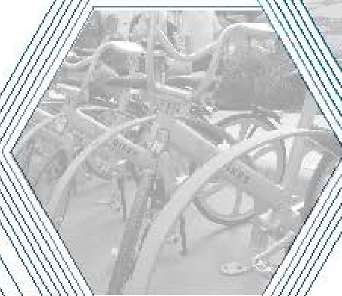

Evaluation of Cost-effective Alternative Designs for Rural Expressway Intersections

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FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

EVALUATION OF COST-EFFECTIVE ALTERNATIVE DESIGNS FOR RURAL EXPRESSWAY INTERSECTIONS

FINAL PROJECT REPORT

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Sponsorship:
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16. Abstract
Despite numerous studies demonstrating the effectiveness of Restricted Crossing U-Turn (RCUT) intersection design, its implementation remains uneven and close to zero in some large states, including California. This research provides a comprehensive framework to estimate the operational and safety performance of future RCUT designs in California. The framework is demonstrated for five intersections located on high-speed rural expressways in Caltrans districts 5 and 6. The operational evaluation relies on microscopic simulation models of existing two-way stop control (TWSC) and alternate RCUT designs used to estimate network-wide performance measures. Two approaches were demonstrated for future safety estimation; first, an HSM-prescribed Empirical Bayes approach that uses Safety Performance Function (SPF) predictions combined with the crash history of the site. For typical applications, Empirical Bayes estimates may be combined with CMFs for RCUT found in the literature. This approach remains the preferred option for safety estimation. However, for geometrically constrained locations where atypical RCUT designs need to be evaluated, a surrogate measure-based method that uses trajectory data from the simulation model is described. The framework demonstrated here may be used by agencies to estimate the future benefits of the first-time application of treatments that have been successful elsewhere. Based on the results, a reduction of the number of high-severity (fatal and injury) crashes is expected by constructing an RCUT intersection; however, the number of low-severity (no injury) crashes might be increased. Regarding traffic operation, no significant difference was identified between RCUT designs and the existing intersection designs at four of the five intersections evaluated. One of the intersections did result in travel time savings due to moderately high left-turn traffic from the minor road.

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Safety, Surrogate measures, R-CUT, J-turn, Rural Expressways

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Abstract

Despite numerous studies demonstrating the effectiveness of Restricted Crossing U-Turn (RCUT) intersection design, its implementation remains uneven and close to zero in some large states, including California. This research provides a comprehensive framework to estimate the operational and safety performance of future RCUT designs in California. The framework is demonstrated for five intersections located on high-speed rural expressways in Caltrans Districts 5 (three locations) and 6 (two locations). The operational evaluation relies on microscopic simulation models of existing two-way stop control (TWSC) and alternate RCUT designs to estimate network-wide performance measures. Two approaches were demonstrated for future safety estimation; first, an HSM-prescribed Empirical Bayes (EB) approach that uses Safety Performance Function (SPF) predictions combined with the crash history of the site. For typical applications, EB estimates may be combined with CMFs for RCUT found in the literature. This approach remains the preferred option for safety estimation. However, for geometrically constrained locations where atypical RCUT designs need to be evaluated, a surrogate measure-based approach that uses trajectory data from the simulation model is described. The framework demonstrated here may be used by agencies to estimate the future benefits of the first-time application of treatments that have been successful elsewhere. Based on the results, a reduction of the number of high-severity (fatal and injury) crashes is expected by constructing an RCUT intersection; however, the number of low-severity (no injury) crashes might be increased.

Chapter I: Introduction

1.1 Problem Statement

Despite the significant amount of research on alternative intersection designs [1]–[10], [10]–[18] there are still existing gaps in the literature, for example, with regards to Restricted Crossing U-Turn RCUT intersections (also called superstreet, synchronized, J-Turn, and reduced conflict intersections) on rural expressways. Rural high-speed expressways functionally operate like freeways but have at-grade intersections with minor roads. These intersections are often key access points for rural communities. Several rural communities rely on 2-way STOP-controlled intersections with high-speed expressways for access to markets or tourism traffic. However, these intersections do present operational and safety challenges [19]. As operational and/or safety concerns arise at these at-grade intersections, and if the economic cost of converting Stop-controlled approaches into a grade-separated interchange cannot be justified, often the concerned agencies shut down the intersections, severely impacting businesses such as local farms and wineries (e.g., (Middecamp, n.d.), ("Safety and Economic Development Challenges on US-127 between Ithaca and St. Johns, Michigan - Bing," n.d.)) [20]. RCUT intersections are an innovative low-cost intersection design where all traffic on the minor road must turn right at the main intersection, thereby eliminating the conflicts leading to severe far-side angle crashes. Figure 1 shows a typical rural RCUT intersection [1].

Despite the lower cost and potential to address operational and safety concerns through the elimination of severe conflicts (See, e.g., [1]–[17]), their application is not uniformly distributed throughout the US. For example, they are widely used in North Carolina and Michigan, but to the best of our knowledge, there is no known application of these designs on rural expressways in CA.

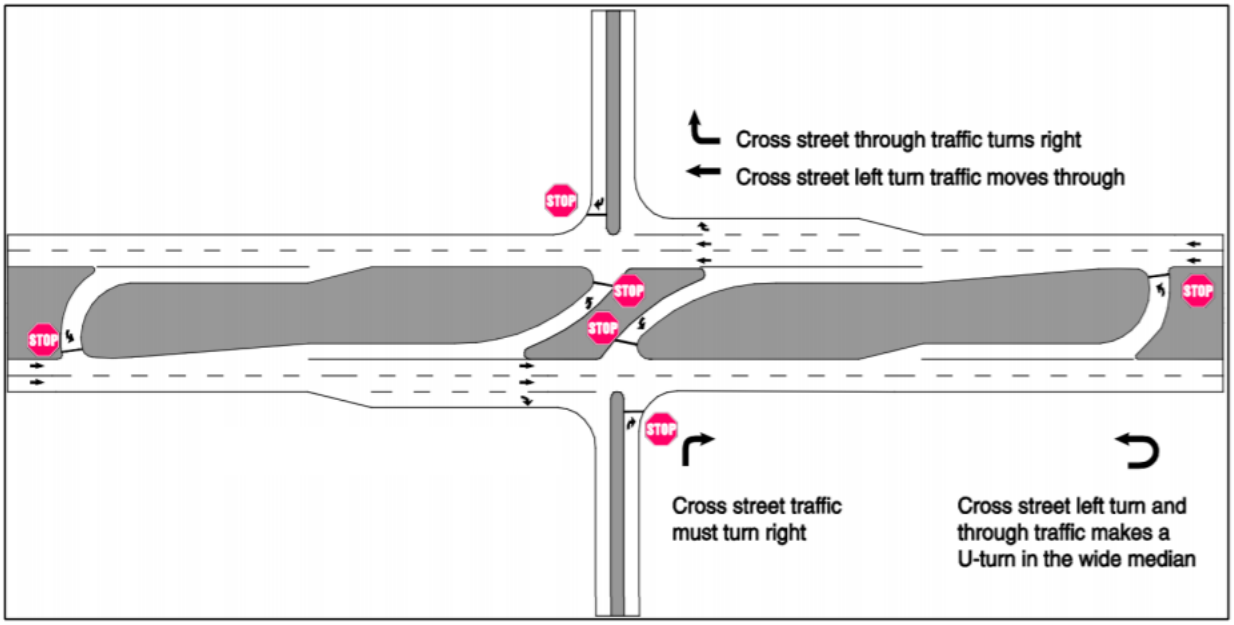

Figure 1. A typical RCUT design on rural intersections [1]

1.2 Objective

This research evaluates RCUT intersections for their suitability on the high-speed expressways in the States of California. In discussions with the stakeholders (San Luis Obispo Council of Governments (SLOCOG), and California Department of Transportation (Caltrans), investigators have identified the reasons why these intersection treatments are rarely considered in this large state. The chief among them is the reluctance to divert drivers off the shortest path and the novelty of the design. This research is developed to help address these issues so that innovative intersection infrastructure design (i.e., RCUT) is included among the alternatives considered during the Intersection Control Evaluation (ICE) process. The stakeholders also noted the need for evidence of these treatments' effectiveness to realize the potential cost-savings. For this purpose, this research estimates the expected safety and operational performance of RCUT intersection designs as possible substitutes for conventional Two-way Stopped Controlled (TWSC) intersections in CA. This evaluation framework is proposed with five rural California intersections with various geometric design and right-of-way (ROW) features in Caltrans

Districts 5 and 6 as case study examples. The analysis framework for considering and evaluating such treatments would lead to a more cost-effective intersection design. Moreover, published research that matches the local or regional context may push practitioners in large states like California to evaluate such alternatives where they may be appropriate. The framework used in this study will allow agencies to:

1. Define possible RCUT alternatives and identify geometric constraints that may affect the range of the alternatives.
2. Estimate the expected future operational conditions, including the vehicle travel times for the RCUT designs compared to existing TWSC.
3. Establish a procedure to estimate the safety performance of the RCUT designs in comparison to the existing intersections by using the following methods:
    a. EB approach prescribed by the Highway Safety Manual (American Association of State Transportation Officials) [21].
    b. A surrogate measure-based approach.
4. Discuss the relative merits and select from the two approaches to estimating safety

The study utilized the microsimulation approach to estimate the operational performance. Simulation output from PTV-VISSIM is also used in conjunction with SSAM (Surrogate Safety Assessment Model) [22] for the surrogate measure-based safety estimation. The simulation models can also help stakeholders and the public visualize the intersection treatment's functioning, thereby supporting outreach and tech transfer for this research.

1.3 Case Study Sites

The case study sites used to demonstrate the framework are located in Caltrans Districts 5 and 6 in CA. The intersections are listed below:

1- US-101 and Tassajara Creek Road in San Luis Obispo County (Caltrans District 5)

2- CA-46 and Mill Rd in San Luis Obispo County (Caltrans District 5)

3- CA- 46 and McMillan Canyon Rd in San Luis Obispo County (Caltrans District 5)

4- CA-41 and Nebraska Avenue in Fresno County (Caltrans District 6)

5- CA-65 and Avenue 184 in Tulare County (Caltrans District 6)

Figure 2 shows a satellite view from the first intersection listed above: US-101 and Tassajara Creek Road in San Luis Obispo County (Caltrans 5).

Figure 2 The existing intersection on US 101 @ Tassajara Creek Road

Based on the Caltrans database [23], the Annual Average Daily Traffic (AADT) for the US-101 segment was 52,060 in 2018. However, no daily traffic data was available for the minor road (Tassajara Creek Rd). The research team collected data during multiple hours of the day during Summer and Fall of 2020 to estimate minor road traffic data. Overall, six crashes were reported at the intersection between 2015 and 2019, with 2 of those crashes resulting in injuries. US 101 is an expressway with a speed limit equal to 65 mph in this segment. Similar to Figure 1, left-turn movements from the major road (US 101) and all traffic movements coming in from the minor roads are stop controlled. In terms of geometry, there are two through traffic lanes and one exclusive lane for each turning movement from the major road, while there is only one traffic lane in each direction on the minor road. Also, as shown in Figure 2, the intersection is located on a horizontal curve. This fact might create a safety concern. Note that the most recommended intersection angle is 90 degrees based on the AASHTO Green book [24].

Figure 3 illustrates CA-46 and Mill Road intersection geometry in San Luis Obispo County (Caltrans 5).

Figure 3 The existing intersection on CA 46 @ Mill Road

Based on the traffic data collected [23], the AADT for the CA-46 segment was 26,200 veh/day in 2019, while no AADT data is available in Mill Road. Again, to address the lack of daily data, the research team collected traffic data over multiple hours of the day. The data also supported the calibration and validation of the simulation models. Overall, four crashes were recorded in this intersection in 2017-2019, with three crashes resulting in injuries. CA-46 is an expressway with a posted speed limit equal to 60 mph west of Mill Road and 65 mph east of Mill Road. There is no stop sign for the left-turn movements from the major road (CA 46); however, all traffic movements coming in from the minor roads (Mill Road) are stop controlled. There are two through traffic lanes and one exclusive lane for each turning movement from the major road with acceleration lanes for both right and left-turn movements onto the mainline in terms of lane figuration. In comparison, there is only one traffic lane in each direction on the minor road.

Figure 4 illustrates CA-46 and McMillan Canyon Road's existing intersection in San Luis Obispo County (Caltrans 5).

Figure 4 The existing intersection on CA 46 @ McMillan Canyon Road

Based on the Caltrans database [23], the AADT for this segment of the CA-46 was 18,900 in 2019. However, no AADT data was available for the minor road McMillan Canyon

Rd. According to crash datasets, there were five collisions recorded at the intersection of CA-46 and McMillan Canyon Rd between 2017 and 2019, with one collision resulting in injuries. It should be mentioned that the intersection was under construction until early 2019. Also, no speed limit sign was found near the intersection. Therefore, the speed limit is 65 mph on CA-46 based on California Manual for Setting Speed Limits [25]. No stop sign is installed for the left-turn movements from the major road (CA 46); however, all traffic movements coming in from the minor roads (Mill Road) are stop controlled. Similar to the other intersections in District 5, there are two through traffic lanes and one exclusive lane for each turning movement from the expressway. In comparison, there is only one traffic lane in each direction on the minor road.

Figure 5 shows a view of CA-41 and Nebraska Road's existing intersection in Fresno County (Caltrans 6).

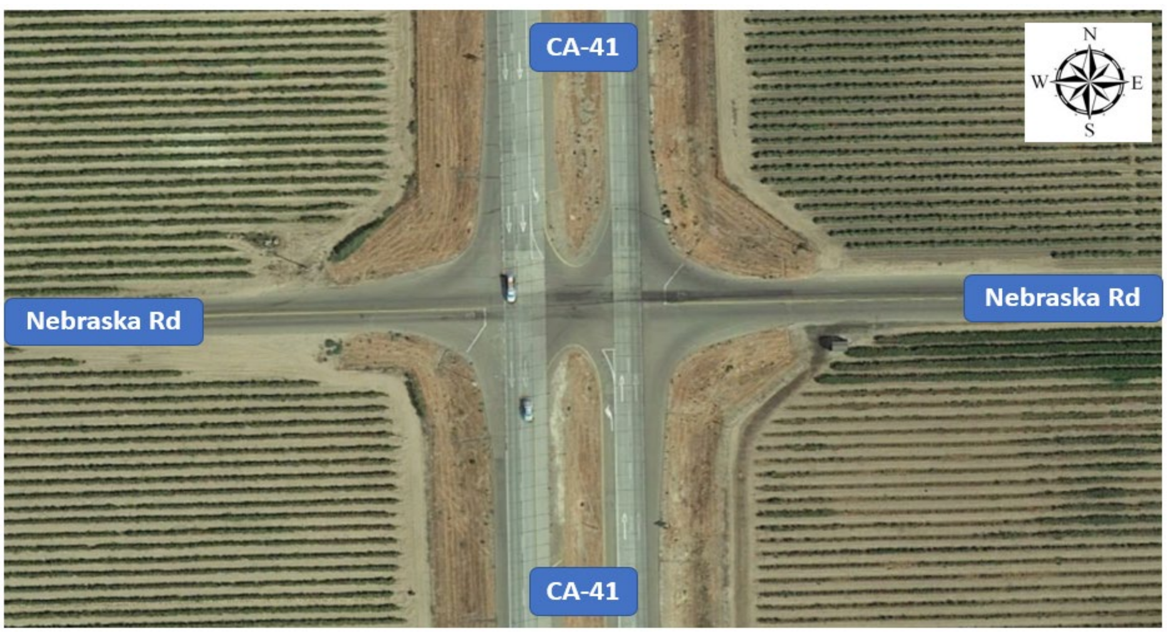

Figure 5 The existing intersection on CA 41 @ Nebraska Road

Based on the Caltrans database [23] the latest AADT for the CA-41 segment was 21,200 veh/day on CA-41 and 900 veh/day on Nebraska Rd. Overall, seven crashes were reported at the intersection between 2017 and 2019 (36 months), with none of those crashes resulting in injuries. There is no speed limit sign near the intersection. Therefore, according to the California Manual for Setting Speed Limits, the speed limit should be considered 65 mph on CA-41 [25]. Also, no stop sign is installed for the left-turn routes from the major road (CA 41); however, all traffic demand coming in from the Nebraska Rd are stop controlled. In terms of geometry, there are two through traffic lanes and one exclusive lane for each turning movement from the major road, while there is only one traffic lane in each direction on the minor road.

As the last location included in this study, the existing intersection on CA-65 and Avenue 184 Tulare County (Caltrans 6) is shown in Figure 6.

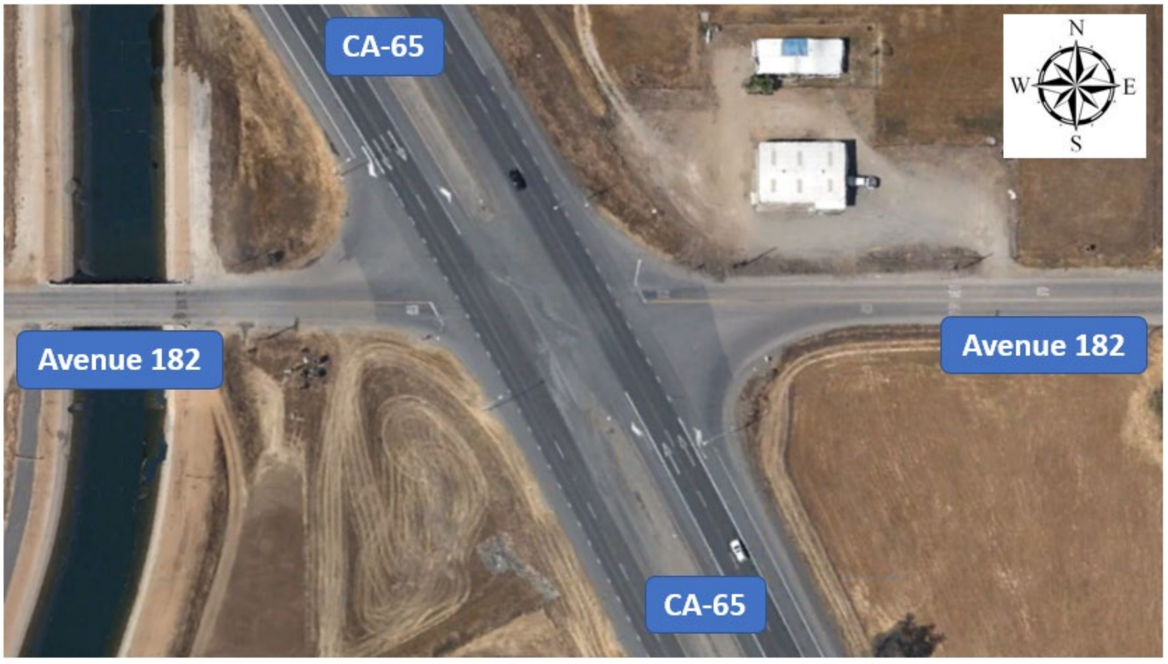

Figure 6 The existing intersection on CA 65 @ Avenue 184

Based on the most recent available database [23], the AADT was 22,900 on CA-65 and 1,100 on Avenue 184. Like the other intersection located in District 6, seven crashes were recorded at this intersection between 2017 and 2019 (36 months), with one collision resulting in a fatality and two collisions resulting in injuries. Since there is no speed limit near the intersection, the speed limit should be considered equal to 65 mph on CA-65 based on California Manual for Setting Speed Limits [25]. All traffic movements coming in from the minor roads are stop-controlled, while there is no stop sign for the left-turn routes from the expressway. Also, there are two through traffic lanes and one exclusive lane for each turning movement from the major road, while there is only one traffic lane in each direction on the minor road.

1.4 Organization of the Report

The report is organized as follows: In the next chapter, a background literature review is provided. Chapter 3 provides the methodologies used for evaluation. Chapter 4 provides Analysis and Results from operational and safety analysis using simulation models and HSM-based safety analysis. Chapter 5 also includes the B/C ratio estimation for R-CUT installation at one of the locations for demonstrating the use of the ICE (Intersection Control Evaluation) process used by Caltrans. Chapter 6 provides overall Conclusions and venues for Future exploration and tech transfer.

Chapter II: Literature Review

2.1 Introduction

Rural expressways are high-speed (≥50 mph), multilane, divided highways with partial access control [26]. Like rural freeways, rural expressways are typically four-lane divided facilities (i.e., two lanes in each direction separated by a wide, depressed, turf median). However, unlike the freeways, which have grade separations and interchanges, expressway interchanges are generally limited to locations where the additional expenditure can be justified (i.e., at junctions with major highways, along bypasses, or at intersections with a historically disproportionate rate of serious crashes). Parts of Highway US 101 in the San Luis Obispo County, CA, are classified as rural expressway segments. Recently, US 101 intersections at Welsona Road in the north San Luis Obispo (SLO) County [20] and El Campo Road in the south SLO County [27] have experienced fatal crashes. These crashes have led to an outcry to address the safety at these intersections. At present, the solutions considered by Caltrans for rural expressway intersections involve intersection warning signs (possibly as an interim measure) and, ultimately design and construction of grade-separated interchanges. On expressway intersections with low-volume minor roads, grade-separation may not be the cost-effective alternative [20], [26], [27]. This study examines a potentially more cost-effective solution, an alternative design called RCUT for these intersections.

2.2 Restricted Crossing U-Turn: Background

The first traces of alternative to the traditional 4-legged intersections go back about 70 years ago when jug-handle intersections were constructed in New Jersey [28]. Median U-turn (MUT) intersections were introduced in Michigan in the 1960s, and there are many of them all around the US that still perform well. On arterial streets, MUT intersections could improve traffic operation and safety in locations with lower left-turn traffic by reducing the number of signal phases and conflict points [29]. Alternative intersections gained great attention again during the

1990s with growing traffic volume and tighter budgets for funding new infrastructure in the US. In the last three decades, hundreds of alternatives to traditional 4-legged intersections designs, including roundabouts, quadrants, RCUTs, and Contraflow intersections (CFIs), have been built in the US.

RCUT intersection (it is also called a superstreet, synchronized J-turn, or reduced conflict intersection) is a variation of the MUT design. However, in contrast to the MUT, traffic coming from the minor roads cannot proceed straight across the major road. Also, left-turn traffic on the major roads would access the minor roads using exclusive left-turn lanes at the intersection (instead of using U-turns like MUTs). Edara et al. [16] described the difference in the operation of the traditional TWSC vs. RCUT intersection as follows:

"At a TWSC intersection on a four-lane divided highway, vehicles accessing the major highway from the minor road can make a left turn or through movement at the intersection by crossing the major road movements. Highways with high volumes or high speeds may make these movements unsafe to execute and cause long delays. On the other hand, in a J-turn design, vehicles accessing the major highway from the minor road make a right turning movement and then use a U-turn at a downstream location."

Figure 7 shows the RCUT or J-turn intersections in contrast to traditional two-way stopped control (TWSC) intersection control. RCUT intersections could be stop-controlled, yield controlled or signalized. Figure 1 shows a typical rural RCUT intersection [1].

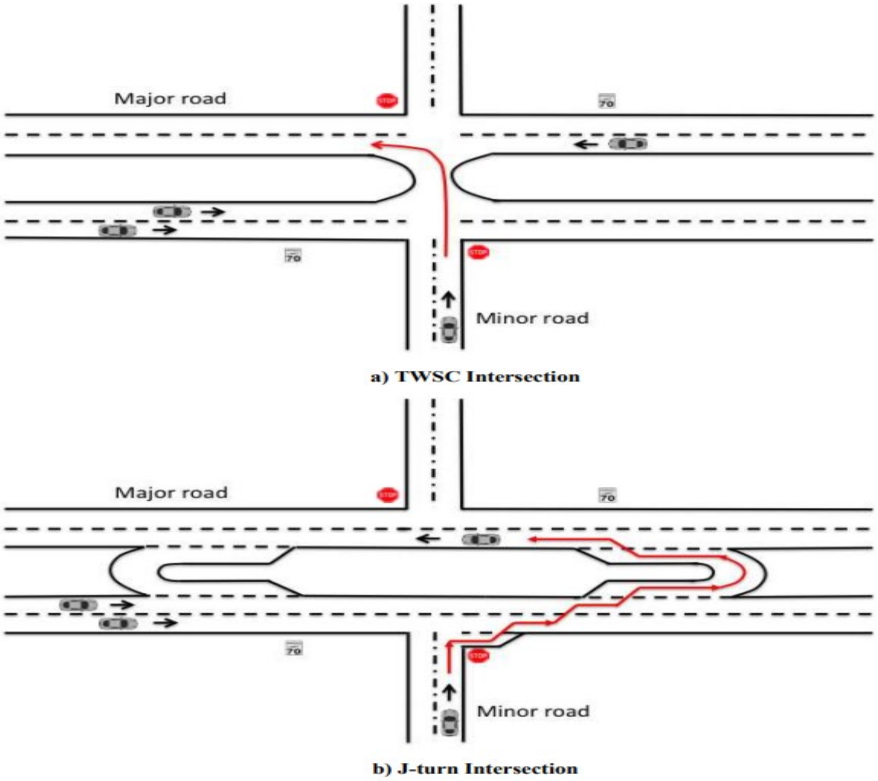

Figure 7 TWSC (on top) vs RCUT intersection (bottom) [9]

RCUT intersections have fewer conflict points and less severe conflicts than conventional two-way stop control (TWSC) intersections. Figure 8 shows the conflict points of a typical RCUT compared to the traditional TWSC intersection [1]. Overall, there are 14 conflict points in a typical RCUT (as shown in Figure 8), while the conventional TWSC intersection has 32 conflict points. The superior safety performance of RCUT intersections could be even more significant because there are only two crossing points (only between the left-turn and through traffic demands on the expressway). On the other hand, there are 16 crossing conflict points in a conventional TWSC intersection. Note that there is no crossing conflict point in the other version of RCUT intersections indicated in Figure 7. All left-turn movements must use the U-crossovers (which create merging conflict points with through traffic demand on the expressway). Also noteworthy is that all conflict points exist in the middle of the intersection in a TWSC design. However, conflict points are spread out in a larger space with separation from each other.

Moreover, fewer vehicles are conflicting in each of the conflict points of RCUT intersections than conventional intersections. According to past research, this results in better safety performance [30].

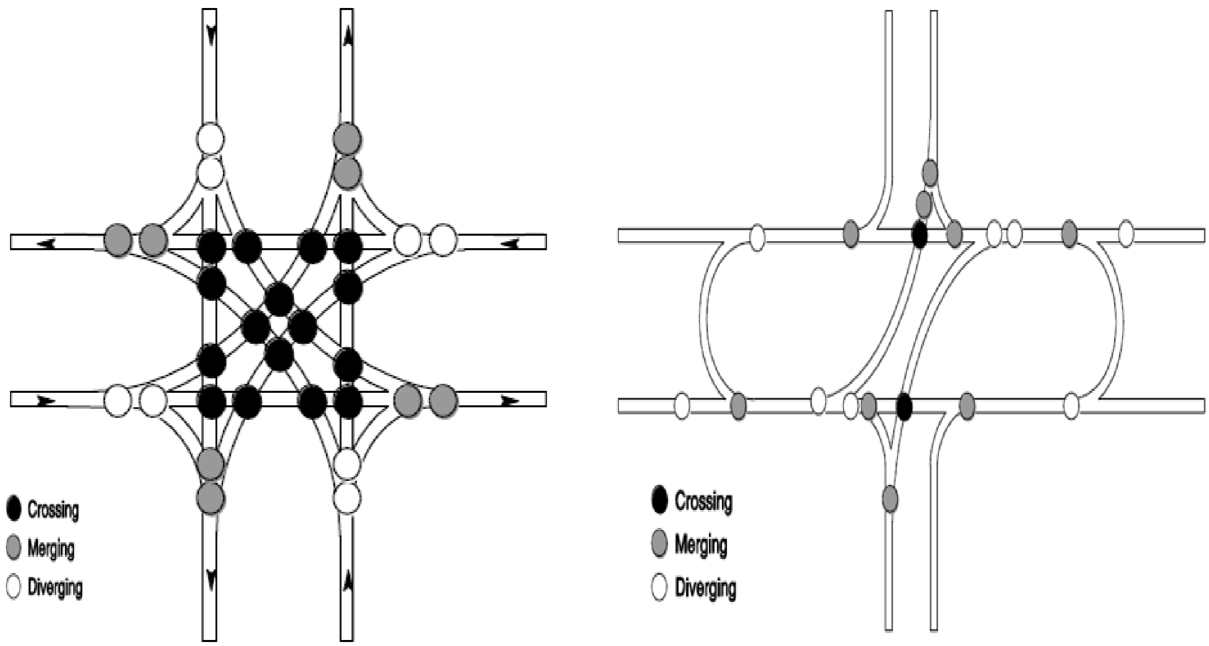

Figure 8 Conflict points in TWSC (left) vs RCUT intersection (right) [1]

Hence, these intersections have the potential to improve safety. They have been implemented in some states (e.g., MD [31], NC, and MN [32]) but have rarely been considered on rural expressways in CA. According to past studies ([7], [10], [31]) RCUT intersections provided excellent safety and operational performance when there is a low through and left-turn demand on the minor road.

A study on a rural four-lane high-speed major road in Missouri [33] showed high potential for RCUT in terms of traffic safety performance; however, the vehicle travel times at RCUT intersections were slightly higher than the existing TWSC intersection. A before-after analysis of fatal and injury, angle, and left-turn crashes showed that these crashes reduced by more than half after upgrading a conventional stop-controlled intersection to an RCUT intersection. Sideswipe, rear-end, and other crash types decreased by a lesser degree or slightly increased [1]. Another study examined the safety performance of five RCUT (with stop signs) installations on a rural, four-lane highway compared to a conventional stop-controlled intersection on minor roads [16]. Data was gathered three years before and after the installations. It was found that the RCUT intersections reduced the total number of reported crashes by an average of 35%. Additionally, no fatal crashes happened during the study period after installation.

While the literature provides significant evidence of the efficacy of these intersections based on post hoc analysis, the literature is lacking in framework to evaluate the future expected performance of RCUT intersections for jurisdictions (e.g., Caltrans) where they have not yet been implemented. This study provides such a framework for future safety and operational performance evaluation framework using a case study from five sites in rural California. Through communication with Caltrans District 6 Deputy Director for Operations (Mr. John Liu) it was learned that the reluctance to divert drivers off the shortest path and lack of a framework to demonstrate its effectiveness is why they are scarcely considered by Caltrans districts. Caltrans Office of Traffic safety (Mr. Thomas Scriber) also noted that if example evaluation using Caltrans' ICE framework may be demonstrated, it will aid the Caltrans districts in considering these designs where appropriate.

2.3 Other Alternatives: CFI, MUT, and Reverse RCUT intersections

In addition to the RCUT intersection, the possibility of considering three other alternative designs were reviewed by the research team in the first phase of the study. The three possible alternatives were CFI, MUT, and Reverse RCUT intersections. Figures 9, 10, and 11 have shown examples of the three designs.

Figure 9 An example of partial CFI concept at the intersection of U.S. Route 30 and Summit Drive in Fenton, MO [3]

Figure 10 An example of partial MUT intersection at the intersection of M-24 and E Scripps Rd in Orion Charter Township, MI

Figure 11 An example of reverse RCUT intersection in North Carolina

In this study, the CFI was not considered in the evaluation because of two reasons: (1) the extent of the additional ROW needed and (2) crossing conflicts between movements. CFI requires a bigger ROW compared to the existing intersections because of the exclusive lanes for the left-turn and right-turn demands (as shown in Figure 9). According to the Federal Highway Administration (FHWA), continuous flow intersections (CFIs) can be considered in either urban or suburban environments as long as there are relatively large parcels of land available [34]. Hummer and Reid reported that an environment should also have a high through traffic volume [35]. The extra ROW could significantly increase the construction costs, especially due to the challenging geometric features in a few of the case study sites in this research. Moreover, crossing conflict points between major and minor roads, which cause the main safety concerns at the existing intersections, would still exist in the CFI. Therefore, no significant safety improvement could be expected by reconstructing the intersections being considered here to a CFI. CFIs have fewer conflict points in comparison to conventional intersections. However, there are other intersection designs used to address high through traffic volumes that exhibit fewer conflict points than CFIs. These include Jug handles or superstreets (RCUTs), making them a safer option to implement under certain circumstances [36]. CFIs are most effective at signalized intersections because of the ability to eliminate one or two signal phases in partial and full CFI designs, respectively. Since the scope of this study is unsignalized intersections on rural expressways, CFIs are not worth considering.

For similar safety concerns (crossing conflict points) mentioned above, MUT was not considered an alternative in this study. It should be noted that there are a total of16 conflict points in a typical MUT, of which four of those conflict points are crossing conflicts.

Regarding the reverse RCUT design, the travel time of the left-turn demand coming from the expressway could be increased significantly due to the distance between the main intersection and the U-turn crossovers. Based on the Caltrans Highway Design Manual [37], a minimum deceleration length of 500 ft is required for the left-turn demand coming from the expressway. Also, the deceleration lanes need to be located after a merging area needed for the left-turn demand entering the expressway (from the minor road). Therefore, the left-turn movement's travel distance (from the expressway) would increase by close to half of a mile. This may be one reason why unsignalized reverse RCUT installations do not exist to the best of our knowledge. Therefore, the reverse RCUT was not a promising alternative at this time for the unsignalized case study sites in California. The authors acknowledge the information provided by experts at the North Carolina Department of Transportation in personal communication regarding existing reverse RCUT intersections.

Hummer [38] identified Safest Feasible Intersection Design (SaFID) (corresponding to all crashes and injury crashes) based on available CMF studies and traffic demand at the intersection. According to Hummer’s findings, RCUT intersection should be the safest design (corresponding to reducing all crashes and injury crashes) for the five case study locations. In the next section, background information on Surrogate Safety Assessment Model is provided.

2.4 Surrogate Safety Assessment Model

Surrogate measures of safety are measures that may be used in place of crash counts/rates. These measures typically are based on conflicts between vehicles and/or vehicles and other road users. A conflict is defined as a situation in which vehicles approach each other such that there is a risk of collision if their movements remain unchanged [22]. Gettman and Head's [39] study was one of the first attempts at using surrogate safety measures derived from simulation modeling. Consequently, in another research by the same authors, the first version of SSAM was released by the Federal Highway Administration (FHWA) in 2008 [22]. SSAM uses the trajectory files of traffic simulation models (like VISSIM) to identify the type and frequency of interactions (simulated conflicts or near misses) between road users during the simulation period. Figure 12 illustrates the conflict angle diagram used in SSAM to recognize the type of simulated conflicts [22].

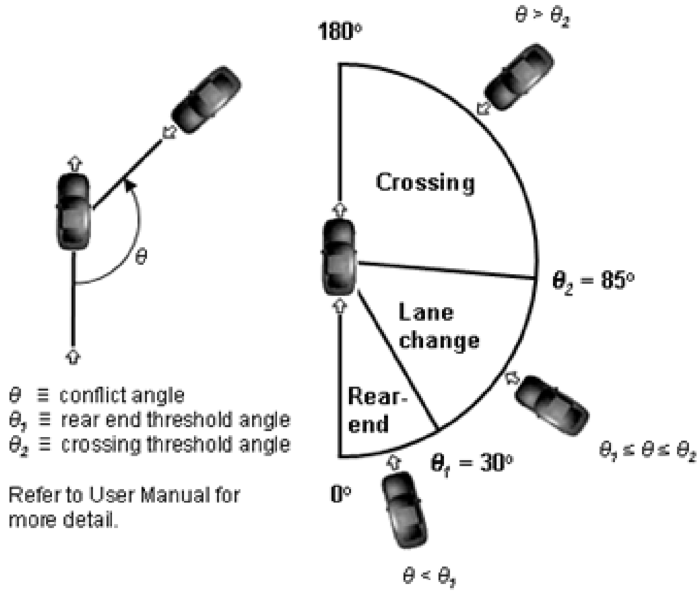

Figure 12 Conflict angle diagram in SSAM [22]

Being able to estimate the safety performance of highway networks before implementing a new safety countermeasure is one of the main advantages of using SSAM. Traditionally, safety engineers need to wait for enough crashes to occur before being able to estimate the safety of a roadway location. However, it might take many years to get access to such a dataset. Moreover, unfortunately, some transportation users have to experience those crashes. Surrogate measures of safety allow for a more proactive measurement of safety.

The majority of past studies on SSAM were on validation and calibration of the model. Fan et al. [40] compared the frequency of near misses observed in a field study with VISSIM and SSAM models' estimated number. They found an acceptable consistency between the results of the comparison. Despite the satisfactory results regarding the validation of SSAM, past studies [40]–[42] highly suggested calibrating driver behavior in the simulation procedure to increase the accuracy of SSAM by most the previous studies. A calibrated driver behavior model in VISSIM could reduce the errors by up to 50% [40].

2.5 Conclusions from the Literature Review

Literature review points to the effectiveness of Restricted Crossing U-Turn (RCUT) intersection design at rural expressway locations. It also points to the need to develop an evaluation framework so that R-CUT design may be considered by agencies where appropriate. Based on the literature findings, we will adopt two approaches for future safety estimation; first, an HSM-prescribed EB approach that uses Safety Performance Function (SPF) predictions combined with the site's crash history. For typical R-CUT applications, EB estimates may be combined with existing CMFs for RCUT. This approach remains the preferred option for safety estimation. However, for geometrically constrained locations where atypical RCUT designs need to be evaluated (and SPFs available in the literature may not be applicable), a surrogate measure-based approach that uses trajectory data from the simulation model may be needed. The simulation model developed for operational evaluations combined with SSAM (reviewed in the previous section) will be used for this purpose. The next chapter describes the safety and operational performance evaluation methodologies.

Chapter III: Methodology

This study uses two different approaches to conduct the evaluation of the R-CUT intersection on rural expressways. The first approach described in the next section is based on simulation models that provide metrics for operational evaluation as well as surrogate safety assessment.

3.1 Simulation Modeling Approach

Since the study's objective is to propose and evaluate a framework for proposed designs for the future, microsimulation was the most appropriate tool for the operational evaluation. Note that the simulation output is also used for surrogate measure-based safety evaluation. PTV VISSIM was chosen to model the existing and proposed designs. VISSIM can realistically model various traffic patterns with detailed geometric features and drivers' behavioral characteristics [43]. Besides, VISSIM is one of the microscopic simulation packages from which the vehicle trajectory data (in the form of .trj files) may be used directly with SSAM. SSAM was used to estimate the frequency and type of narrowly averted vehicle-to-vehicle interactions (i.e., conflicts). SSAM utilizes the vehicle trajectory files from VISSIM along with a specified time-to-collision (TTC) threshold to identify the number and type of simulated conflicts (i.e., near misses) between vehicles. In other words, Surrogate measures of safety are indirect measures that reflect the crash experience of a facility. Surrogate measures included in SSAM are shown in Table 1. Details of the SSAM functionality may be found in Gettman et al. (2008) [22].

In this study, the research team developed microscopic traffic simulation models for existing TWSC intersections. Additionally, different configurations of the RCUT alternatives were simulated for the same locations. For existing and proposed alternatives, surrogate safety and operational measures were derived from the simulation models. In addition, the operational measures related to vehicle travel time differences between conventional and RCUT intersections were derived. The simulation models were calibrated to capture driver behavior at specific locations. Ultimately, the simulation outcomes were compared to real data collected to validate the results.

Table 1. Surrogate measures and their description [22]

Surrogate Conflict Measure	Description
Gap Time (GT)	Time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path.
Encroachment Time (ET)	Time duration during which the turning vehicle infringes upon the right-of-way of through vehicle.
Deceleration Rate (DR)	Rate at which crossing vehicle must decelerate to avoid collision.
Proportion of Stopping Distance (PSD)	Ratio of distance available to maneuver to the distance remaining to the projected location of collision.
Post-Encroachment Time (PET)	Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision.
Initially Attempted Post-Encroachment Time (IAPT)	Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.
Time to Collision (TTC)	Expected time for two vehicles to collide if they remain at their present speed and on the same path.

3.2 Simulation Scenarios

In District 6 sites, traffic volume was collected during AM peak (7:00 AM to 9:00 AM), mid-day (11:00 AM to 1:00 PM), and afternoon (4:00 PM to 6:00 PM) on Tuesday and Wednesday on February 25 and 26 of 2020, and during mid-day (11:00 AM to 1:00 PM) on Saturday and Sunday on February 22 and 23, 2020, to include both weekday and weekend data in the analysis. For this purpose, video cameras were installed at sites by Caltrans district 6. Then, traffic data was collected and entered into spreadsheets by reviewing recorded videos. Finally, peak hours were identified and considered for simulation modeling. Figure 13 shows a screenshot of one of the videos recorded in CA-65 and Avenue 184 in Tulare County. It should be mentioned that traffic collected in Caltrans District 6 should represent a normal traffic condition because the first positive test of COVID-19 was identified on March 11, 2020, in Tulare County [44].

Figure 13 A screenshot of one of the videos recorded for traffic data collection

In District 5 sites, traffic data was collected manually by the research team on-site in July and November 2020. Also, video cameras were installed to extract the speed of at least 100 vehicles in each time slot (AM, Noon, and PM peak periods). Regarding the time of data collection, peak hours (AM, Noon, and PM) were selected based on available historical peak hour data for the mainline expressway from Caltrans resources. We compared this data with the data from past studies in 2011 and 2018 at the same location in District 5 and found no significant difference due to the COVID-19 pandemic. This is a reasonable result as the highway two of the corridors studied are primarily freight corridors with some recreational traffic from the CA central valley to the central coast, which were relatively unaffected by COVID-19. Therefore, the results presented in this study is expected to be valid for typical operation with little impact due to the pandemic. Moreover, based on conversations with Caltrans experts, traffic growth on the side roads is expected to be negligible in the case study sites, and therefore, a common growth rate was applied to the intersection based on historical traffic count data. The growth rates used were a straight line projection based on at least ten years of AADT data for the mainline. The traffic growth rates were between 1.6% and 2.3% on the case study sites.

In addition to exiting traffic demand conditions for three different times of day, a series of simulation scenarios were also defined to estimate the performance of the intersections based on future traffic demands. For this reason, after discussion with experts from Caltrans Districts 5 and 6, a constant growth factor was estimated for each location and then applied to existing traffic data to project the traffic volumes for 2030. It should be noted that the design year for roads is 20-25 years based on the AASHTO Green book [24]. However, a 10-year design year (2030) was chosen in this study because evaluating the potential widespread use of CAVs by 2040 was out of the scope of this study. By 2030, we expect the vehicle mix to still be similar to the current one, with few driverless vehicles.

Also, two different RCUT designs were considered to identify the best alternative for reconstructing the existing intersections. A general concept for the two RCUT designs is shown in Figures 7 and 8; however, the last part of the methodology (section 3.4) will also discuss the geometric features considered for each design in this study. Overall, 126 simulation scenarios were tested using the simulation approach in this study. Each simulation scenario was repeated five times with a different random seed in VISSIM, and the average of those runs was chosen as the outcome for each scenario. Averaging output from multiple runs ensures statistically robust results. Also, Analysis of Variance (ANOVA) was conducted on the simulation outcomes using IBM SPSS ("IBM SPSS Statistics 26 Documentation," n.d.) to compare vehicle travel time of the designs. Table 2 shows the factors considered to create 126 different traffic condition/intersection design scenarios. These factors include:

- 4: time of day scenarios (Weekday: AM, noon, and PM, and Weekend noon),
- 2: Existing and 2030 conditions based on an annual growth rate specific to each location,
- 3: Intersection designs (TWSC, RCUT#1, RCUT #2),
- 5: Study sites

However, it should be noted that there were small differences in factors (included in Table 2) for a few of the locations. After discussion with Caltrans experts, two weekend days were included for the intersections located on CA-46 because the corridor sees the largest traffic volumes on the weekends. CA-46 is a primary east-west corridor that regularly sees a large tourist and recreational traffic couplet of traffic heading to the coast Friday night and Saturday morning and returning Sunday afternoon—traffic that continued to be observed during the pandemic. On the other hand, no reason was found for modeling a weekend day in US-101 and Tassajara Rd intersection as it sees more typical weekday commuter traffic but minimal traffic on the weekend. Table 3 shows existing traffic volume at the five intersections during AM, noon, and PM peak hours. Overall, traffic volume scenarios were found to be between 3,313 and 12,838 veh/hr in this study. Considering the traffic growth rate, traffic volume varied between 3,912 and 14,937 veh/hr for scenarios in the year 2030. The next section elaborates on the key points of the calibration and validation of simulation networks.

Table 2. Category levels used for generating scenarios included for each intersection

Time (4 levels)	**Year (2 levels)**	**Designs (3 levels)**
Weekday, AM Hour	2020 (Existing)	Existing TWSC

Weekday, Noon Hour	2030	RCUT #1
Weekday, PM Hour		RCUT #2
Weekend Noon Hour		

Besides the 126 base simulation scenarios, 30 additional scenarios were tested in the intersection of CA-46 and MacMillan Canyon Rd to evaluate the effect of distance between the main intersection and the U-turn crossovers on traffic operation and safety. Hence, four RCUT alternatives were considered with lengths of 800, 1200, 1500, and 1800 ft between the intersections. More information is provided in section 3.5 (Intersection Designs Considered).

3.3 Calibration and Validation

The video data was collected for each of the locations with the camera installed at one corner of the intersection. The recording of the traffic that was counted was reviewed to estimate operational speed and allowable gap for the turning traffic. Then, these measures (vehicle speed and acceptable gap for turning movements) from the recorded videos were used to calibrate the simulation model. Due to the large footprint of the intersections using only one camera, speed data was only collected for one direction of travel along the main line that passed nearest the camera. The opposing direction that was opposite the side the camera was installed on was too far away, and the resolution too low to accurately measure vehicle speeds. Based on video data collected, traffic coming from the minor road, the left-turn demand from the major road, and the U-turn vehicles (in RCUT designs) could start their movements when there was a minimum gap equal to 4.5 seconds between the conflicting vehicles. By default, VISSIM considers a 3-sec minimum gap for conflicts between through traffic and turning traffic movements. However, the 3-sec gap would not be acceptable in this study because of the high speed on the major road.

Table 4 shows a summary of speed and headway data collected from videos. According to the data in Tables 4 and 5, speed distributions with a mean speed ranging between 54 and 79 mph were added into VISSIM on all lanes of the major road of sites 1-5, depending on the location and time of day. No data was collected on minor roads, and an average speed of 25 mph (same as the speed posted) was assumed on the minor road approach. All of the existing minor road approaches were stop-controlled, making vehicle speeds less relevant for the minor roads since all vehicles must come to a stop at the intersection.

Table 3. Traffic volume (veh/hr) collected during peak hours at each study location in 2020

Study Site	Peak Hour	NB			SB			WB			EB			Total
		Left Turn	Thru	Right Turn	Left Turn	Thru	Right Turn	Left Turn	Thru	Right Turn	Left Turn	Thru	Right Turn	
US-101 and Tassajara Creek Road	AM	1	1,091	0	2	2,251	1	0	0	0	2	0	5	3,353
	Noon	6	1,726	1	2	1,872	9	0	0	0	4	0	6	3,626
	PM	13	2,591	1	1	1,589	8	0	0	1	0	0	11	4,215
CA-46 and Mill Rd	AM	151	0	41	0	0	13	27	6,485	0	10	5,454	76	1,2257
	Noon	74	0	26	0	0	0	29	4,505	0	9	4,295	69	9,007
	PM	97	0	17	0	0	6	12	4,170	0	12	4,728	28	9,070
	Saturday	23	0	39	0	0	0	13	4,477	0	0	2,390	54	6,996
	Sunday	113	0	31	0	0	0	36	5,018	5	0	5,668	53	10,924
CA- 46 and McMillan Canyon Rd	AM	287	0	0	0	0	6	6	1,293	0	5	1,567	149	3,313
	Noon	343	22	7	0	8	5	7	4,130	0	3	3,540	144	8,209
	PM	252	0	20	0	0	6	15	2,588	0	23	3,010	583	6,497
	Saturday	196	7	3	4	0	12	13	5,499	12	5	2,585	256	8,592
	Sunday	192	6	21	9	5	10	8	3,012	6	0	4,743	238	8,250
CA-41 and Nebraska Avenue	AM	22	4,199	29	90	3,564	57	29	78	62	192	79	0	8,401
	Noon	5	2,507	11	37	2,627	60	15	45	3	72	66	8	5,456
	PM	16	4,239	26	64	3,902	71	29	111	33	61	141	8	8,701
	Saturday	6	2,366	9	33	2,268	47	23	74	8	51	50	7	4,942
CA-65 and Avenue 184	AM	130	6,224	88	41	5,915	42	59	39	38	23	21	218	12,838
	Noon	35	3,471	44	29	3,230	18	34	122	37	6	133	15	7,174
	PM	180	5,395	78	46	5,608	4	30	70	42	7	51	207	11,718
	Saturday	70	3,676	63	24	2,794	8	45	18	10	9	5	78	6,800

Table 4. Average vehicle speed data for US-101 and Tassajara Creek Road collected for calibration and validation by reviewing videos

Intersection	**Parameters**	**Speed on the Major Road (mph)**	
		Left Lane	**Right Lane**
US-101 and Tassajara Creek Road	**Average**	72	73
	Median	70	75
	Minimum	61	61
	Maximum	82	82

Table 5. Vehicle speed distribution data for calibration and validation by reviewing videos

Intersection	**Parameters**	**AM Peak Hour***		**Noon Peak Hour****		**PM Peak Hour**		**Weekend Peak Hour**	
		Left Lane	**Right Lane**	**Left Lane**	**Right Lane**	**Left Lane**	**Right Lane**	**Left Lane**	**Right Lane**
CA-46 and Mill Rd	**Average**	67	65	66	62	70	66	69	70
	Median	65	65	65	65	69	65	69	72
	Minimum	57	49	55	45	46	27	46	57
	Maximum	86	76	89	72	81	125	86	86
CA- 46 and McMillan Canyon Rd	**Average**	78	73	75	74	78	70	65	66
	Median	79	74	74	74	79	68	64	64
	Minimum	55	55	46	42	52	44	51	51
	Maximum	85	100	92	100	98	98	102	85
CA-41 and Nebraska Avenue	**Average**	60	56	63	59	62	59	60	58
	Median	58	54	63	58	63	58	58	58
	Minimum	48	43	48	43	48	41	51	48
	Maximum	74	68	74	74	74	68	74	68
CA-65 and Avenue 184	**Average**	57	63	56	64	56	63	56	64
	Median	57	61	57	61	57	61	57	61
	Minimum	49	49	49	57	49	49	49	57
	Maximum	67	92	67	82	105	82	67	82

*AM peak hour data not collected for 46 and Mill, Friday PM Peak data shown.
**Noon peak hour data not collected for 46 and McMillan Canyon Rd, Friday PM peak hour data shown.

The VISSIM models were created with desired speed distributions set by lane at the entry points to the model on the highway's mainline. The desired speed distributions were set based on the real-world video data that was collected at each location. Most of the locations had multiple hours of video data collected, and each of those hours was modeled with different speed distributions. With is setup, occasionally, vehicles would change lanes downstream and not change their desired speed to match the lane they were currently in. However, the difference in the measured average speed for each lane in the video data was typically less than 5 mph, so the potential for error due to lane changes was likely minimal.

When the VISSIM models were run, the program was set to output the vehicle speed and headway data to a file for each run. The results of a batch run were then aggregated into a common result for the scenario. To validate the VISSIM models, the collected video data for vehicle speeds were compared with the vehicle speed data outputted from the VISSIM model via ANOVA to the $95^{\%}$ confidence level.

3.4 HSM-based Analysis

In addition to the simulation-based surrogate measures, the research team conducted an EB estimation for before-after analysis of the intersection locations. The EB analysis is established as the best method for before/after safety evaluations [45]. It seeks to use the crash records for the study site as well as comparative sites to determine the impact of a treatment. An illustration of the EB process for safety estimation is shown in Figure 14. It involves comparing the counterfactual estimate of safety (i.e., B in Figure 13) with the real safety experience post-treatment (i.e., A in Figure 14). Safety Performance Factors (SPFs) play a critical role in obtaining the counterfactual estimate of safety (See Figure 14). Details of Highway Safety

Manual (HSM) recommended EB before/after evaluation approach to evaluate the effectiveness of the treatment may be found in Hauer et al. [46].

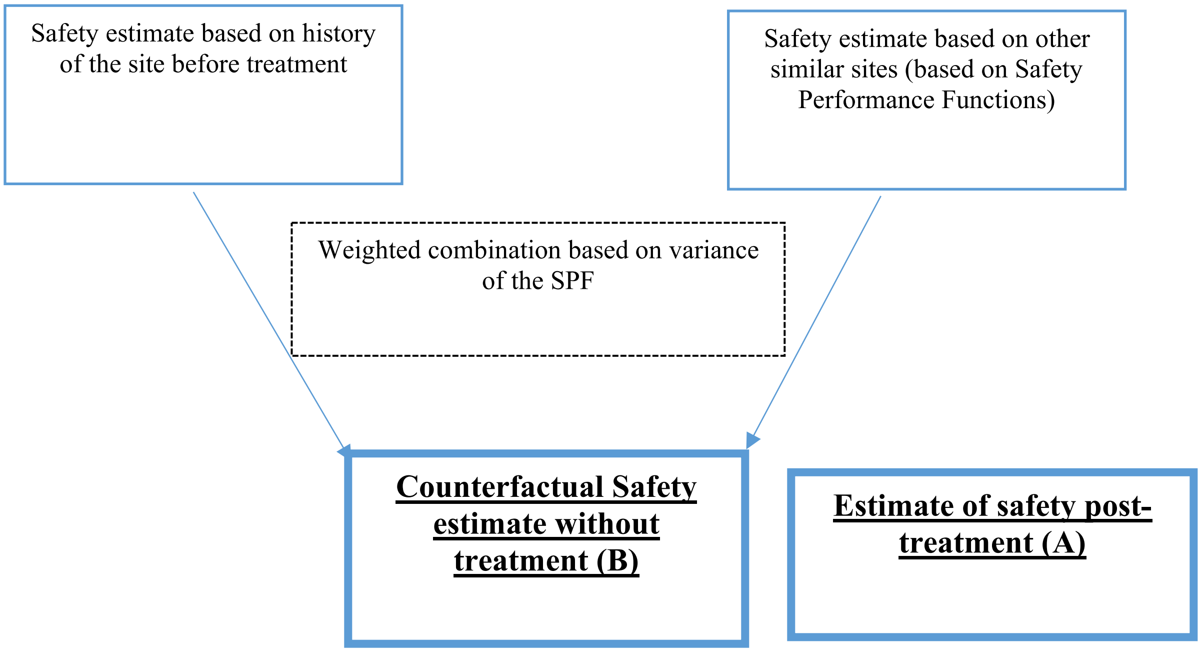

Figure 14 EB before/after evaluation framework

In discussions with one of the stakeholders (Caltrans District 6), the study team identified that an example process for evaluation of these intersections within the ICE process framework would be helpful for further implementation of these intersections. ICE a two-step process framework: i) Engineering assessment of intersection control options and ii) Design and traffic analysis of practical alternatives. The results from EB evaluation can inform the evaluation of RCUT alternatives in the ICE framework used by Caltrans for evaluating intersection design.

3.5 Intersection Designs Considered

As mentioned earlier, two RCUT alternatives were included in this study to be compared with the existing TWSC design:

- RCUT #1: an RCUT with a distance of 400-800 ft between the main intersection and the U-turn crossovers and with no left-turn lanes in the center of the intersection. In this design, all left turn demands (both from the minor and major roads) will use the U-turn crossovers (like Figure 7),
- RCUT #2: an RCUT similar to alternative #1 but with additional left-turn lanes for the left-turn demands from the expressway (like Figure 8)

Figures 15 through 19 show the two proposed alternatives modeled in VISSIM for each of the five study sites. Based on the FHWA guideline on RCUT [1], a distance of 400-800 ft is recommended from the main intersection to the U-turn at an RCUT intersection with stop signs. Therefore, this study typically considered a distance equal to 700 ft between the main intersection and the U-turn crossovers. However, due to limitations in the existing geometry of the intersections, U-turn crossovers at some locations had to be located further away from the main intersection. To evaluate the impact of the distance, three models with the distances from the main intersection to the U-turn crossovers of 1100, 1500, and 1800 ft were also included in one of the locations (CA-46 and McMillan Canyon Rd intersection).

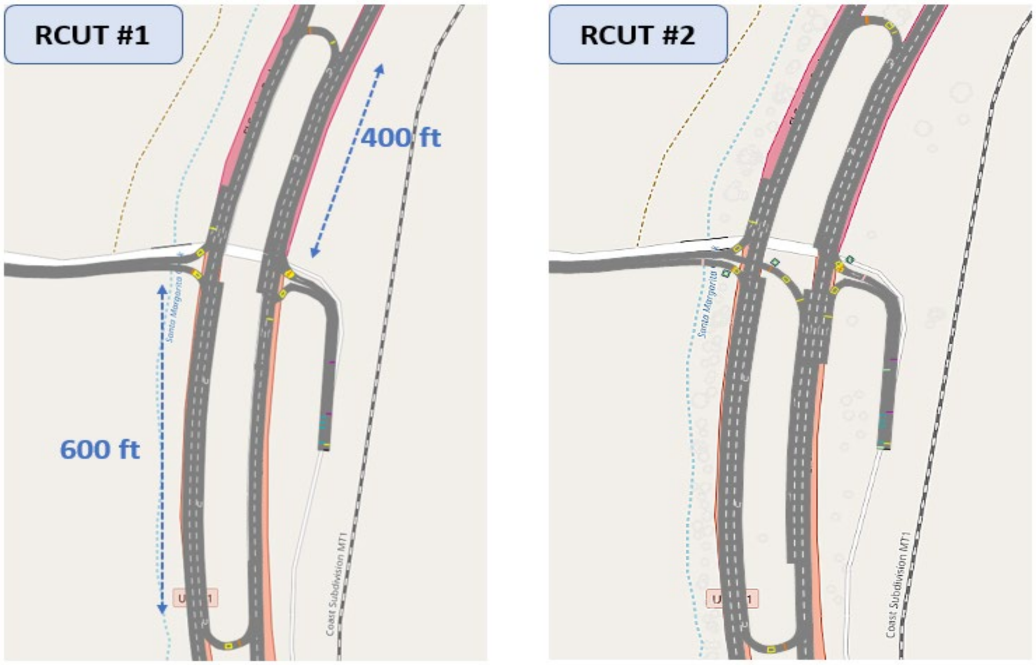

Figure 15 VISSIM models of the proposed RCUT designs in US-101 and Tassajara Rd (not to scale)

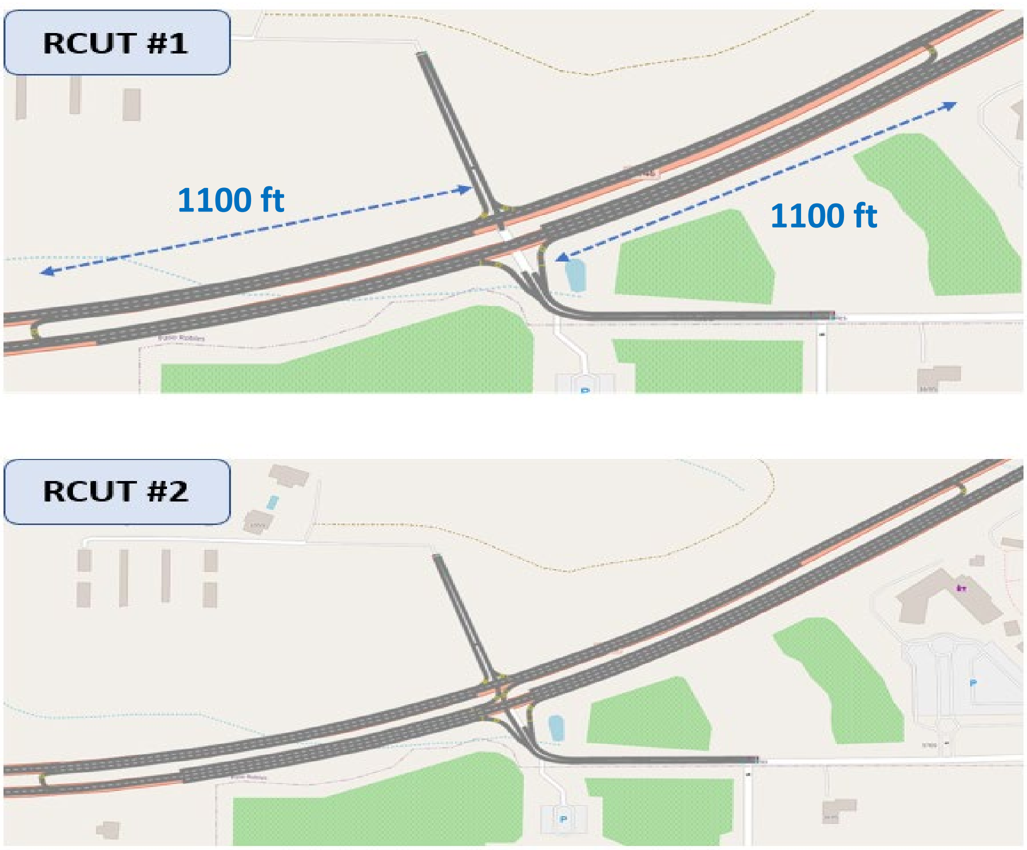

Figure 16 VISSIM models of the proposed RCUT designs in CA-46 and Mill Rd (not to scale)

For the locations on CA-46, a slightly longer separation between the U-turn crossovers and the main intersection was studied. This was in part due to the desire to keep the U-turn crossover separate from the existing left-turn pocket for the intersection. Additionally, when running the microsimulation, we observed that due to the higher speed of mainline traffic, when the U-turn separation was a shorter distance (600 ft) that vehicles attempting to access the U-turn from the side street would frequently stop in the mainline to wait for a gap. It was found that longer separation distances of 700 to 1200 ft typically prevented this undesirable behavior.

Due to the configuration of the existing intersection and turn lanes, it was chosen that the U-turn crossovers for the CA-41 and Nebraska intersection would be situated outside of the existing left turn lane envelope. This meant that the U-turns were located about 700 feet from the main intersection (Figure 18).

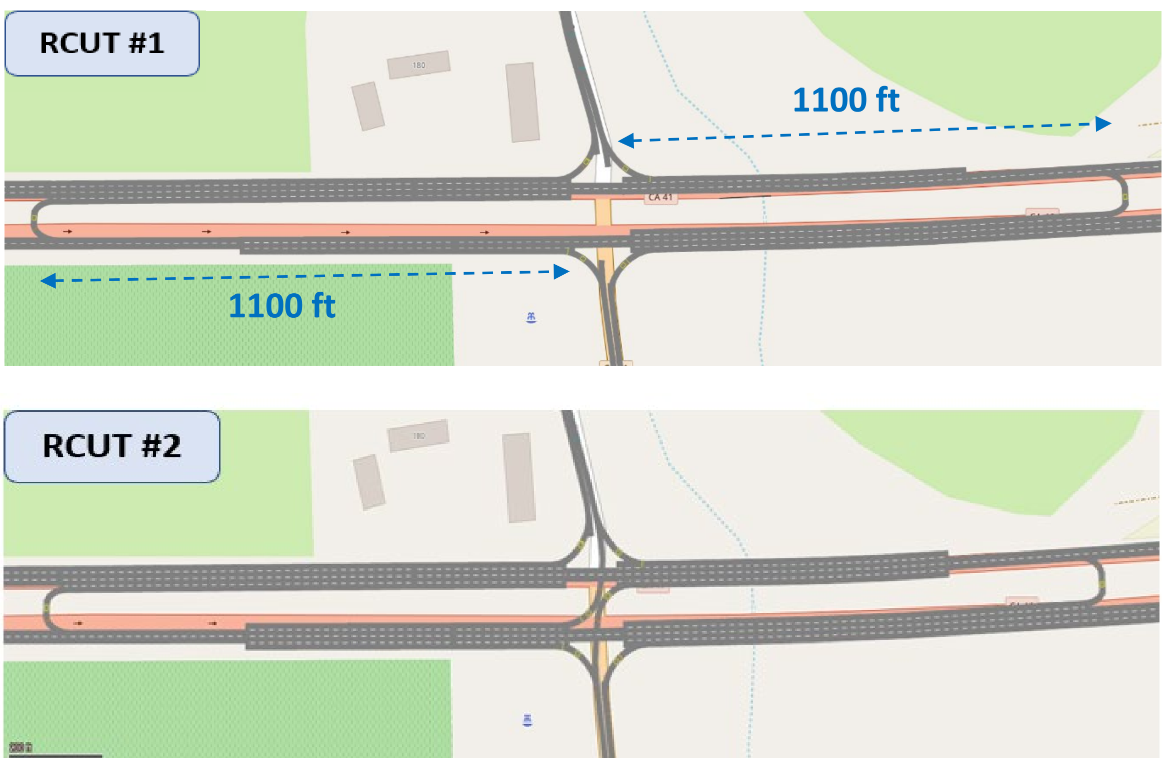

Figure 17 VISSIM models of the proposed RCUT designs in CA-46 and McMillan Canyon Rd (not to scale)

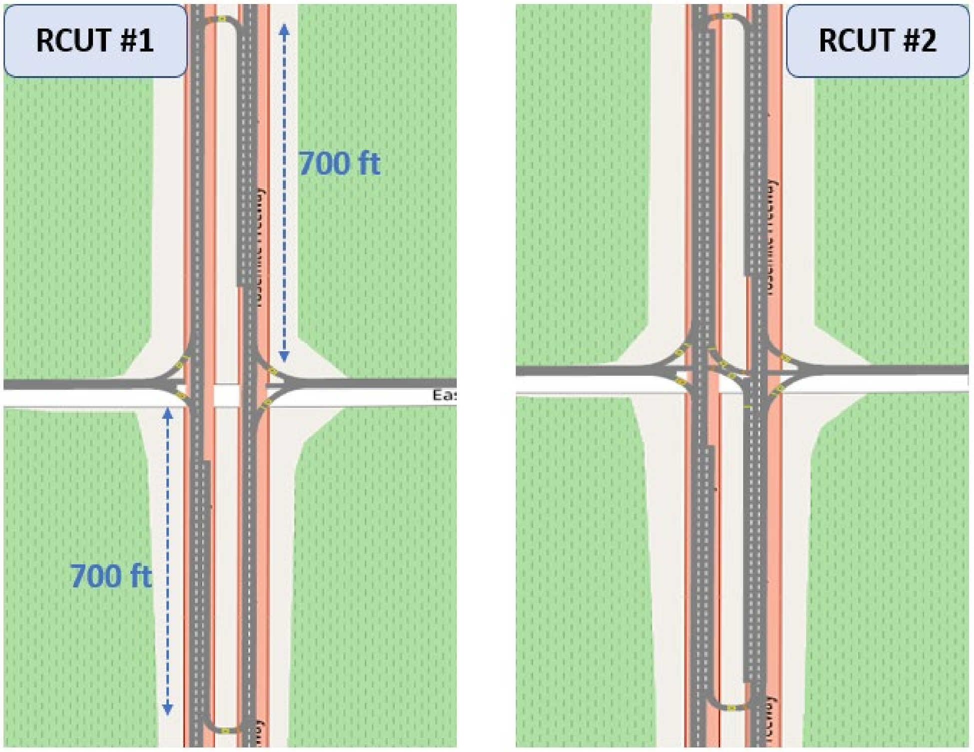

Figure 18 VISSIM models of the proposed RCUT designs in CA-41 and Nebraska Avenue (not to scale)

Similarly, for the CA-65 and Avenue 184 intersection, the U-turn on the south side was located about 800 feet from the main intersection so that the U-turn crossover would be separate from the existing left-turn lane. However, on the north side of the intersection, there is an existing pair of bridges where the highway crosses a canal adjacent to the intersection. The configuration of the structures did not allow a U-turn crossover to be proposed in advance of the bridges, and therefore it was determined that the U-turn crossover would need to be built north of the bridges. The existing structure was not wide enough to support an additional lane, so the selected design proposes building a standard 670-foot deceleration lane starting after the bridge for the U-turn. This required the U-turn crossover for the north side of the intersection to be located 1200 feet away from the main intersection (Figure 19).

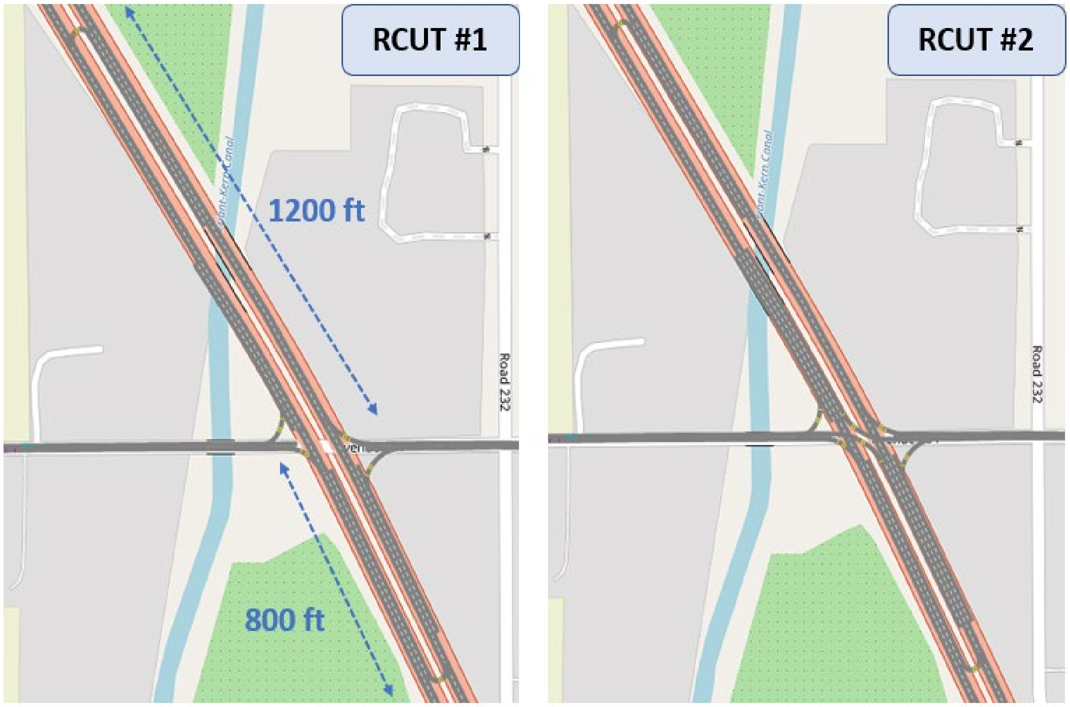

Figure 19 VISSIM models of the proposed RCUT designs in CA-65 and Avenue 184 (not to scale)

As one of the design constraints in this study, the existing intersection of US-101 and Tassajara Rd is located on mountainous terrain, and examining potential RCUT design for such location remains a relatively unexplored question in the literature. Due to the significant elevation difference between northbound (NB) and southbound (SB) directions of the north of the intersection, it is not possible to consider a U-turn crossover at a typical distance of 600-ft from the main intersection. Figure 20 shows a clear view of this issue. Therefore, the middle left-turn coming from the SB was excluded in RCUT #2 design due to insufficient length for an appropriate deceleration length for vehicles. Based on Table 3, this fact should not create an operational concern because only a few (less than three veh/hr) vehicles make a left turn from SB of the expressway. Also, the distance between the main intersection and the U-turn crossover was increased to 1200 ft because there is a bridge with limited ROW on the northern side of the intersection of CA-65 and Avenue 184. Therefore, the NB left-turn deceleration lane had to be considered after the bridge.

Figure 20 The significant elevation difference between the two directions at US-101 and Tassajara Rd

Table 6 shows geometric data collected from 14 existing RCUT intersections in a past study [10], and it guided the RCUT designs modeled in VISSIM. It should be mentioned that the existing median width at all of the intersections was appropriate for upgrading the existing design to an RCUT design. The same number of lanes as the existing intersection was considered for the proposed designs to make a fair comparison. All the other geometric features were considered based on the AASHTO Green Book [24], Caltrans Highway Design Manual (Highway Design Manual (HDM) | Caltrans," n.d.), and data reported in Table 5 [37];.

Table 6. A summary of geometric data of 14 existing RCUT intersections [10]

Parameters	Radius of U-turn, (ft)	Radius of Loon, (ft)	Median Width, (ft)	Distance from U-turns to the Center, (ft)
Average	29	47	31	1030
Median	28	45	22	900
Minimum	15	40	8	500
Maximum	40	60	130	2400

In the next section, the results of the scenarios from the simulation runs are described followed by the expected safety performance of the R-CUT design.

Chapter IV: Results

5.1 Traffic Operation Analysis

For operational analysis, the travel times for each movement were used as a measure of performance. Table 7 shows average travel times obtained from VISSIM for 2020 and 2030 traffic scenarios. Note that RCUT #1 and #2 showed no significant difference in average travel times for all vehicles traversing the network compared to the existing TWSC design in all the case studies except the CA-46 and McMillan Canyon Rd intersection. This is consistent with past studies [16], [28], [33], [47], and RCUT designs should not result in higher travel time in locations with lower demands (AADT < 25,000 vpd) on the minor roads. In fact, travel times were reduced at one of the locations considered in our study. Therefore, even though the left-turn and through traffic from the minor road need to travel a longer distance in RCUT designs, the difference does not significantly impact the average travel time.

Table 7 PM Peak hour Mean travel time (sec) based on VISSIM

Location	Design	2020	2030
101 and Tassajara	Existing	109	110
	RCUT #1	109	110
	RCUT #2	109	112
46 and Mill	Existing	51	51
	RCUT #1	52	52
	RCUT #2	49	49
46 and McMillan Canyon	Existing	82	83
	RCUT #1	61	62
	RCUT #2	62	62
41 and Nebraska	Existing	41	42
	RCUT #1	43	43
	RCUT #2	43	43
65 and Ave. 184	Existing	47	48
	RCUT #1	49	49
	RCUT #2	48	48

Average vehicle travel times were identified to be even shorter for RCUT designs compared to the existing intersection of CA-46 and McMillan Canyon Rd intersection. Note that converting minor street movements from the shared left, through, and right into all right should reduce delay at the stop bar. The other possible reason for the superior performance of RCUT designs may be attributed to the high left-turn demand coming from one of the minor roads (NB) at the intersection of CA-46 and McMillan Canyon Rd. Based on Table 3, the NB minor road includes a range of 192-343 left-turn vehicles per hour (3.2-5.7 vehicles per minute). Therefore, in a conventional TWSC intersection, a long delay could be expected for those vehicles because of the lower possibility of finding an adequate gap with both directions of the major road. On the other hand, the left-turn vehicles from the minor road could find an acceptable gap faster in merging conflict points with only one direction of the major road (instead of a crossing conflict point with both directions). Also, drivers driving on the major roads might react by reducing the vehicle speed when the minor road vehicles have short gaps with them in the conflict points.

Therefore, in terms of traffic operation, either of the two RCUT designs would be an acceptable alternative for these locations, given its low travel demand from the minor street approaches.

5.2 Surrogate Safety Assessment

For the surrogate measure-based approach, vehicle trajectory information from each of the simulation scenarios was used in SSAM to identify the number and type of simulated conflicts for each scenario. Based on a review of past studies on applying SSAM [41], [42], [48], a TTC (Time to collision) threshold of 1.5-sec was selected for this study. Table 8 shows the SSAM outcomes on conflicts.

Table 8 Average simulated conflicts based on SSAM

Location	Design	2020				2030			
		Total	Crossing	Rear-End	Lane Change	Total	Crossing	Rear-End	Lane Change
101 and Tassajara	Existing	18	1	10	7	24	2	14	9
	RCUT #1	21	0	12	8	28	0	17	11
	RCUT #2	24	0	14	10	30	1	27	12
46 and Mill	Existing	4	1	3	2	6	1	4	2
	RCUT #1	6	1	5	1	7	1	6	2
	RCUT #2	7	1	5	3	10	1	7	4
46 and McMillan Canyon	Existing	6	2	2	3	6	2	3	3
	RCUT #1	9	0	7	2	14	0	11	4
	RCUT #2	11	0	6	6	17	1	9	9
41 and Nebraska	Existing	5	2	3	2	8	2	5	2
	RCUT #1	10	1	6	5	17	1	9	9
	RCUT #2	8	1	5	4	13	1	7	6
65 and Ave. 184	Existing	7	3	3	2	9	3	4	3
	RCUT #1	15	3	7	7	23	3	10	11
	RCUT #2	11	1	6	4	16	2	8	7

According to Table 8, RCUT #1 (the alternative with no left-turn lane in the center) would be the safest alternative. Even though RCUT #1 had more rear-end and lane-change conflicts compared to the existing design, RCUT #1 design eliminates crossing conflicts. On the other hand, the existing design has the potential for safety concerns dues to the presence of crossing conflicts. It should be noted that the overall number of conflicts does increase with the two RCUT designs. It is likely caused by minor road traffic being involved in weaving maneuvers to access the U-turn crossovers. In other words, there may be a trade-off between the RCUT and existing design such that RCUT designs increase the less severe conflicts even as they reduce/eliminate crossing conflicts. Based on the FHWA guide for RCUT designs [1], the number of fatal, injury, angle, and left-turn crashes could be reduced by more than half after upgrading a conventional stop-controlled intersection to an RCUT intersection. However, sideswipe, rear-end, and other types of crashes decrease either by a lesser degree or increase slightly. Note that the majority of the first category of crashes (fatal, injury, angle, and left turn) are usually due to crossing conflicts at intersections, while lane change and rear-end conflicts mostly result in crashes with a lower severity (like sideswipe and rear-end).

5.3 The Impact of the U-Turn Spacing

As mentioned earlier, the FHWA guide for RCUTs [1] recommends a range of the U-turn spacing of 400-800 ft. Unfortunately, only a few studies have evaluated the performance of RCUT designs in different U-turn spacings. In one of the recent studies [17], it was found that increasing the U-turn spacing could reduce the number of crashes but increase the travel time. Therefore, the study [17] recommended longer lengths, such as 2,000 ft, at intersections with high traffic demands. On the other hand, it should be noted that short U-turn spacing could result in shorter travel time and a lower likelihood of driving violations.

Table 9 Simulation results for 2020 scenarios in networks with different spacings between U-turns and the main node at the intersection of CA-46 and McMillan Canyon Rd

Design	SSAM				VISSIM
	Total	Crossing	Rear-end	Lane Change	Vehicle Travel Time (sec)
RCUT #2 with 800' spacing	11	0	7	4	61
RCUT #2 with 1200' spacing	12	0	6	6	62
RCUT #2 with 1500' spacing	12	0	6	6	62
RCUT #2 with 1800' spacing	11	0	5	6	62

To identify the impact of the spacing between the U-turn crossovers and the main intersection, four different U-turn spacings were considered in testing the 2020 scenarios of the intersection of CA-46 and McMillan Canyon Rd. Table 9 shows the results obtained in terms of simulated conflicts and vehicle travel time. According to Table 9, no significant difference was identified between the performance of RCUT designs with different spacings between the U-turn crossovers and the main intersection. This result could be due to the lower traffic demand at the case study site compared to the previous research [17]. Therefore, there would be no benefits in considering a longer U-turn spacing in the intersections considered.

5.4 Expected Safety Performance

As mentioned previously, there are two approaches to conduct the safety analysis. The HSM-prescribed EB approach is considered the preferred option for estimating expected safety performance. With this HSM-prescribed framework, one could estimate the expected number of crashes per year that would occur if the intersection were left as a TWSC intersection (i.e., the counterfactual). The step-by-step EB estimation framework for counterfactual estimation is provided below.

1. Apply Safety Performance Function from HSM to obtained predicted crashes

The first question to be resolved was the nature of the SPF used for the analysis. The HSM provides the following SPFs for 3-legged and 4-legged rural TWSC intersections, respectively [21]:

$$N_{SPF,4ST} = EXP\left[-10.008 + 0.848 * ln\left(AADT_{Maj}\right) + 0.448 * ln\left(AADT_{Min}\right)\right] \quad [1]$$

$$N_{SPF,3ST} = EXP\left[-12.526 + 1.204 * ln\left(AADT_{Maj}\right) + 0.236 * ln\left(AADT_{Min}\right)\right] \quad [2]$$

where, $AADT_{Maj}$ = AADT of Major Approach (vpd)

$AADT_{Min}$ = AADT of Minor Approach (vpd)

2. Combine SPF prediction with crash history of the site to get expected crashes

We then combined the crash history of the site with the SPF prediction obtained from Equation1 1 or 2 using the appropriate overdispersion parameter corresponding to each SPF. Equations 3 and 4 were used for this purpose.

$$N_{expected} = w * N_{predicted} + (1 - w) * N_{observed} \qquad [3]$$

$$w = \frac{1}{1 + k\left[\sum_{all\ study\ years} N_{predicted}\right]} \qquad [4]$$

where, $N_{observed}$ = observed historical crashes at a site

w = weighted adjustment to be placed to the PSF prediction

k = overdispersion parameter from the associated SPF

The expected crash counts from Equation 3 may be used to then estimate the crash counts for the R-CUT installation using the CMF available at the CMF Clearinghouse portal by the FHWA [49]. It should be noted that the CMFs available for RCUT would only be applicable for the two Caltrans District 6 locations and one District 5 location at SR 46 and McMillan Canyon Road. The other two District 5 locations are atypical in geometry and/or proximity to other intersections, and therefore, the existing CMFs available from the clearinghouse are not applicable. The counterfactual estimate for each of the five sites is provided in the subsections below.

5.4.1 US 101 and Tassajara Creek Rd (District 5, CA)

Considering the existing 4-legged configuration of the intersection, Equation 1 should be applied for this intersection. However, due to low traffic volume in the WB direction on the minor road, the equation corresponding to 3-legged stop control intersection may be a more reasonable predictor of the safety performance. This is why we ultimately selected Equation 2 for this analysis.

The range of AADT for US 101 that would cover the peak hour volume scenarios described for the simulation models was between 50,000 and 60,000 vehicles per day (vpd). For the minor road (Tassajara Creek Rd), the range considered was 50 to 1600 vpd.

We then combined the crash history of the site (6 crashes from 2015 through 2019) with the SPF prediction obtained from Equation 2 (at the range of AADT values mentioned in Step 1) using the appropriate overdispersion parameter (2.17; for Equation 2). Equations 3 and 4 were used for this purpose.

The output expected crash frequency for TWSC at different AADT values is depicted in Figure 21.

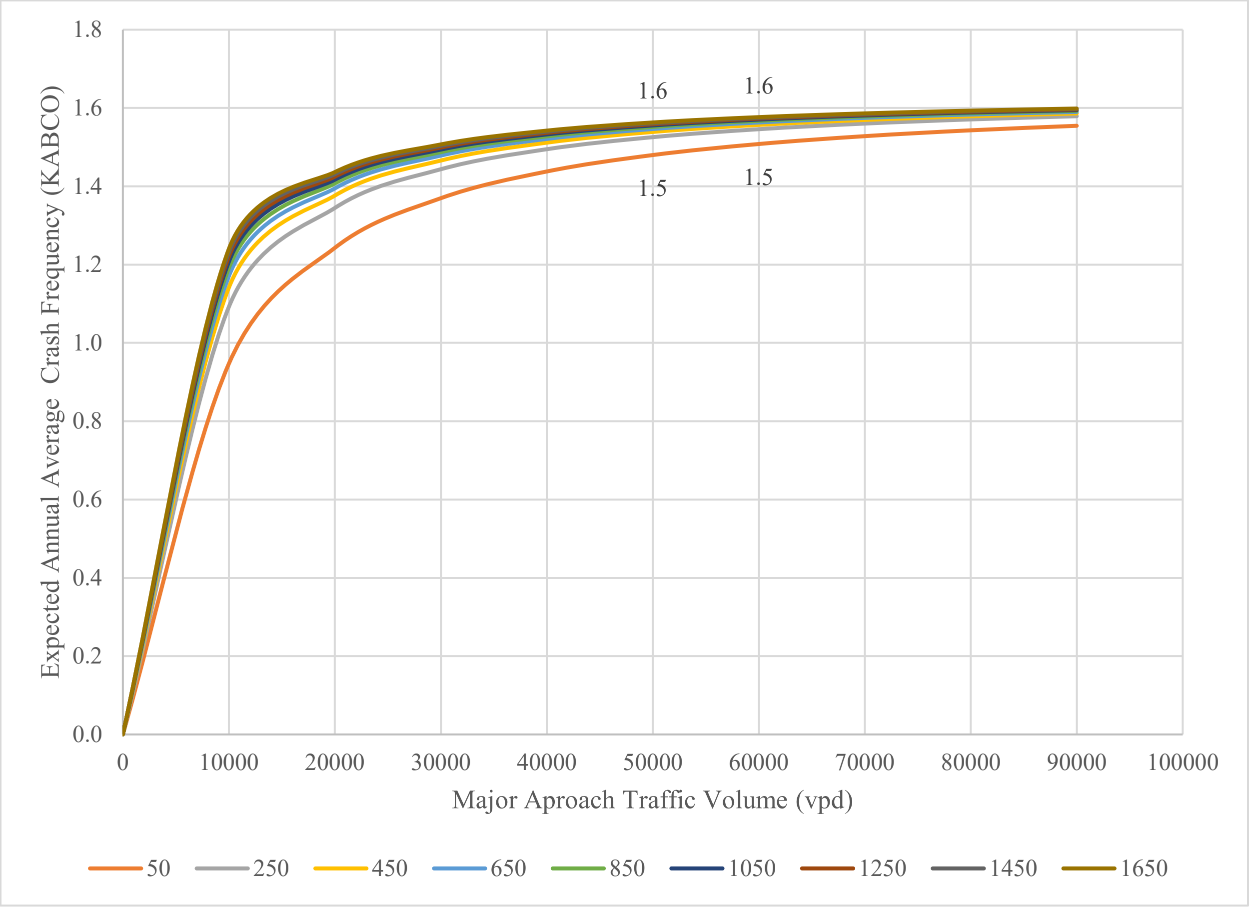

Figure 21 Expected Annual Average Crashes of All Severity at Rural 3-Leg Stop Control Intersection (California)

It should be noted that the site would be expected to have 1.5 to 1.6 crashes per year as the US 101 AADT increases from 50,000 to 60,000 vpd (See Figure 21). For a typical RCUT application, the next step would be to apply the crash modification factor for converting a TWSC into an RCUT to obtain expected crash counts for the modified intersection scenarios. These CMF may be found from the CMF clearinghouse [49].   However, given the geometric constraint of the location, the RCUT designs used here are not typical, and hence the CMFs from the literature may not be applicable. In such a situation, a surrogate measure-based approach is recommended for estimating expected safety.

5.4.2 Highway 46 and Mill Road (Distract 5, California)

Considering the existing 4-legged configuration of the intersection, Equation 1 should be applied. The range of AADT for HWY 46 that would encompass peak hour volume scenarios described for the simulation models was between 50,000 and 60,000 vehicles per day (vpd). For the minor road (Mill Road), the range considered was 200 to 1800 vpd. We combined the crash history of the site (6 crashes from 2015 through 2019) with the SPF prediction obtained from Equation 1 (at the range of AADT values mentioned in Step 1) using the appropriate overdispersion parameter (2.02; for Equation 1). The output expected crash frequency for TWSC at different AADT values is depicted in Figure 22.

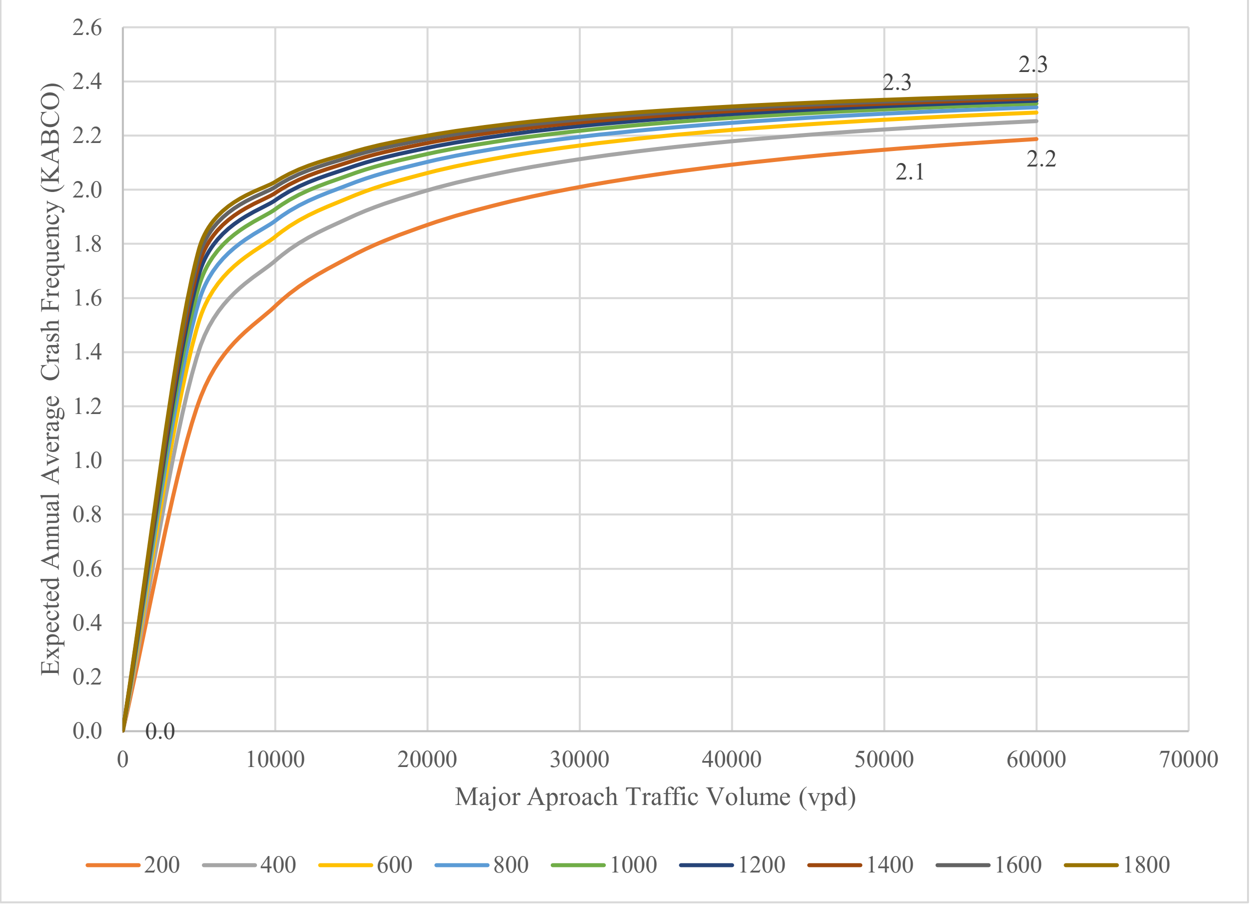

Figure 22 Expected Annual Average Crashes of All Severity at Rural 4-Leg Stop Control Intersection (Highway 46 and Mill Road, California)

It should be noted that the site would be expected to have 2.1 to 2.3 crashes per year as the CA 46 AADT increases from 50,000 to 60,000 vpd (See Figure 22). The expected value can serve in as the baseline to evaluate future traffic safety changes at this location resulting from any redesign. Due to the proximity of the intersections to other intersections, the CMFs available from the FHWA's CMF clearinghouse [49] may not be applicable.

5.4.3 Highway 46 and McMillan Canyon Road (Distract 5, California)

Considering the existing 4-legged configuration of the intersection, Equation 1 should be applied. The range of AADT for HWY 46 that would cover the peak hour volume scenarios described for the simulation models was between 50,000 and 60,000 vehicles per day (vpd). For the minor road (McMillan Canyon Road), the range considered was 200 to 1800 vpd. The output expected crash frequency for TWSC at different AADT values is depicted in Figure 23.

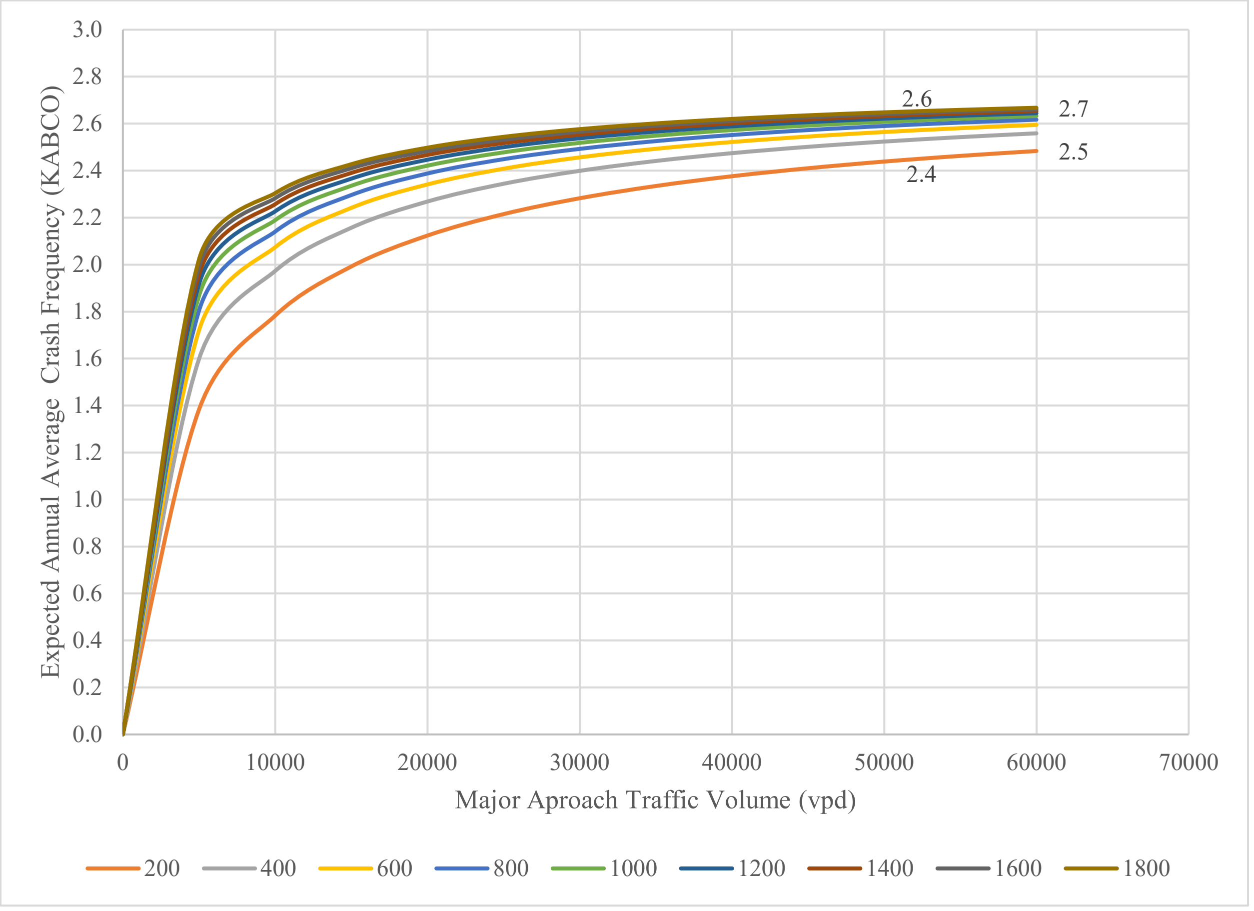

Figure 23 Expected Annual Average Crashes of All Severity at Rural 4-Leg Stop Control Intersection (Highway 46 and McMillan Canyon Road, California)

It should be noted that the site would be expected to have 2.4 to 2.7 crashes per year as the CA 46 AADT increases from 50,000 to 60,000 vpd (See Figure 23). This is the location we are recommending for further evaluation of RCUT design given the constraints at other SLO county sites.

5.4.4 Highway 41 and Nebraska Avenue (Distract 6, California)

Considering the existing 4-legged configuration of the intersection, Equation 1 should be applied. The range of AADT for HWY 41 that would cover the peak hour volume scenarios described for the simulation models was between 50,000 and 60,000 vehicles per day (vpd). For the minor road (Nebraska avenue), the range considered was 400 to 2000 vpd.

We then combined the crash history of the site (7 crashes from 2017 through 2019) with the SPF prediction obtained from Equation 1 (at the range of AADT values mentioned in Step 1) using the appropriate overdispersion parameter (2.02; for Equation 1).

The output expected crash frequency for TWSC at different AADT values is depicted in Figure 24.

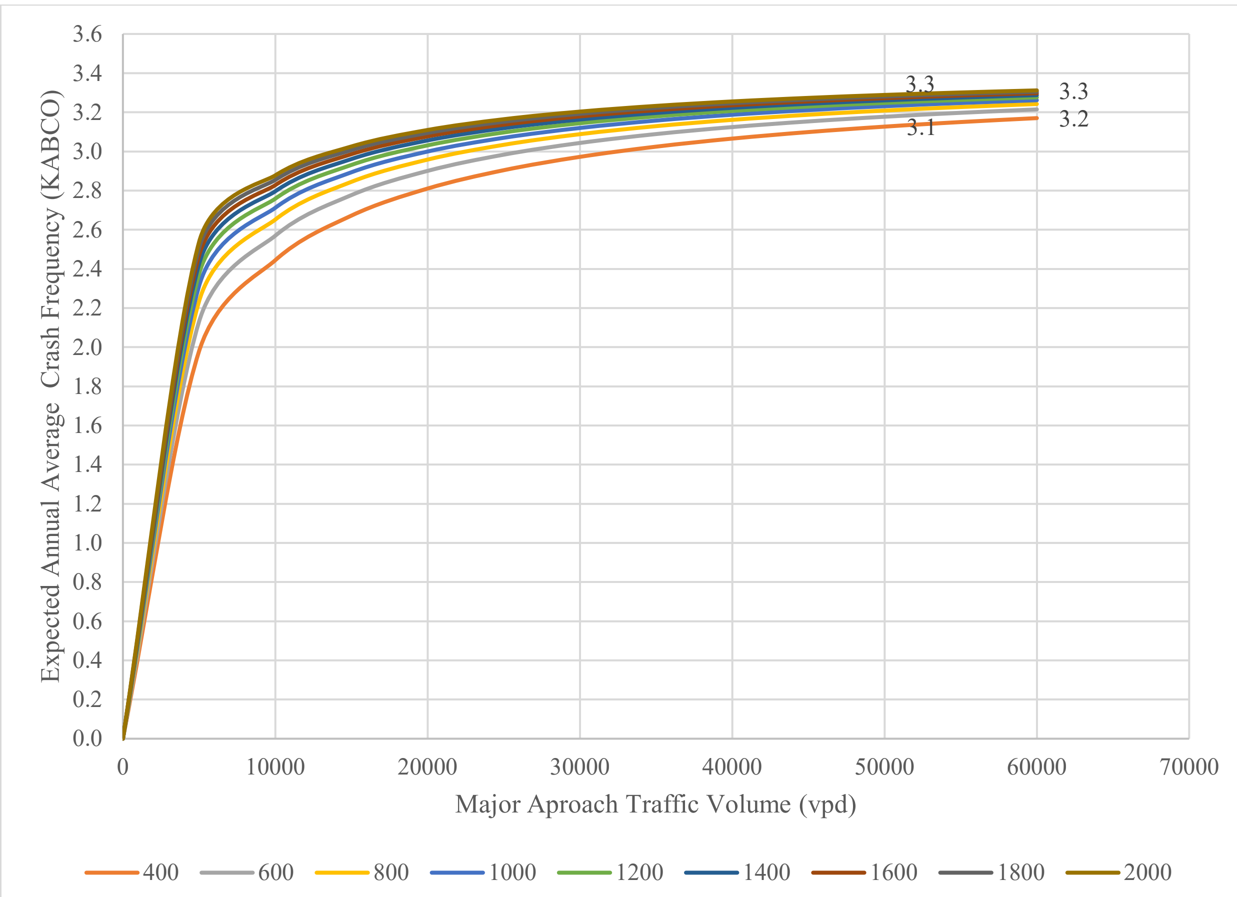

Figure 24 Expected Annual Average Crashes of All Severity at Rural 4-Leg Stop Control Intersection (Highway 41 and Nebraska Avenue, California)

It should be noted that the site would be expected to have 3.1 to 3.3 crashes per year as the CA 41 AADT increases from 50,000 to 60,000 vpd (See Figure 24). The expected value can serve as the baseline to evaluate future traffic safety changes at this location resulting from any redesign and for future B/C ratio estimation.

5.4.5 Highway 65 and Avenue 184 (Distract 6, California)

Considering the existing 4-legged configuration of the intersection, Equation 1 should be applied. The range of AADT for HWY 65 that would cover the peak hour volume scenarios described for the simulation models was between 50,000 and 60,000 vehicles per day (vpd). For the minor road (Avenue 184), the range considered was 800 to 4000 vpd. We then combined the crash history of the site (7 crashes from 2017 through 2019) with the SPF prediction obtained from Equation 1 (at the range of AADT values mentioned in Step 1) using the appropriate overdispersion parameter (2.02; for Equation 1). The output expected crash frequency for TWSC at different AADT values is depicted in Figure 25.

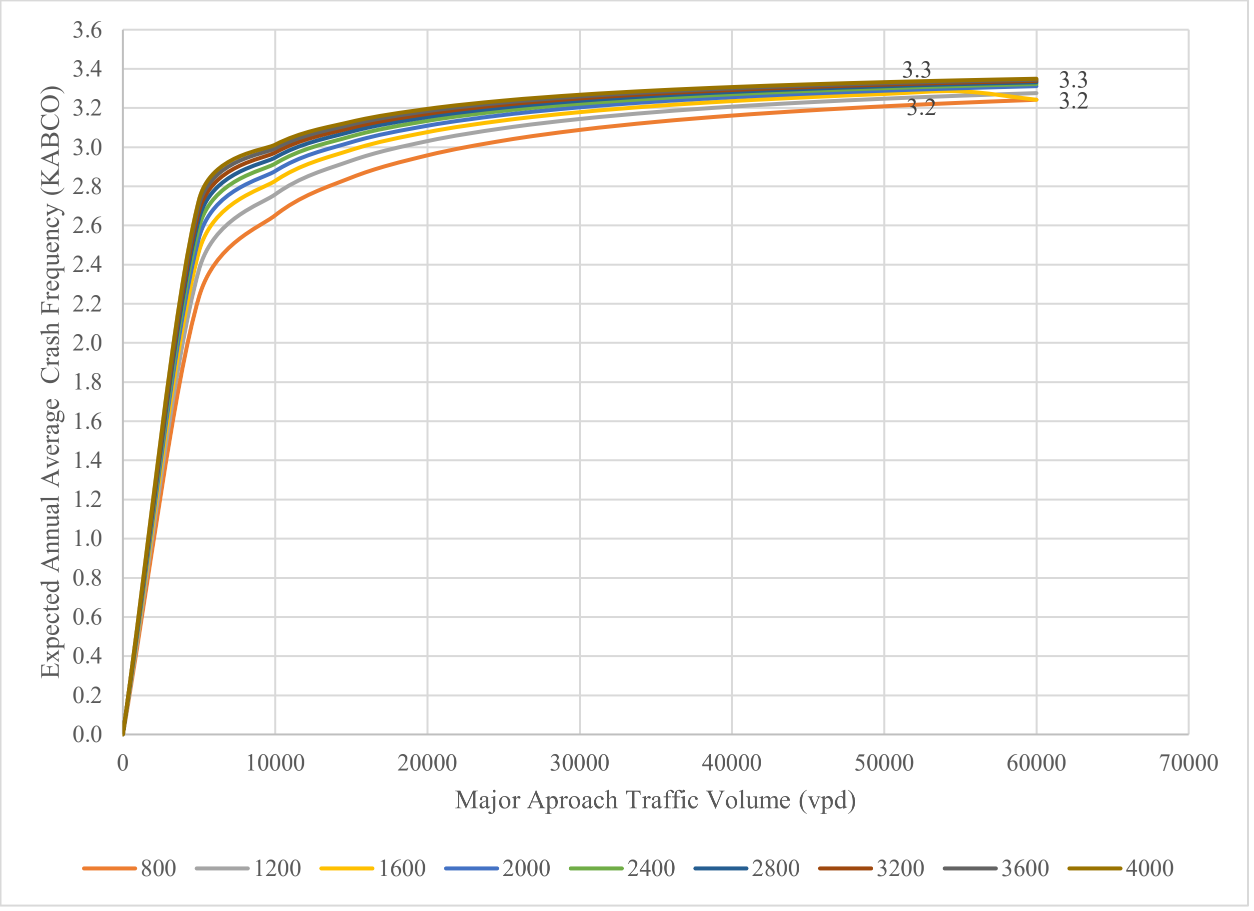

Figure 25 Expected Annual Average Crashes of All Severity at Rural 4-Leg Stop Control Intersection (Highway 65 and Avenue 184, California)

It should be noted that the site would be expected to have 3.2 to 3.3 crashes per year (with existing TWSC configuration) as the CA 65 AADT increases from 50,000 to 60,000 vpd (See Figure 25). This can serve as a baseline for future evaluation of safety benefits.

5.5 B/C Ratio Estimation

As mentioned previously, based on safety performance and relatively unconstrained geometric design, we are proposing further consideration of R-CUT design at Highway 46 and McMillan Canyon Road in Caltrans District 5. For this location, the CMF obtained from the FHWA clearinghouse [49] was used to estimate the Benefit/Cost (B/C) ratio for installing RCUT at this location. The process of estimating the B/C ratio is documented in the form of Caltrans's ICE (Intersection Control Evaluation) worksheet template is provided in Appendix A. Intersection Control Evaluation (ICE) is the process and framework that Caltrans and a growing number of transportation agencies nationwide have adopted to objectively screen alternatives and identify optimal geometric and control solutions for an intersection [50]. The appendix provides the B/C estimation process in a template already being used by Caltrans. This will ensure that the agency personnel are able to add R-CUT as a potential alternative to a grade-separated interchange on rural interchanges. The B/C ratio for RCUT at this location was estimated to be 7.35. The estimate considers construction and right-of-way costs and safety benefits resulting from R-CUT design compared to the existing TWSC design. The cost of implementing the R-CUT design is estimated to be $1.4M, which is significantly lower than a fully grade-separated interchange design.

Chapter V: Conclusions

Intersection treatments, even with proven effectiveness, often have a wide discrepancy in their applications from one jurisdiction to the next. Agencies applying a certain new treatment often need a way to estimate future operational and safety benefits for their sites. Such estimations are not trivial to obtain merely based on post hoc studies from other jurisdictions. A robust framework to estimate the future operational and safety benefits of intersection treatments is proposed in this research. The framework may be summarized as follows:

- Develop microsimulation models for existing and potential treatment designs,
- Estimate operational benefits using a well-calibrated simulation model using Measures of Performance, e.g., travel time,
- Review CMF clearinghouse and other literature for assessing the safety benefits for the treatment. If the intersection treatment is typical, use the HSM-prescribed Empirical Bayes method to estimate the safety performance of the proposed design. Otherwise, use a surrogate safety-measure based approach,
- Estimate B/C ratio for upgrading the existing intersections using the estimate of right-of-way and construction costs as well as benefits resulting from the potential reduction in severe crashes.

This study demonstrated this framework in the context of potential RCUT designs for five rural California intersections. Overall, 126 simulation scenarios were models using VISSIM for estimating operational performance at varying levels of travel demand for the intersection. The scenario included the base condition with TWSC intersection and two RCUT designs. Note that given the topography of the locations, geometric features of the RCUT alternatives were considered consistent with right-of-way (ROW) and geometric restrictions. Due to differences in terms of environmental conditions and driving behavior, the available CMFs (obtained in other states) in the literature might not be directly applicable to these locations. Hence a surrogate measure-based safety analysis was also conducted after calibrating the simulation networks based on real-world data.

Based on the simulation results, the proposed RCUT designs reduced or eliminated the more severe crossing conflicts. For both RCUT designs considered in the study, there was an increase in rear-end and lane-change conflicts compared to the TWSC design. It may indicate a future trade-off between (reduced) severe vs. (increased) non-severe crashes following the installation of RCUT. It should also be noted that increasing the U-turn distance at one of the intersections where it was feasible to do so did not eliminate the weaving maneuvers that lead to increased conflicts.

For one of the District 5 locations, a detailed B/C ratio analysis was performed using ICE framework used for by Caltrans and several other DOTs. The B/C ratio for the location was estimated to be 7.35. The template may be used for the analysis of future locations where RCUT may be appropriate. The webinars to modify existing templates used by Caltrans to include RCUT designs are going to feature in future teach transfer activities for this project.

References

[1] J. Hummer, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen, “Restricted crossing u-turn: informational guide.,” Federal Highway Administration, United States, Office of Safety Research and Development, 2014.

[2] A. M. Holzem, J. E. Hummer, C. M. Cunningham, S. W. O’Brien, B. J. Schroeder, and K. Salamati, “Pedestrian and bicyclist accommodations and crossings on superstreets,” *Transportation research record*, vol. 2486, no. 1, pp. 34–44, 2015.

[3] W. Hughes, R. Jagannathan, D. Sengupta, and J. Hummer, “Alternative intersections/interchanges: informational report (AIIR),” Federal Highway Administration, United States, United States., 2010.

[4] J. E. Hummer, “Moving Beyond CAP-X to Combinations of Alternative Intersections That Might Be Worth Further Investigation,” *Transportation Research Record*, vol. 2674, no. 8, 2020.

[5] J. E. Hummer, “Unconventional left-turn alternatives for urban and suburban arterials—part two,” *ITE journal*, vol. 68, no. 11, pp. 101–106, 1998.

[6] J. E. Hummer and R. Jagannathan, “An update on superstreet implementation and research,” presented at the 8th National Conference on Access Management, 2008.

[7] J. E. Hummer and S. Rao, “Safety Evaluation of Restricted Crossing U-Turn Intersection,” Federal Highway Administration, United States, FHWA-HRT-17-082, 2017.

[8] J. D. Reid and J. E. Hummer, “Travel time comparisons between seven unconventional arterial intersection designs,” Transportation Research Record, 01–2957, 2001.

[9] S. E. Ott, R. L. Haley, J. E. Hummer, R. S. Foyle, and C. M. Cunningham, “Safety effects of unsignalized superstreets in North Carolina,” *Accident Analysis & Prevention*, vol. 45, pp. 572–579, 2012.

[10] A. M. Molan and J. E. Hummer, “Safety analysis of the new synchronized and Milwaukee B interchanges in comparison to existing designs,” *Accident Analysis & Prevention*, vol. 109, pp. 29–35, 2017.

[11] A. M. Molan and J. E. Hummer, “Simulation modeling of pedestrian performance in the new synchronized and Milwaukee B interchanges versus existing designs,” *Transportation research record*, vol. 2672, no. 35, pp. 151–160, 2018.

[12] A. M. Molan and J. E. Hummer, “Proposing the new parclo progressA design as a substitute for the conventional partial cloverleaf A interchanges,” *International Journal of Modelling and Simulation*, pp. 1–15, 2020.

[13] A. M. Molan and J. Hummer, “Queue Lengths Produced by the New Synchronized and Milwaukee B Interchanges Compared to Existing Designs,” presented at the International Conference on Transportation and Development 2020, 2020.

[14] A. M. Molan and J. E. Hummer, “Improving Traffic Operations at Service Interchanges Using the New Offset Diamond Design,” *Transportation Research Record (TRR)*, 2020.

[15] A. M. Molan and J. E. Hummer, “Travel time evaluation of synchronized and Milwaukee B as new interchange designs,” *Journal of Transportation Engineering, Part A: Systems*, vol. 144, no. 2, 2018.

[16] P. Edara, C. Sun, and S. Breslow, “Evaluation of j-turn intersection design performance in Missouri,” Missouri. Dept. of Transportation, Organizational Results, 2013.

[17] C. Sun, P. Edara, C. Nemmers, and B. Balakrishnan, “Driving simulator study of J-Turn acceleration/deceleration lane and U-turn spacing,” Midwest Transportation Center, 2016.

[18] A. M. Molan, J. E. Hummer, and K. Ksaibati, “Introducing the super DDI as a promising alternative service interchange,” *Transportation research record*, vol. 2673, no. 3, pp. 586–597, 2019.
[19] J. A. Bonneson and P. T. McCoy, “Estimation of safety at two-way stop-controlled intersections on rural highways,” *Transportation Research Record*, vol. 1399, pp. 83–89, 1993.
[20] L. Holden, “Highway 101’s deadly Wellsona Road intersection defies easy solutions,” *San Luis Obispo Tribune*, Nov. 19, 2016.
[21] D. Part, “Highway safety manual.” AASHTO, 2010.
[22] D. Gettman, L. Pu, T. Sayed, S. Shelby, and I. T. S. Siemens, “Surrogate safety assessment model and validation,” Federal Highway Administration, United States, Office of Safety Research and Development FHWA-HRT-08-051, 2008.
[23] “Traffic Census Program,” *Caltrans*, Accessed: Dec. 21, 2020. [Online]. Available: https://dot.ca.gov/programs/traffic-operations/census.
[24] “A Policy on Geometric Design of Highways and Streets,” *American Association of State Highway and Transportation (AASHTO)*, 2018.
[25] “California Manual for Setting Speed Limits,” *Caltrans*, p. 94, 2020.
[26] T. Maze, J. Hochstein, R. Souleyrette, H. Preston, and R. Storm, “Median intersection design for rural high-speed divided highways,” NCHRP Report, 650, 2010.
[27] A. Goare, “Family of Cal Poly student killed on Highway 101 pushes for safety improvements,” *KSBY*, Oct. 15, 2018.
[28] A. M. Molan, “Evaluation of Milwaukee B and synchronized as new service interchange designs,” 2017.
[29] P. W. Dorothy, T. L. Maleck, and S. E. Nolf, “Operational aspects of Michigan design for divided highways,” *Transportation Research Record*, vol. 1579, no. 1, pp. 18–26, 1997.
[30] A. M. Molan, J. E. Hummer, and K. Ksaibati, “Modeling safety performance of the new super DDI design in terms of vehicular traffic and pedestrian,” *Accident Analysis & Prevention*, vol. 127, pp. 198–209, 2019.
[31] V. W. Inman and R. P. Haas, “Field evaluation of a restricted crossing U-turn intersection,” Federal Highway Administration, United States, Office of Safety Research and Development FHWA-HRT-11-067, 2012.
[32] W. Zhang and N. Kronprasert, “The ABCs of Designing RCUTs,” *Public Roads*, vol. 78, no. 2, 2014.
[33] T. Adams, “Restricted Crossing U-turns at Rural Intersections,” University of Nebraska - Lincoln, 2019.
[34] H. Steyn, Z. Bugg, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen, “Displaced Left Turn Informational Guide,” Federal Highway Administration, 2014.
[35] J. Hummer and J. Reid, “Unconventional left-turn alternatives for urban and suburban arterials: an update,” presented at the Urban Street Symposium, 2000.
[36] L. A. Rodegerdts, “Signalized intersections: Informational guide,” Federal Highway Administration, United States, 2004.
[37] “Highway Design Manual (HDM),” *Caltrans*, Accessed: Jul. 08, 2020. [Online]. Available: https://dot.ca.gov/programs/design/manual-highway-design-manual-hdm.
[38] J. E. Hummer, “Developing, Using, and Improving Tables: Showing the Safest Feasible Intersection Design,” *ITE journal*, vol. 90, no. 5, 2020.

[39] D. Gettman and L. Head, “Surrogate safety measures from traffic simulation models,” *Transportation Research Record*, vol. 1840, no. 1, pp. 104–115, 2003.

[40] R. Fan, H. Yu, P. Liu, and W. Wang, “Using VISSIM simulation model and Surrogate Safety Assessment Model for estimating field measured traffic conflicts at freeway merge areas,” *IET Intelligent Transport Systems*, vol. 7, no. 1, pp. 68–77, 2013.

[41] F. Huang, P. Liu, H. Yu, and W. Wang, “Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections,” *Accident Analysis & Prevention*, vol. 50, pp. 1014–1024, 2013.

[42] M. Essa and T. Sayed, “Transferability of calibrated microsimulation model parameters for safety assessment using simulated conflicts,” *Accident Analysis & Prevention*, vol. 84, pp. 41–53, 2015.

[43] P. Liu, X. Qu, H. Yu, W. Wang, and B. Cao, “Development of a VISSIM simulation model for U-turns at unsignalized intersections,” *Journal of Transportation Engineering*, vol. 138, no. 11, pp. 1333–1339, 2012.

[44] “COVID-19 IN TULARE COUNTY.”

[45] A. Molan *et al.*, “Evaluation of Coordinated Ramp Metering (CRM) Implemented By Caltrans,” Minetra Transportation Institute, 2020.

[46] E. Hauer, *Observational before/after studies in road safety. Estimating the effect of highway and traffic engineering measures on road safety*. 1997.

[47] X. Sun, M. A. Rahman, and M. Sun, “Safety Analysis of RCUT Intersection,” 2019, pp. 1–6.

[48] U. Shahdah, F. Saccomanno, and B. Persaud, “Integrated traffic conflict model for estimating crash modification factors,” *Accident Analysis & Prevention*, vol. 71, pp. 228–235, 2014.

[49] “Crash Modification Factors Clearinghouse.” http://www.cmfclearinghouse.org/ (accessed Mar. 03, 2021).

[50] “Intersection Control Evaluation (ICE) | Caltrans.” https://dot.ca.gov/programs/traffic-operations/ice (accessed Mar. 08, 2021).

Appendix A: ICE for RCUT at Route 46 and McMillan Canyon Road[1]

Intersection Control Evaluation

Collision Cost Analysis and B/C

-- Fill in tan boxes along with 'Area' --*

County	Rte	Postmile	Location Description
SLO	46	45.48	/S of Rte 46 and McMillan Canyon R

Intersection Types:
F - Four-Legged
M - Multi-Legged
S - Offsett -Tee
Y - "Y" Wye
Z - Others

Existing Condition	Area	# of Years for Analysis	Rate Group
Stop Control (Minor Leg), Type F, M or S	Rural	20	I 02

Existing ADT (x1000)		Future ADT (x1000)			
Mainline	Cross St	Mainline	Cross St	Average ADT	VCF
18.6	1.3	22.2	1.5	21.8	1.10

Est. Capital Cost (x1000) for Desired Improvement			
Desired Improvement	Const	R/W	Total
Restricted Crossing U-Turn	$ 1,300	$ 100	$ 1,400
		.	$ -

Existing Collision Data			
Number of Years	3	Total Collisions	5
Injury	1	PDO	4
Fatal	0	Fat + Inj	1

	Collision Cost (x1000)						B/C
	Existing Condition		Desired Improvement		Projected Savings		
1	Stop Control (Minor Leg), Type F, M or S	$13,083	Restricted Crossing U-Turn	$2,791	$10,292		7.35

[1] https://cpslo-my.sharepoint.com/:x:/g/personal/apande_calpoly_edu/EQh2rFj1CmBHtz04i3wzwfsBgWDxh5pkJSeebqabBcwmiw?e=SEmxR7

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Appendix B: Technology Transfer

T2 Activities

Activity Date	Represented Stakeholder Organization	Details
1/16/2019	SLOCOG	Discussion of the role of simulation for future planning (Pre-proposal)
11/15/2019	SLOCOG, Caltrans	Literature Update, Research Plan
3/20/2020	SLOCOG, Caltrans	Research Plan review in light of the Pandemic-related issues
5/28/2020	SLOCOG	Preparation for meeting with San Luis Obispo regional Transportation Safety Partnership Meeting
6/9/2020	San Luis Obispo regional Transportation Safety Partnership committee (SLOCOG, Caltrans, and consulting professionals in SLO County)	Preliminary research findings
10/16/2021	SLOCOG	Results Update and Feedback
11/2/2021	Caltrans District 6	Results Update and Feedback
1/20/2021	SLOCOG - Technical Transportation Advisory Committee (TTAC)	Results Update and Feedback
2/3/2021	SLOCOG Board of Supervisors	Final project findings presentation to SLO community and elected officials

Post-project T2 Plan

Several stakeholders from Caltrans and SLOCOG have shown interest in the intersection treatment. We are recording a webinar for developing the ICE spreadsheet for rural Caltrans District 6 intersections in April 2021. We are also looking to incorporate this treatment as one of the Left-Turn Conflict Intersection designs in the future Caltrans Local Roadway Safety Manual. It will allow RCUT to be considered as part of the HSIP grant application process.

CENTER FOR TRANSPORTATION EQUITY, DECISIONS & DOLLARS

The **Center for Transportation, Equity, Decisions and Dollars (CTEDD)** is a USDOT University Transportation Center, leading **transportation policy research** that aids in **decision making** and **improves economic development** through **more efficient, and cost-effective use of existing transportation systems,** and offers **better access to jobs and opportunities.** We are leading a larger consortium of universities focused on **providing outreach** and **research to policy makers**, through **innovative methods** and **educating future leaders of the transportation field.**

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