 1.1 meters. Figure 1 shows the typical geometric design of an intersection with and with-out positive left-turn lane offsets.

The implementation of positive offsets is a low-cost safety countermeasure. Persaud et. al. (6) has estimated that the costs range from a low of $200/approach, if only repainting is needed, to a high of $15,000/approach, if minor reconstruction is required. These estimates are based on modifying an existing left-turn bay with a length of 45.7 meters (150 feet). The researchers used empirical-Bayesian models to assess the safety implication of this countermeasure based on data from 92 sites in Nebraska, 13 sites from Florida, and 12 sites from Wisconsin. The models fitted from Nebraska and Florida data showed minimum impacts on safety. However, the Wisconsin analysis showed that total accidents, injury accidents, left-turn accidents, and rear-end accidents decreased by over 30 percent. A major limitation of their study is that their empirical Bayesian accident prediction models are only a function of the major road AADT. This is due to data limitations from their study sites.

Khattak et. al (7) also researched the impacts of left-turn lane offsets from data observed at 8 intersections in Lincoln, Nebraska (6 treated and 2 untreated). A Poisson accident model was fitted to the data. The results of their study showed a 24% decrease in property damage accidents and a 40% decrease in total accidents. However, an analysis by Naik (8) using the same data, but fitting an empirical Bayesian model, showed only 1.5 percent reduction in total accident. Both the Poisson and empirical Bayesian accident prediction models were functions of the major and minor AADT. Poisson regression models are generalize linear models of the form:

$$\mathrm{Log}[E(Y|x_i)] = a + bx_i \qquad (1)$$

where, Y = expected number of accidents
$x_i$ = attributes such as Major AADT or Minor AADT

Equation 1 is used to predict accidents when the underlying accident distribution follows a Poisson distribution. The empirical Bayesian accidents prediction models is a data fusion of site-specific observed accident data with either the Poisson or Negative Binomial prediction model, and can be expressed as:

$$E(k|K) = \alpha\, E(k) + (1-\alpha)\, K \qquad (2)$$

Where, K = is the site-specific historical accident rate
E(k) = the predicted accident rate based on either a Poisson or Negative Binomial model
α = is the weight given to the prediction model (value from 0 to 1)

A summary of all three aforementioned studies is found in Table 1.

A major limitation in all these observational studies is they did not assessed whether the presence of the countermeasure and its interaction with various traffic factors, such as left-turn movement volumes and truck percentages, had statistically significant effects. This is due to the lack of available data to fit meaningful empirical Bayesian and Poisson accident prediction models for these interaction factors. As Easa and Muhammad (5) noted in their research, cars and trucks have different sight distance requirements for the left-turn movement. In lieu of sufficient observed data, microscopic traffic simulation may be an alternative in determining these interaction effects. The basic objective of this paper is to determine the statistical significance of the left-turn lane offset (countermeasure) and its interaction with traffic factors, such as major AADT, minor AADT, truck percentages and left-turn movement volumes, on various types of accidents (e.g. rear-end, angled, and merging).

## METHODOLOGY

Gettman and Head (9), in 2003, found that certain microscopic traffic simulation platforms (e.g. VISSIM and PARAMICS) allowed for the estimation of safety performance through simulated vehicle tracking data. Simulation also provides a way to investigate different traffic scenarios, when vehicle tracking data is not available for these specific traffic conditions of interest. In 1987, Hyden described a ‘safety continuum’ as ‘vehicle interactions’ categories with corresponding crash risks, as illustrated in Figure 2. The use of surrogate safety performance measures, such as “time to collision” (TTC) *(11),* “post encroachment time” (PET) (*12*), “deceleration rate to avoid the crash” (DRAC) (*13*), can be used to map this ‘safety continuum’. Within this ‘safety continuum’ there is a subset of ‘vehicle interactions’ that can be classified as ‘conflicts’. Accidents (crashes) are highly correlated with ‘conflicts’ since they are a subset within the ‘conflicts’ category.

Gettman et. al (14) developed at Surrogate Safety Assessment Model (SSAM) for the FHWA that can be used to estimate conflicts from simulated vehicle trajectory data using various simulation packages such as VISSIM, PARAMICS, TEXAS or AIMSUM. In this paper, the SSAM program is used in conjunction with VISSIM. This simulation package is governed by underlying car-following, lane-changing, and gap-acceptance models.

### SSAM Program

The SSAM program is open sourced (freeware) and can be downloaded online from the FHWA website. Conflicts are based on TTC and PET thresholds of 1.5 seconds and 5 seconds, respectively. Hayward (11) proposed the use of time to collision (TTC) and defined it as “*the time require for two vehicles to collide if they continue at their present speeds and on the same path*”. For rear-end collisions TTC can be defined mathematically as:

$$TTC_{i,t} = [(x_{i-1,t} – x_{i,t}) – L_{i-1,t}] / (u_{i,t} – u_{i-1,t}) \qquad (3)$$

where t = time interval
x = position of the vehicles (i = response vehicle, i-1 = stimulus vehicle)
L = length of the stimulus vehicle
u = velocity

Figure 3 illustrates the TTC concept for rear-end conflicts. For angled or merging collisions TTC can be described mathematically as:

$$TTC_{i,t} = D_{i,t} / V_{i,t} \qquad (4)$$

Where $D_{i,t}$ = the projected distance to the point of collision on the major approach
$V_{i,t}$= the velocity of the reaction vehicle

PET is defined as the time difference between the time the stimulus or reaction vehicle leaves a potential conflict zone (***$t_1$***) and the time the other vehicle (e.g. reaction or stimulus) vehicle arrives at the same conflict zone (***$t_2$***). Mathematically, PET can be defined as:

$$PET = t_2 - t_1 \tag{5}$$

An illustration of the PET concept is shown in Figure 4.

The rear end angle and crossing angle were set at 30 degrees and 85 degrees, respectively. A conflict is consider a 'rear-end' conflict if the angle of approach of the following (reaction) vehicle is less than or equal to 30 degrees. A conflict is consider a "lane change" conflict if the angle of approach of the following (reaction) vehicle is between 30 degrees and 85 degrees. Finally, if the angle of approach is greater than and 85 degrees the conflict is consider a crossing conflict, as illustrated in Figure 5.

## VISSIM Simulation Platform

VISSIM uses psycho-physical car following models, developed by Wiedemann [(15),(16), (17)]. Wiedemann's car-following model separates driver behavior into the following four types of regimes: i) un-influenced driving, ii) closing process, iii) following process, and iv) emergency braking (illustrated in Figure 6).

In the un-influence driving regime, the response (following) driver tries to reach his/her's desired speed once there is no stimulus (lead) vehicle at a reasonable distance (e.g. 150 meters) or when the distance between these vehicles is decreasing and the 'long distance speed difference' (SDV) threshold has not be surpassed. When the distance between the stimulus and response vehicle is less than a distance of 150 meters and the SDV threshold has been exceeded, then the following (response) vehicle is in the closing process. The response vehicle will begin to decelerate since the driver realizes that he/she is approaching a slower moving vehicle. During the following regime, the response and stimulus vehicles have similar speeds and acceleration/deceleration rates oscillate within a narrow bandwidth. The boundary between the closing and following regimes occurs when the 'speed differential' (DV) is less than the spacing threshold (SDX). The response vehicle enters the emergency braking regime when the spacing between the stimulus and response vehicle is less than the minimum desired distance for a standing vehicle (AX).

In the lane-change model, the driver uses a hierarchical process to determine whether to change lanes, and this process is as follows (17):

i) Is there a desire to change lanes?

ii) Is traffic conditions better in the target lane compared to the current lane?
iii) Is the lane change movement to the target lane possible?

Figure 7 illustrates the decision process of the lane change maneuver.

Lane changes are either mandatory or voluntary. For mandatory lane changes, the drivers have to change lane in order to maintain their routes. The desire for a voluntary lane change is triggered when the response vehicle is obstructed by a slower moving stimulus vehicle. The driver then evaluates through the hierarchal process whether to execute the lane change maneuver.

VISSIM uses two strategies to model the gap acceptance maneuvers, called the ‘priority rules’ and the ‘conflict areas’. For the ‘priority rules’, the user defines major and minor priority movements and define a minimum acceptable gap time (e.g. critical gap). This model is deterministic since the driver will accept the gap if the available gap exceeds the critical gap and vise-versa. ‘Conflict areas’ have been introduced in VISSIM to provide a more realistic driver gap-acceptance behavioural model. VISSIM detects overlapping conflict areas for vehicle pair based on the geometry of the roadway. The user defines major and minor movements that establish the right-of-way for the different vehicle movement types. The driver in a lower priority movement observes the other ‘conflicting movement’ drivers. The driver proceeds with the gap acceptance based on the available gaps in the conflicting traffic steam, the situation behind the conflict area, and his/her current speed and acceleration profile.

To ensure the validity and reliability of results from simulation the parameters that govern underlying car-following, lane-changing and gap-acceptance models must be calibrated and validated against observed traffic data (18). Cunto (19) had previous calibrated VISSIM driver behavior parameters for intersections using NG-SIM vehicle tracking data from Lankershim Boulevard in California. This study uses these driver behavior model parameters from Cunto’s (19) calibration research.

## CASE STUDY

Two intersections were designed with and without the left-turn lane offset. This offset was set at 1.1 meters in order to satisfy the desired offset requirements for trucks (5). Both the major and minor approaches had two-lanes in each direction and dedicated left-turn lanes. All lanes widths were 3.5 meters and the left-turn lane was approximately 53 meters in length. The signal timing followed a 100 second cycle and was fully actuated using a NEMA controller. Figure 8 is a screenshot of the no left-turn offset scenario.

In this paper, the countermeasure and four traffic-related factors are analyzed. Using factorial experimental design, 34 scenarios made up of combinations of the factors are sufficient to provide meaningful inference on statistical significance. 10 random seeds for each scenario were undertaken in order to account for the randomness in the simulation. Table 2 shows the various factors assessed in this paper. Table 3 shows the resultant conflict outputs using the 34 scenarios for merging (angled), rear-end, and crossing conflicts.

## DATA ANALYSIS

Linear regression modeling was using on the data from Table 3 to test the significance of the response variables (e.g. merging, rear-end, crossing, and total conflicts). Table 4 shows the results for total conflicts.

For total conflicts, which includes merging, rear-end, and crossing conflicts, the statistically significant main effects were the countermeasure, major approach AADT, minor approach AADT, and left-turn lane volumes. For two-factor interactions, the interaction between the countermeasure and major AADT and between the major AADT and left-turn lane volumes was statistically significant at the alpha 5% level. It should be noted that truck percentages was not significant. Three-factor and greater interactions were assumed to be not important and were not tested in this study. Table 5 shows the regression data for merging (angled) conflicts.

For merging or angled conflicts, the significant main effects were the countermeasure, major AADT, minor AADT, and left-turn lane volumes. Angled conflicts had the same significant two-factors as total conflict with the addition of Major AADT x Left-turn volume and truck percentages x left-turn volume. For angled conflicts truck percentages have an impact. Table 6 shows the regression data for rear-end conflicts.

The rear-end regression modeling showed that rear-end conflicts are affect by the same main factors as merging and total conflicts. However, for rear-end conflicts only the interaction factor of major AADT and left-turn volume had statistical significance. Table 7 shows the regression data for crossing (lane change) conflicts.

For the crossing (lane change) conflicts, the countermeasure, major AADT, minor AADT, and left-turn lane volume were statistically significant. In terms of two-factor interactions only the countermeasure x major AADT, countermeasure x minor AADT and major AADT x left-turn lane volumes were statistically significant at the 95% confidence interval. In all types of conflicts the presence of the left-turn lane offset had positive effects on safety.

## CONCLUSIONS

The following are observations that can be drawn from the data analysis:

- The statistically significant main factors were “left-turn lane offset presence”, major AADT, minor AADT, and left-turn lane volume for all types of conflicts [e.g. total, merging (angled), rear-end, and crossing (lane-change)].
- The presence of the positive left-turn lane offsets had a positive effect on safety, reducing the conflict.
- For total, angled, and crossing conflicts the interaction between the countermeasure and major AADT were significant.

The positive safety benefit of positive left-turn lane offsets found in this study confirms the findings of previous research in the literature. The author concludes that care must be taken into consideration of the traffic scenario for the specific signalized intersection when evaluating the implementation of left-turn lane offsets. The use of surrogate safety measures in conjunction with microscopic simulation promises to give practitioner a method to gauge the relative safety benefit or dis-benefit before implementing the positive left-turn lane offsets.

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## TABLES

### TABLE 1: Summary of previous literature on the safety implication of left-turn lane offsets

| | | | | Findings (percentage reduction) | | | |
|---|---|---|---|---|---|---|---|
| **Study** | **Origin of Data** | **Sample Size** | **Model Type** | **Total** | **Injury** | **crossing (angled)** | **rear-end** |
| Persuad et. al. (6) | Nebraska | 92 | Empirical Bayes | 3.4 | 0.2 | 11.4 | -5.3 |
| | Florida | 13 | Empirical Bayes | -0.5 | **6.2** | **-45.0** | **-6.9** |
| | Wisconsin | 12 | Empirical Bayes | **33.8** | **35.6** | **38.0** | **31.7** |
| Khattak et. al. (7) | Nebraska | 8 | Poisson | **40.0** | **27.0** | | |
| Naik (8) | Nebraska | 8 | Empirical Bayes | **1.5** | | | |

Bold denotes effects were significant at the 95% confidence level

### TABLE 2: Factors and their different levels

| | | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|---|
| **Level\Factor** | | **Geometric Design** | **Major Road (vehicle/h/lane)** | **Minor Road (veh/h/lane)** | **Truck %** | **LT volume percentage (% of Major)** |
| High | 1 | with offset | 1500 | 500 | 15 | 30 |
| Low | -1 | without offset | 500 | 100 | 2 | 10 |
| Center | 0 | N/A | 1000 | 300 | 8.5 | 20 |

## TABLE 3: Conflict Response and Corresponding Scenario

| | | | | | | | Conflicts | | |
|---|---|---|---|---|---|---|---|---|---|
| Run | A | B | C | D | E | Total | Angled | RearEnd | LaneChange |
| 1 | 1 | -1 | -1 | -1 | -1 | 9.8 | 2.1 | 5.1 | 2.6 |
| 2 | 1 | 1 | -1 | -1 | -1 | 25.4 | 8.1 | 11.5 | 5.8 |
| 3 | 1 | -1 | 1 | -1 | -1 | 16.6 | 2.8 | 9.5 | 4.3 |
| 4 | 1 | 1 | 1 | -1 | -1 | 31.7 | 10 | 15.3 | 6.4 |
| 5 | 1 | -1 | -1 | 1 | -1 | 9.7 | 2.6 | 4.8 | 2.3 |
| 6 | 1 | 1 | -1 | 1 | -1 | 31.3 | 9.6 | 12.7 | 9 |
| 7 | 1 | -1 | 1 | 1 | -1 | 18 | 4.6 | 9.7 | 3.7 |
| 8 | 1 | 1 | 1 | 1 | -1 | 48.2 | 15.1 | 23 | 10.1 |
| 9 | 1 | -1 | -1 | -1 | 1 | 10.9 | 3.9 | 4.2 | 2.8 |
| 10 | 1 | 1 | -1 | -1 | 1 | 48.4 | 20.5 | 17.1 | 10.8 |
| 11 | 1 | -1 | 1 | -1 | 1 | 16.1 | 2.9 | 8.2 | 5 |
| 12 | 1 | 1 | 1 | -1 | 1 | 63.3 | 24.9 | 25.6 | 12.8 |
| 13 | 1 | -1 | -1 | 1 | 1 | 13.2 | 4.7 | 4.4 | 4.1 |
| 14 | 1 | 1 | -1 | 1 | 1 | 56.9 | 16.7 | 25.2 | 15 |
| 15 | 1 | -1 | 1 | 1 | 1 | 22.4 | 6.8 | 9.6 | 6 |
| 16 | 1 | 1 | 1 | 1 | 1 | 62 | 18.7 | 29 | 14.3 |
| 17 | -1 | -1 | -1 | -1 | -1 | 9.8 | 1.6 | 5.4 | 2.8 |
| 18 | -1 | 1 | -1 | -1 | -1 | 43 | 10.8 | 19.4 | 12.8 |
| 19 | -1 | -1 | 1 | -1 | -1 | 19.6 | 2.7 | 10.1 | 6.8 |
| 20 | -1 | 1 | 1 | -1 | -1 | 57.4 | 14 | 24.7 | 18.7 |
| 21 | -1 | -1 | -1 | 1 | -1 | 10.7 | 2.2 | 4.9 | 3.6 |
| 22 | -1 | 1 | -1 | 1 | -1 | 31.3 | 9.6 | 12.7 | 9 |
| 23 | -1 | -1 | 1 | 1 | -1 | 22.4 | 5.4 | 9.6 | 7.4 |
| 24 | -1 | 1 | 1 | 1 | -1 | 63 | 14.6 | 29.3 | 19.1 |
| 25 | -1 | -1 | -1 | -1 | 1 | 11.9 | 3.2 | 4.4 | 4.3 |
| 26 | -1 | 1 | -1 | -1 | 1 | 60.8 | 24.6 | 19.9 | 16.2 |
| 27 | -1 | -1 | 1 | -1 | 1 | 19.9 | 4 | 8.8 | 7.1 |
| 28 | -1 | 1 | 1 | -1 | 1 | 84.7 | 26.4 | 34.7 | 23.6 |
| 29 | -1 | -1 | -1 | 1 | 1 | 14.4 | 4.6 | 5.3 | 4.5 |
| 30 | -1 | 1 | -1 | 1 | 1 | 74.3 | 20.5 | 34.4 | 19.4 |
| 31 | -1 | -1 | 1 | 1 | 1 | 26.7 | 8.2 | 11.3 | 7.2 |
| 32 | -1 | 1 | 1 | 1 | 1 | 103.7 | 23.6 | 52 | 28.1 |
| 33 | 1 | 0 | 0 | 0 | 0 | 25.6 | 8.9 | 10.5 | 6.2 |
| 34 | -1 | 0 | 0 | 0 | 0 | 75 | 11 | 43.9 | 20.7 |

## TABLE 4: Regression for Total Conflicts

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 36.41 | 1.57 | 23.17 | 0.00 |
| **A** | **-6.44** | **1.57** | **-4.10** | **0.00** |
| **B** | **19.79** | **1.62** | **12.22** | **0.00** |
| **C** | **6.68** | **1.62** | **4.13** | **0.00** |
| D | 2.47 | 1.62 | 1.52 | 0.15 |
| **E** | **7.55** | **1.62** | **4.66** | **0.00** |
| **AB** | **-4.13** | **1.62** | **-2.55** | **0.02** |
| AC | -2.14 | 1.62 | -1.32 | 0.20 |
| AD | 0.00 | 1.62 | 0.00 | 1.00 |
| AE | -1.15 | 1.62 | -0.71 | 0.49 |
| BC | 2.23 | 1.62 | 1.38 | 0.19 |
| BD | 1.03 | 1.62 | 0.64 | 0.53 |
| **BE** | **6.37** | **1.62** | **3.93** | **0.00** |
| CD | 1.10 | 1.62 | 0.68 | 0.50 |
| CE | 0.07 | 1.62 | 0.04 | 0.97 |
| DE | 1.13 | 1.62 | 0.70 | 0.49 |

Bold denote statistical significance at the 95% confident interval

## TABLE 5: Regression for Merging (Angled) Conflicts

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 10.29 | 0.26 | 39.75 | 0.00 |
| **A** | **-0.71** | **0.26** | **-2.74** | **0.01** |
| **B** | **6.42** | **0.27** | **24.05** | **0.00** |
| **C** | **1.23** | **0.27** | **4.61** | **0.00** |
| D | 0.16 | 0.27 | 0.59 | 0.57 |
| **E** | **3.08** | **0.27** | **11.52** | **0.00** |
| **AB** | **-0.59** | **0.27** | **-2.23** | **0.04** |
| AC | -0.13 | 0.27 | -0.49 | 0.63 |
| AD | 0.07 | 0.27 | 0.26 | 0.80 |
| AE | -0.31 | 0.27 | -1.17 | 0.26 |
| BC | 0.45 | 0.27 | 1.69 | 0.11 |
| **BD** | **-0.84** | **0.27** | **-3.14** | **0.01** |
| **BE** | **2.18** | **0.27** | **8.17** | **0.00** |
| CD | 0.43 | 0.27 | 1.59 | 0.13 |
| CE | -0.18 | 0.27 | -0.68 | 0.51 |
| **DE** | **-0.57** | **0.27** | **-2.13** | **0.05** |

Bold denote statistical significance at the 95% confident interval

## TABLE 6: Regression for Rear-end Conflicts

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 16.36 | 1.16 | 14.14 | 0.00 |
| **A** | **-3.10** | **1.16** | **-2.68** | **0.02** |
| **B** | **8.48** | **1.19** | **7.11** | **0.00** |
| **C** | **3.72** | **1.19** | **3.12** | **0.01** |
| D | 1.69 | 1.19 | 1.42 | 0.17 |
| **E** | **2.70** | **1.19** | **2.26** | **0.04** |
| AB | -1.98 | 1.19 | -1.66 | 0.11 |
| AC | -0.91 | 1.19 | -0.77 | 0.45 |
| AD | -0.32 | 1.19 | -0.27 | 0.79 |
| AE | -0.72 | 1.19 | -0.60 | 0.55 |
| BC | 1.33 | 1.19 | 1.11 | 0.28 |
| BD | 1.44 | 1.19 | 1.21 | 0.24 |
| **BE** | **2.88** | **1.19** | **2.42** | **0.03** |
| CD | 0.60 | 1.19 | 0.50 | 0.62 |
| CE | 0.30 | 1.19 | 0.25 | 0.80 |
| DE | 1.33 | 1.19 | 1.12 | 0.28 |

Bold denote statistical significance at the 95% confident interval

## TABLE 7: Regression for Crossing (Lane-change) Conflicts

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 9.78 | 0.43 | 22.60 | 0.00 |
| **A** | **-2.65** | **0.43** | **-6.12** | **0.00** |
| **B** | **4.89** | **0.45** | **10.97** | **0.00** |
| **C** | **1.74** | **0.45** | **3.90** | **0.00** |
| D | 0.63 | 0.45 | 1.40 | 0.18 |
| **E** | **1.78** | **0.45** | **3.98** | **0.00** |
| **AB** | **-1.56** | **0.45** | **-3.49** | **0.00** |
| **AC** | **-1.10** | **0.45** | **-2.47** | **0.02** |
| AD | 0.25 | 0.45 | 0.56 | 0.58 |
| AE | -0.11 | 0.45 | -0.25 | 0.80 |
| BC | 0.46 | 0.45 | 1.02 | 0.32 |
| BD | 0.43 | 0.45 | 0.97 | 0.35 |
| **BE** | **1.31** | **0.45** | **2.93** | **0.01** |
| CD | 0.07 | 0.45 | 0.17 | 0.87 |
| CE | -0.05 | 0.45 | -0.11 | 0.91 |
| DE | 0.38 | 0.45 | 0.84 | 0.41 |

Bold denote statistical significance at the 95% confident interval

## FIGURES

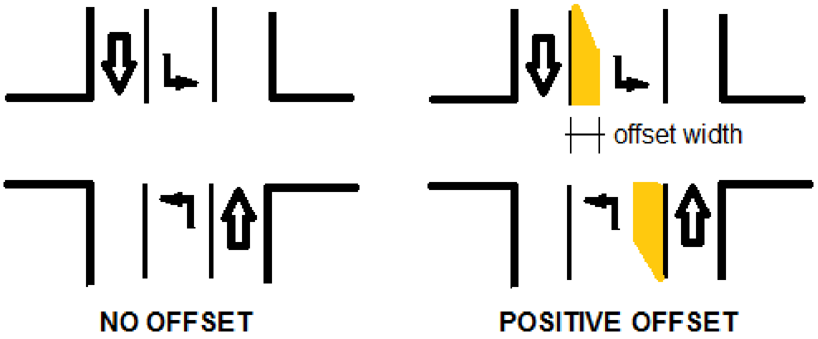


Figure 1: Positive left-turn lane offset versus regular intersection design

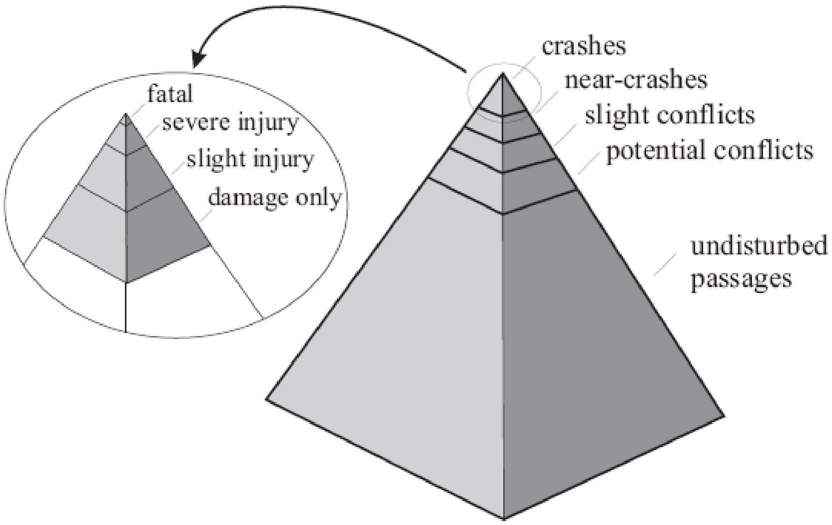


**Figure 2 The Hyden Safety Pyramid**

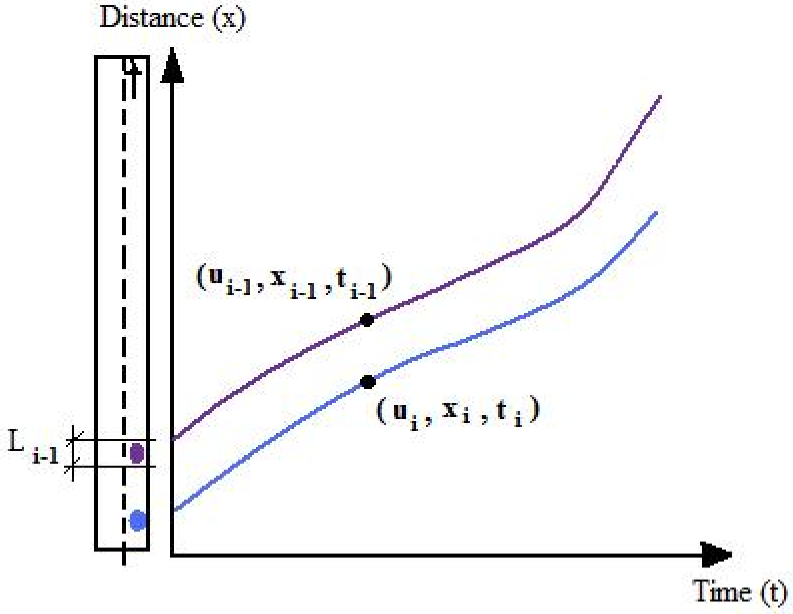


FIGURE 3: Rear-end TTC Space-time diagram

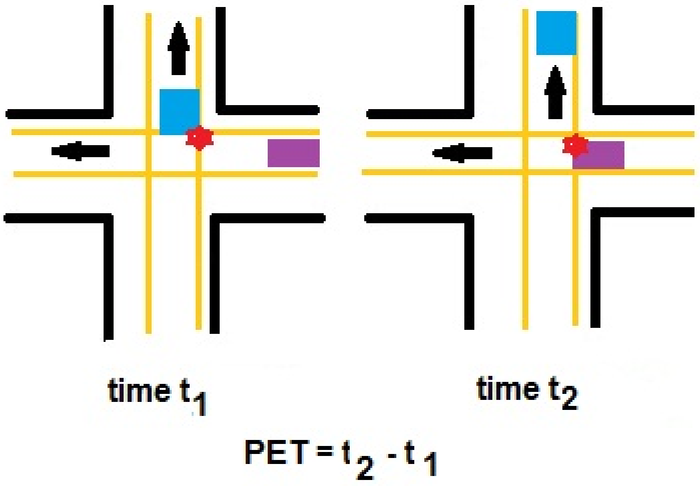
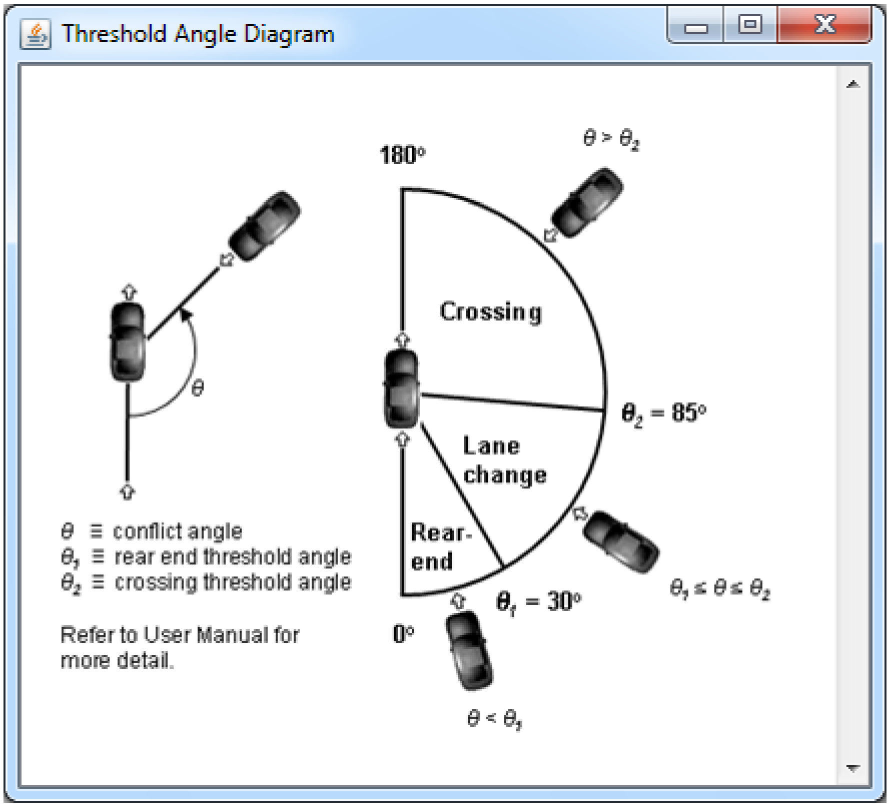


FIGURE 4: Conceptual diagram of PET



$\theta$ ≡ conflict angle
$\theta_1$ ≡ rear end threshold angle
$\theta_2$ ≡ crossing threshold angle

Refer to User Manual for more detail.

**FIGURE 5: Conflict Type Threshold Diagram (14)**

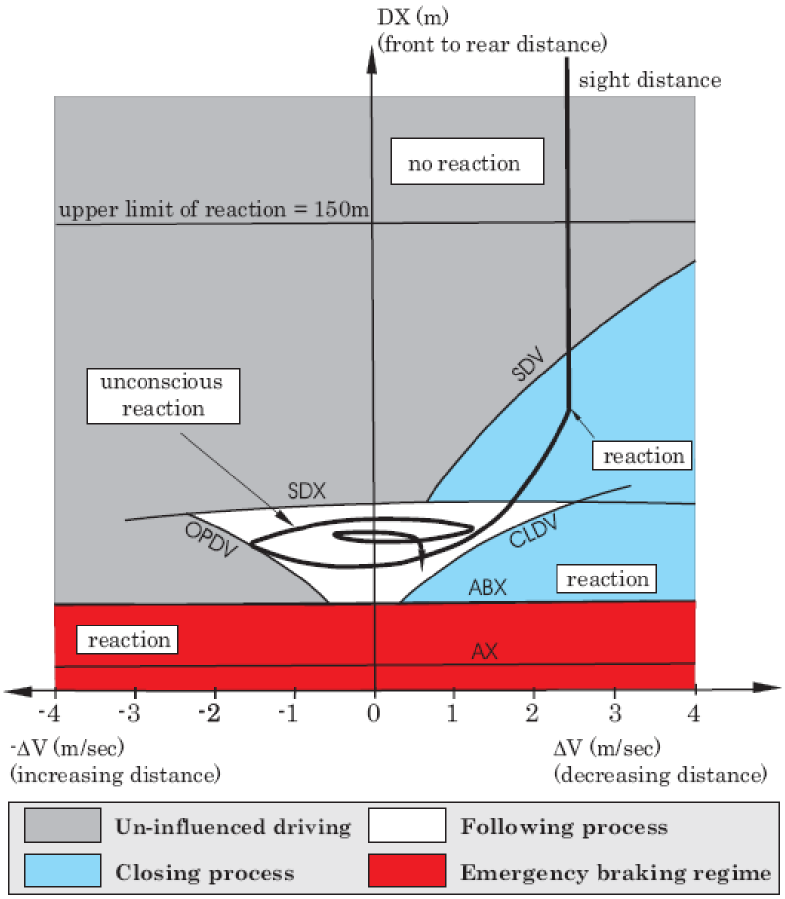


Figure 6: Wiedemann Car-following driver behavior model (15)

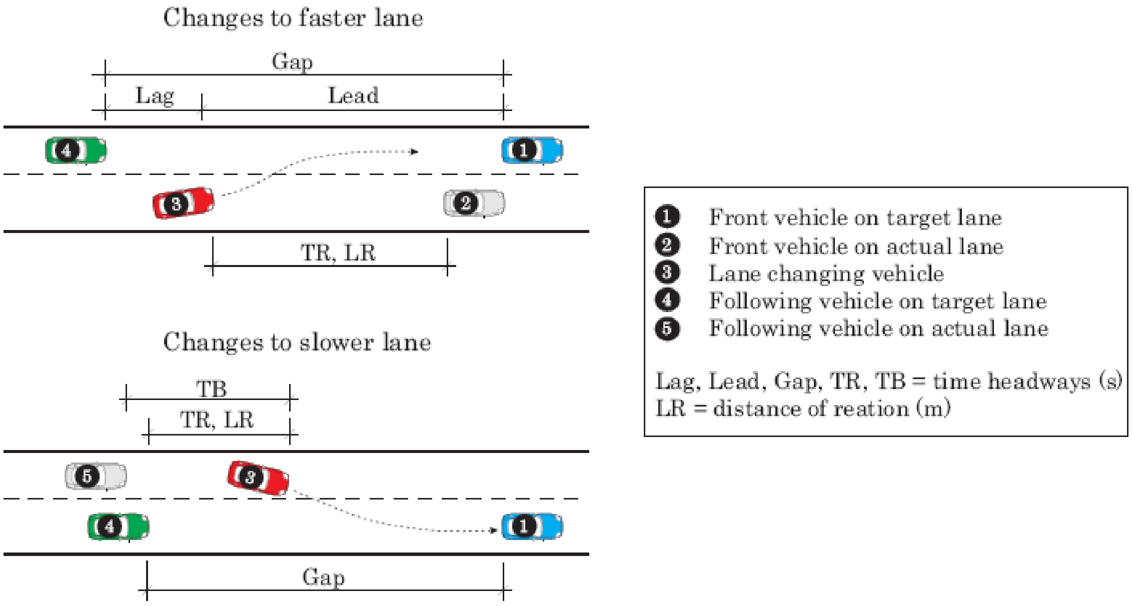


Figure 7 VISSIM Lane-change Model Parameters (15)

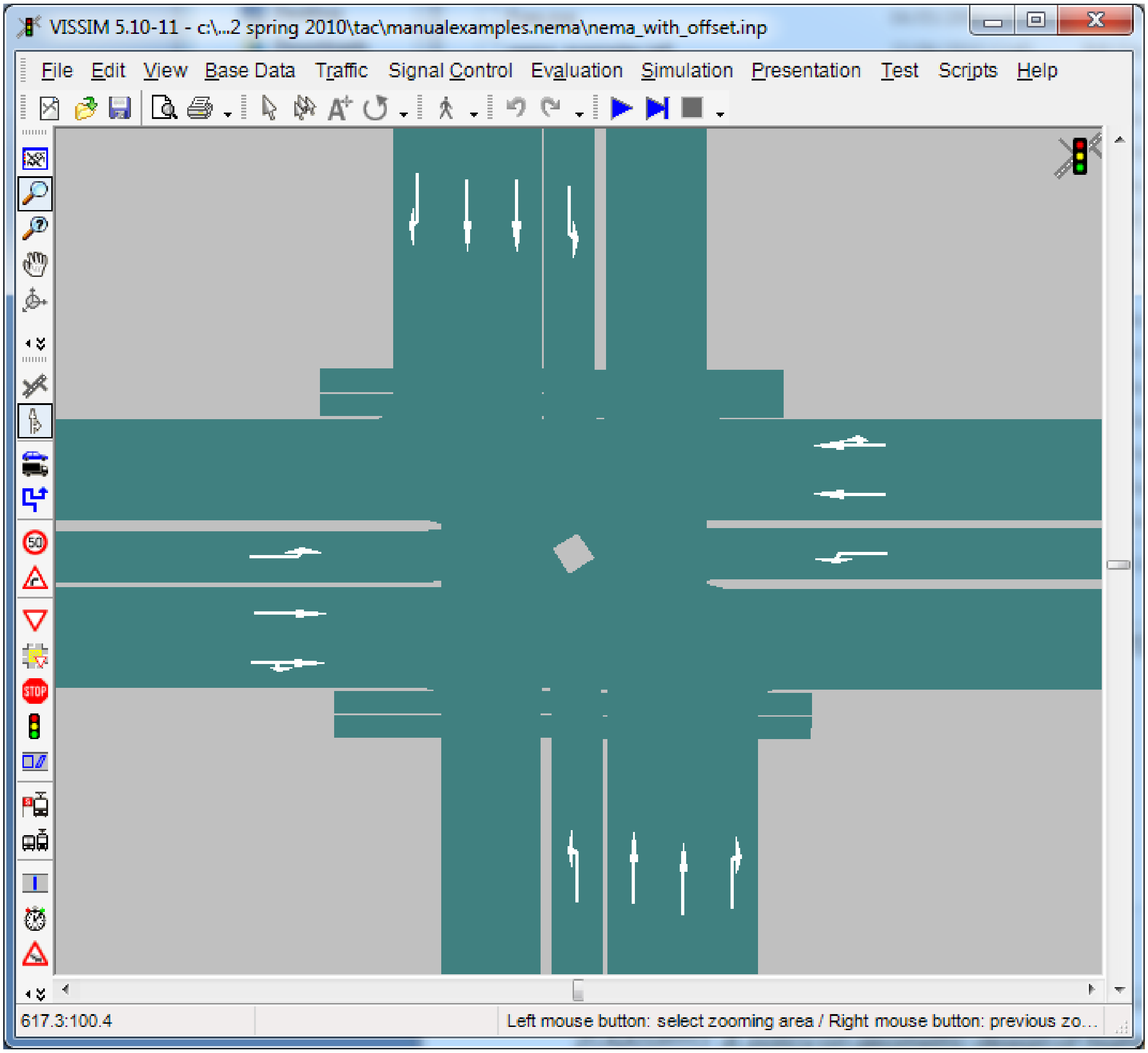


**FIGURE 8: Screenshot of the no left-turn lane offset signalized intersection geometry**