Driver Behavior and Performance in the Vicinity of Closely Spaced Interchange Ramps on Urban Freeways

Research Summary Report: SHRP2 IAP

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1.0 INTRODUCTION

1.1 Problem Statement

Evaluating requests for new access or modifications to existing access on freeways is a frequent activity of state departments of transportation (DOTs). Transportation agency concerns regarding new or modified freeway access include ramp spacing on the mainline and its impact to freeway operations and safety. There is a significant amount of published knowledge on geometric criteria, traffic operations, and signing in the context of freeway ramp spacing. Very little information existed on the safety impacts of ramp spacing until recently, when the University of Utah created both crash modification factors (CMFs) and severity distribution functions (SDFs) for entrance-exit (EN-EX) ramp spacing and auxiliary lane presence (Le & Porter, 2012; Shea et al., 2015). An example CMF is provided in FIGURE 1, and shows expected crash frequencies (all types and severities) increasing as ramp spacing decreases. The rate of increase becomes higher when ramp spacing is less than approximately 2000 feet. The presence of an auxiliary lane between entrance and exit ramps is expected to reduce crash frequencies and its safety benefit becomes larger as ramp spacing becomes shorter.

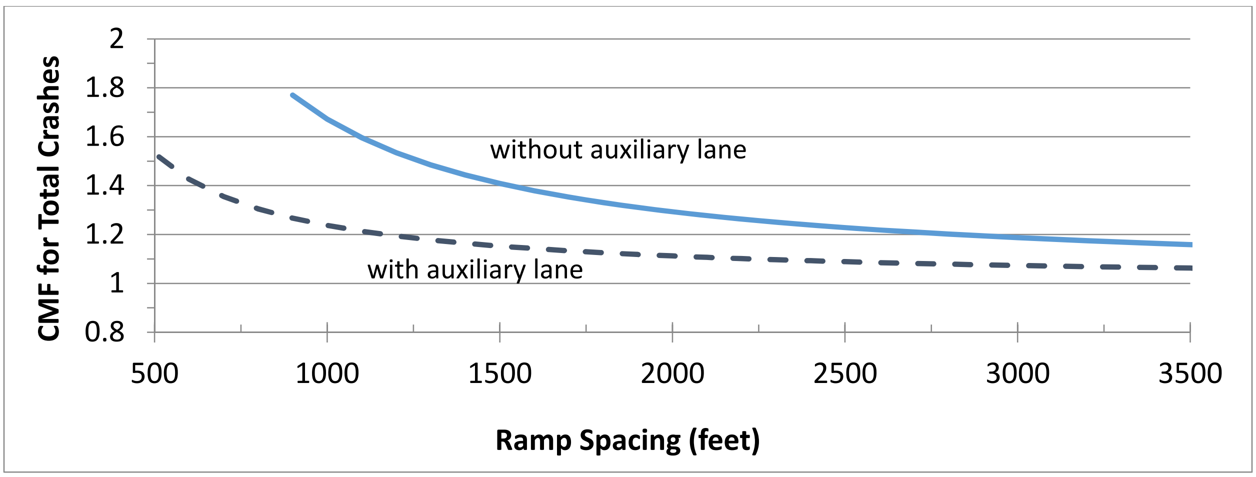


FIGURE 1 Example CMF for EN-EX Ramp Spacing and Auxiliary Lane Presence (Le & Porter, 2012).

While these CMFs can be used by state DOTs to quantify the freeway mainline safety effects of ramp spacing and auxiliary lane presence, they are purely empirical findings that represent statistical associations. Underlying, causative reasons for the crash patterns can be inferred, but are not fully understood. States will continue to assess requests for new access that result in closely spaced interchange ramps. It is unrealistic to deny all such requests, because newly constructed or reconstructed interchanges increase access to nearby destinations and may improve operations and safety on the surrounding network surface streets. A more thorough understanding of the "cause-effect" relationships leading to the crash patterns illustrated in FIGURE 1 is needed so that countermeasures can be identified and installed at current and future locations with closely spaced interchange ramps. It is impractical to design experimental approaches (e.g., basic laboratory studies, driving simulator experiments, test track studies) that truly capture the complexity of gap searching, gap acceptance, merging, diverging, and other lane changing and lane keeping activities that occur on freeway segments with an entrance ramp followed by a downstream exit ramp. The SHRP2 NDS data is the only option to reliably study driver behavior and performance at these locations.

1.2 Research Objectives and Goals

The overall objective of this research is to identify a set of "causal type groupings" for crashes in the vicinity of closely spaced interchange ramps and a corresponding set of alternative, implementable countermeasures for each "causal type grouping." Six primary outcomes and two additional secondary outcomes are expected as a product of accomplishing the overall research objective and are identified in Section 6.1 of this report. Through exploring driver behavior and performance in the vicinity of closely spaced interchange ramps using the SHRP2 NDS data and examining sequences of events which lead to crashes and near crashes in areas with closely spaced interchange ramps, this research will seek to uncover possible changes in design criteria, signing, and markings as well as other promising countermeasures to reduce crash frequencies and severities in these areas.

1.3 Phase 1, Proof of Concept Objectives

This report summarizes the results of a Phase 1, Proof on Concept set of activities associated with the overall research objective. The Phase 1 objectives were to:

- Demonstrate the ability to effectively access and work with the SHRP2 NDS databases;
- Demonstrate progress in data collection, reduction, and analysis activities aimed at achieving the overall research objective;
- Propose a Phase 2 research plan, schedule, and budget for accomplishing the overall research objectives using the lessons learned during Phase 1.

The remainder of this report documents the successful accomplishment of the Phase 1, Proof of Concept objectives. A very brief literature review (Section 2.0) is followed by brief discussions of Phase 1 methods (Section 3.0) and data (Section 4.0). Results of the Phase 1 analysis are presented and interpreted in Section 5.0. This is followed by an overview of future direction (Section 6.0), which includes a list of expected Phase 2 outcomes, and a Phase 2 proposal (Section 7.0), which contains descriptions of needed data, methods, costs, schedule, and a risk management and mitigation plan.

2.0 LITERATURE REVIEW

Areas of closely spaced interchange ramps on freeways, particularly cases of an entrance ramp followed by an exit ramp, have been studied extensively. Methods to model the operations of weaving areas have existed for more than 50 years (e.g., Normann, 1957). Independent efforts to link traditionally used measures of traffic flow and traffic safety have also been made (e.g., Lord et al., 2005; Abdel-Aty et al., 2007; Golob et al., 2008). Driver behavior models have been offered to develop interchange spacing guidelines (Chiu et al., 2004) and explore driver lane changing behavior in weaving areas (Hidas, 2005). Other work has developed empirical models of lane changing behavior and speed using combinations of field and simulated data, and include driver risk taking models, where drivers entering a freeway become willing to take greater merging risks as the distances they have left to merge decrease (Skabardonis et al., 1989; Fitzpatrick et al., 2011; Pesti et al., 2011). The use of lane-change and rear-end conflicts as surrogates to understand safety in weaving areas has also been provided as possible alternatives to crash rates (Fazio et al., 1993). Finally, recent and ongoing studies have looked at patterns of expected crash frequencies and severities between closely spaced entrance and exit ramps (Le & Porter, 2012; Shea et al., 2015; Golob et al., 2004; Bonneson & Pratt, 2009). These studies provide a wealth of statistical associations, with very little known about crash causation. The SHRP2 NDS research conducted in this project is based on the premise that the chance of directly implementable results will be maximized if the topic has been explored extensively (but empirically) up to this point with the driving behavior and performance component as the last "missing piece of the puzzle."

3.0 METHODS OF ANALYSIS

This section briefly summarizes the analysis approaches taken to address the research objective. The focus is on methods to achieve the Phase 1, Proof of Concept objectives of demonstrating abilities to effectively access and work with the SHRP2 NDS databases and demonstrating progress in data collection, reduction, and analysis activities. Phase 2 methods to support the overall research objectives are described in Section 7.1.

A significant portion of Phase 1 consisted of determining whether useful measures of driver behavior and performance in the vicinity of closely spaced interchange ramps could be extracted from the NDS data, visualized, and analyzed for a significant sample of data. Therefore, the Phase 1 methods themselves consisted primarily of developing algorithms for extracting relevant data and estimating useful performance measures. Results of these efforts are described in Section 5.0.

Available driver behavior and performance measures were ultimately a function of data quality and availability in the NDS vehicle trace data. Additional details on what was and was not available and reliable in the trace data are provided in Section 5.7. Following extensive Phase 1 exploratory efforts, algorithms were developed to automate estimation of the following driver behavior and performance measures from the NDS data:

- Locations where "entering" and "exiting" drivers respectively merge and diverge from the freeway mainline;
- Durations of lane change movements for lane changes that occur between entrance and exit ramp gores; and
- Speed differences between "entering" vehicles and other surrounding vehicles during the entering vehicle merge.

Methods of data analysis for Phase 1 consisted of descriptive statistics and graphical comparisons of driver behavior and performance measures across locations with various ramp spacing and auxiliary lane arrangements. Methods also explored whether various levels of driver distraction could be categorized within the study segments. These results are also provided in Section 5.0. More extensive statistical time series analysis to estimate relationships and sensitivities between the driver behavior and performance measures, ramp spacing, auxiliary lane presence, and driver distraction will be conducted with the fuller Phase 2 sample, along with other analysis described in Section 7.1.

4.0 DATA USED

This section provides a brief description of the NDS data used to support the Phase 1, Proof of Concept objectives, as well as other supporting data sources. Phase 2 data needs to support the overall research objectives are described in Section 7.2.

To conduct the Proof of Concept, we acquired a sample of vehicle traces through areas with an entrance ramp followed by a downstream exit ramp, sometimes with and sometimes without an auxiliary lane between entrance and exit ramps (shown in **FIGURE 2**).

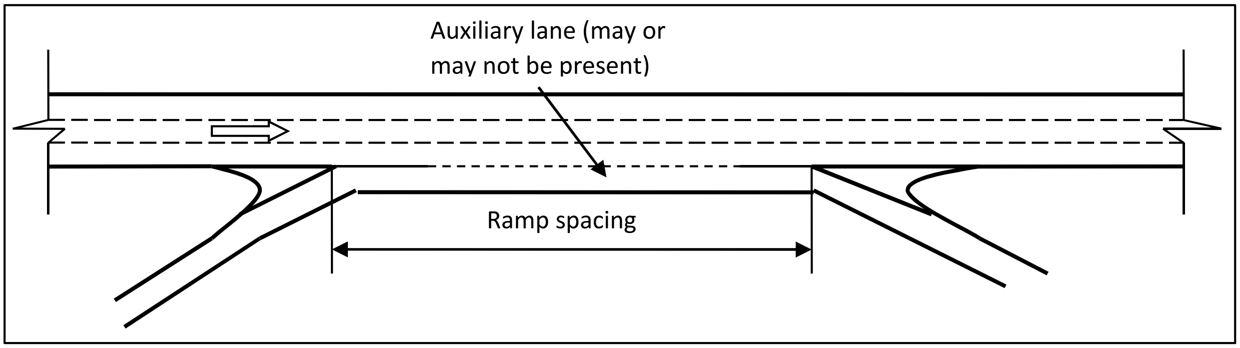


FIGURE 2 Illustration of Study Segments.

Potential study segments were identified on freeways throughout North Carolina and Washington State. Candidate sites were those with a configuration like the one shown in **FIGURE 2** and a significant sample of NDS vehicle traces. Candidate sites were assessed using GIS and Google Earth, with particular attention paid to ramp spacing (measured from painted tip to painted tip using the Google Earth measurement tools), auxiliary lane presence, interchange and ramp types, HOV/HOT lane presence, number of lanes, lane arrangements, and ramp metering presence. North Carolina and Washington State were selected to provide a representative range of freeway and interchange characteristics as well as to maximize the chances of success for future Phase 2 “surrogate verification” efforts because of traffic, interchange, and other data availability in these states.

A total of eight sites with the following ramp spacing characteristics were ultimately studied as part of the Phase 1, Proof of Concept efforts:

- Two sites with ramp spacing greater than 2000 feet and no auxiliary lane;
- Two sites with ramp spacing greater than 2000 feet with an auxiliary lane;
- Two sites with ramp spacing less than 2000 feet and no auxiliary lane; and
- Two sites with ramp spacing less than 2000 feet with an auxiliary lane.

One site from each of the four categories (i.e., four total sites) came from North Carolina, and one site from each category (i.e., the other four sites) came from Washington State.

We obtained vehicle traces for 80 “merging” drivers, 80 “exiting” drivers, and 80 through moving drivers at each of the eight pilot sites (i.e., 240 traces per site, 1,920 total traces across all eight sites). There were approximately 50,000 vehicle traces to choose from with complete GPS data across the eight study sites (additional trips were available, but did not have complete GPS data). VTTI provided trip IDs as well as other basic information for all 50,000 traces. The University of Utah research team then created a sampling algorithm to select trips at each site that: 1) likely captured a range of operating conditions and 2) maximized the size of the “cross section” of drivers (i.e., selected a sample that included as many different drivers as possible, as opposed to many different vehicle traces from the same driver).

The time series vehicle traces through the study segments included the following variables:

- Time stamps;
- Vehicle latitude and longitude;
- Lane width;
- Lane marking types;
- Lane positions (measured to left and right markings);
- Speed (from speedometer and GPS);
- Steering wheel position;
- Break and gas pedal positions;
- Acceleration estimates;
- Head position (as measured in x, y, and z dimensions from a “baseline”); and
- Radar range rates (to determine position and velocities of surrounding objects).

The time series vehicle traces were to desirably begin approximately 10 seconds upstream of the entrance ramp gore and end approximately 10 seconds after the exit ramp gore. In the end, VTTI captured the vehicle trace beginning at an adjacent upstream segment and ending at an adjacent downstream segment. The locations of these upstream and downstream segments varied across study sites, but generally captured the portion of the trip that was needed for our analysis. Each vehicle trace consisted of approximately one minute of data.

We also obtained forward video to confirm roadway features and movement patterns observed in the trace data, particularly when the recorded trace data appeared suspect. Finally, VTTI research staff performed additional data collection by watching video for each of the 1,920 vehicle traces and recording whether the drivers, as they passed through the study segments, were:

1. Not distracted by a cell phone;
2. Talking on a hands-free cell phone;
3. Talking on a hand-held cell phone; or
4. Dialing/texting/manipulating the phone by hand (excluding holding the phone to talk).

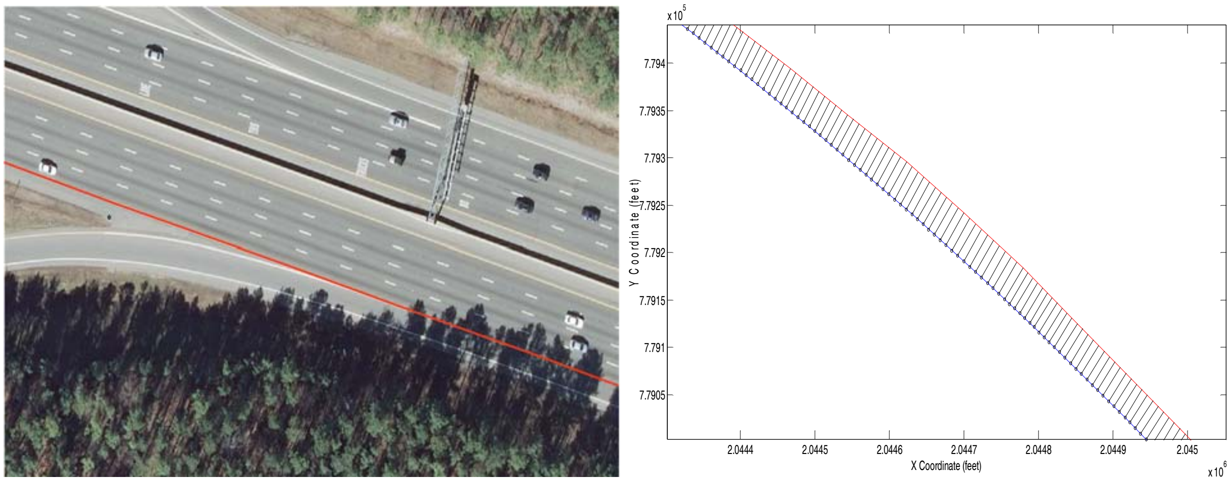
The final sample of vehicle trace and video data were delivered to the Utah research team through a secure server with web interface. The additional driver distraction variables were delivered by email in a Microsoft Excel file attachment.

5.0 RESEARCH RESULTS

5.1 Temporal to Spatial Conversions

One challenge in this research involves comparing analysis results between vehicle trips and across study locations. Each vehicle's trajectory has a different starting point and different timestamps. This means that identifying when a lane change occurs along a vehicle trajectory, or identifying its distance from the beginning of the trip, fails to provide a common reference for comparison with other trips at the same site. To provide this common reference, we assigned each site a roadway edge line. This allows each trajectory to be re-projected along the edge line so that distances can be calculated with a common starting point and the distances can all be calculated along the same path (removing variations in distance due to small lateral position changes).

FIGURE 3a shows an example of a reference edge line at a site in North Carolina, where the edge line follows the lane marking through the weaving segment. The roadway edge line at each study location was defined and located using aerial photography in GIS, resulting in a reference line described using coordinates in a local geographic coordinate system. Once the edge line is defined, the vehicle's GPS trajectory coordinates are converted to a local coordinate system, and then projected to the nearest location on the edge line. This nearest location on the edge line represents the longitudinal location along the roadway segment from a common reference. **FIGURE 3b** shows an example of the results of this mapping procedure.



(a) (b)

FIGURE 3 (a) Example of Reference Edge Line (Red Line) at a North Carolina Study Location. (b) Example Illustrating How Vehicle Trajectory Position (Red Line) is Re-Projected to the Common Reference Edge Line (Blue Line), with New Reference Coordinates Represented by Black Points.

By knowing the timestamp associated with each trajectory coordinate projected on the reference edge line, a relational database search function can be used to associate the location along the reference edge line to any data type available for each trip at a study location, such as the time/location of a lane change maneuver. Additionally, the distance along the reference line to any point is now based on a common starting point, allowing comparisons to be made based on distances along the roadway segment instead of coordinates alone.

Knowing the location/distance associated with a given data point is useful for comparisons at a single site, but it doesn't immediately enable comparisons between sites. Reference edge lines at each site have different starting locations, and each site has different geometric attributes such as the weaving segment length. As a result, distances along the edge line at one site cannot be directly compared with distances along the edge line at another site. To give these sites a common reference for distances, the distance along the edge line is recalculated in terms of its position relative to the physical gores for the entrance and exit ramps in the weaving area.

The physical gore locations were identified by aerial photography at each study location. The physical gore location was then projected to the nearest location on the edge line. This nearest location on the edge line represents the longitudinal location along the roadway segment for the physical gores. Calculating the distance to the physical gore locations away from the beginning of the edge line (as a reference location) provides a common reference distance to these points. A reference distance RD can then be calculated, which allows all points to be translated into a common reference measure based on the distance to the physical gore locations (GD_{Enter} and GD_{Exit}), as shown in Equation 1.

$$RD_x = \frac{ED_x - GD_{Enter}}{GD_{Exit} - GD_{Enter}} \qquad (1)$$

This reference distance can be understood as an indicator of the relative position between the entering and exiting gore. Reference distances less than zero are upstream of the entering gore, and reference distances greater than one are downstream of the exiting gore. Values between zero and one indicate the percentage of the total distance between the entering and exiting gores for a measurement. Now that each site has a common scale, meaningful comparisons between sites can be performed.

5.2 Merge and Diverge Locations

Prior to receiving data from VTTI, the Utah team hoped that GPS trajectory data would be of sufficient accuracy and quality to reasonably determine a vehicle's lateral position on the roadway. Upon receipt and inspection, the GPS data in the sample was found to be subject to significant position accuracy issues. Unfortunately, most of these issues were associated with the lateral position of the vehicle relative to the roadway. As shown using the yellow lines in **FIGURE 4** below, the vehicle trajectories sometimes appear completely off the traveled way, and can sometimes be found at extreme edges of the roadway or on the opposite side of a median barrier.

FIGURE 4 Example of GPS Lateral Position Accuracy Issues, Where GPS Vehicle Trajectory Data is Shown with Yellow Lines Overlaid on the Roadway.

Since the lateral GPS accuracy around the freeways was not sufficient for this purpose, the team had to rely on lane position data for determining when a vehicle moved between lanes or entered/exited the freeway. The lane position data mostly relies on detecting lane markings and measuring the distance from the vehicle center to the detected lane markings. In order to detect these vehicle movements between lanes, an algorithm was devised to identify when a vehicle crosses detected lane markings.

5.2.1 Lane Change Algorithm

The lane position data used in the Utah lane change algorithm describes the distance from the vehicle center to the nearest left and right lane markings. According to the data dictionaries provided for NDS time series data, the left and right distances should pass zero when a vehicle changes lanes (i.e., crosses the pavement marking). Unfortunately, this condition is not always certain when a vehicle changes lanes, possibly due to measurement noise or errors in detecting the lane marking.

To produce more reliable lane change detection results, the Utah algorithm uses the change in the lane marking distances to identify when a lane change occurs. As shown in **FIGURE 5** below, a lane change is typically accompanied by a large change in the distance between the vehicle center and the lane marking. When moving left, the distance to the left marking approaches zero and the distance to the right marking approaches the lane width. Once the vehicle center has crossed over the lane marking, these conditions switch, where the distance to the right lane marking now becomes nearly zero and the distance to the left lane marking approaches the lane width. By detecting the large change in the distance to the lane marking (e.g., from zero to the lane width) for both lane markings, the lane change is more likely to be correctly identified.

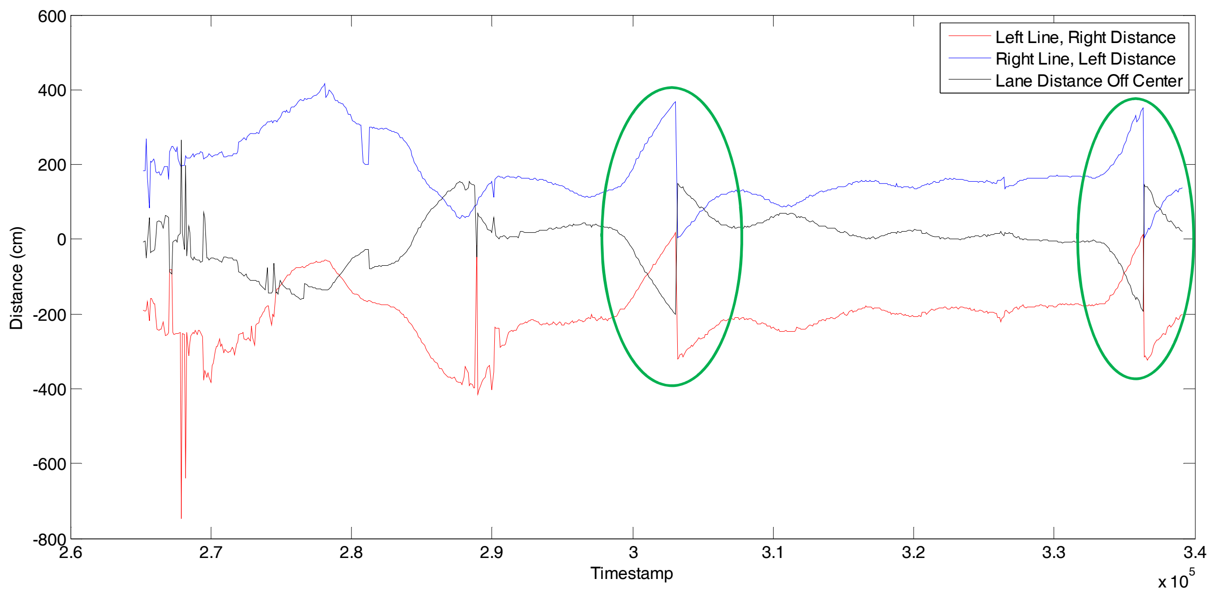
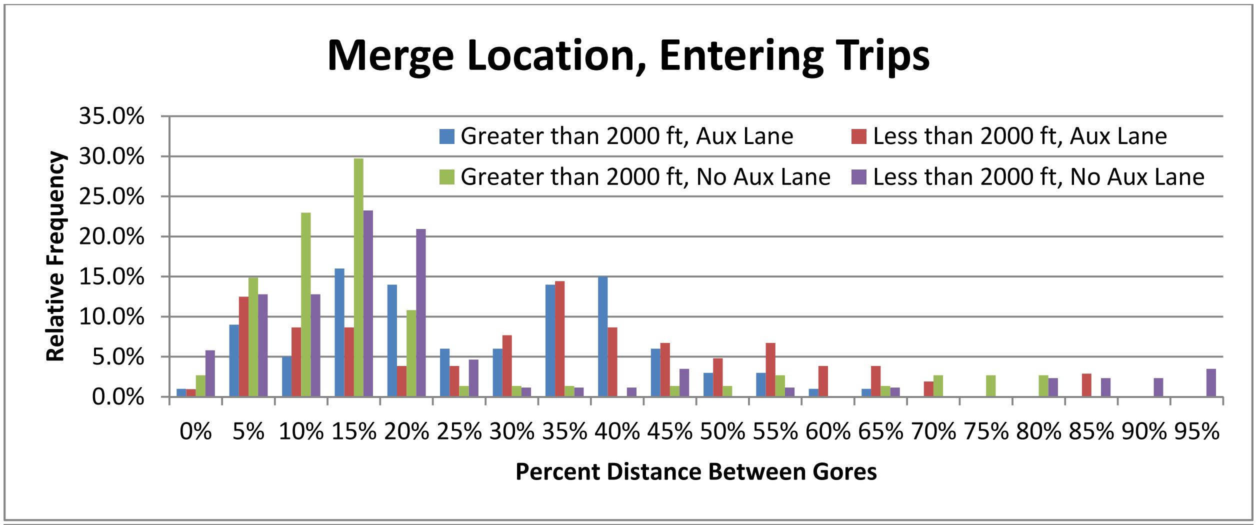


FIGURE 5 Lane Position Data for Trip 331, Showing the Distance from the Vehicle Center to the Left Lane Marking (Red), Right Lane Marking (Blue), and Lane Center (Black), with Lane Changes Highlighted by Green Ovals.

Checking the lane change detection results with the forward-facing video for a subsample in the group, this algorithm appears to find lane changes accurately for study locations with high-contrast lane markings and auxiliary lanes. However, there is still some room for improvement in locations without auxiliary lanes. The combination of lane markings near the end of entrance ramps and the beginning of exit ramps (without auxiliary lanes) often results in very little fluctuation in the distance to the right lane marking (i.e., the lane edge on the ramp becoming the lane edge on the mainline), but unexpectedly large fluctuations in the distance to left lane marking. The fluctuations in the distance to the left lane marking can sometimes be due to the combination of several lane markings on the left side of the lane. The Utah team continues to work on an appropriate strategy to better detect these merge and diverge movements and locations without auxiliary lanes.

5.2.2 Merge and Diverge Location Results

FIGURE 6 compares the relative frequency of merge and diverge locations across all eight study sites, focusing on the presence of auxiliary lanes and the ramp spacing. The lane change locations, identified by the lane change detection algorithm, are located on the x-axis using the reference distance between the physical gores. Lane changes closer to the entrance ramp are closer to zero, and lane changes closer to the exit ramp are closer to one. The figure shows that more lane changes are observed closer to the ramps when auxiliary lanes are not present. For entering traffic, most vehicles merged into traffic before traveling 40% of the distance between the physical gores, and more vehicles waited longer to merge when auxiliary lanes were present. For exiting traffic, locations with auxiliary lanes showed much earlier lane changes than locations without auxiliary lanes. Interestingly, vehicles exiting at locations without auxiliary lanes were observed merging closer to the exit ramp at sites with shorter ramp spacing.



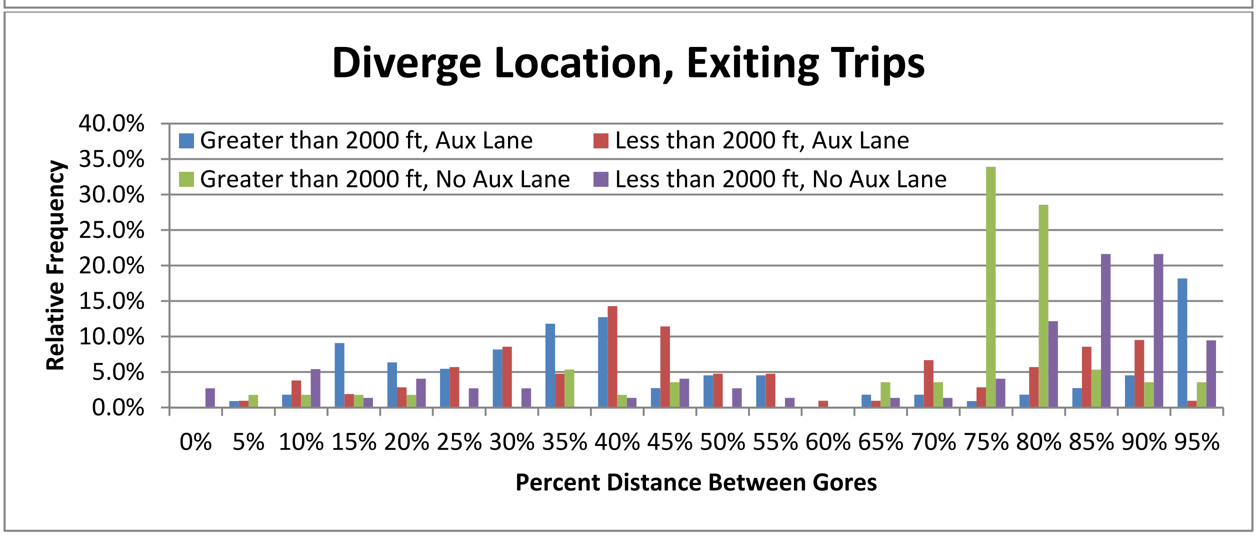


FIGURE 6 Relative Frequency Histograms of Merge and Diverge Locations for Entering and Exiting Trips for all Study Sites, with Varying Weaving Segment Lengths and Auxiliary Lane Presence.

5.3 Lane Change Durations

After identifying a lane change maneuver, the lane change duration can be estimated. In general terms, the lane change duration can be described as the time required to move from one lane to another. However, this definition requires establishing the starting point and ending point of a lane change maneuver, and then finding those points using available lane position data.

Establishing a consistent starting point and end point for a lane change maneuver across multiple sites and multiple drivers with varying conditions was challenging. A simple procedure would be to set a threshold distance to nearby lane markings, where a lane change is said to start and end while a vehicle is within a specific distance from the lane marking. However, this method would likely underestimate the lane change duration since the driver had to start turning the wheel before they reach that distance threshold. Additionally, it may not consider fluctuations in lane width between study sites. Another alternative would be to find the point where the vehicle changed locations in the time leading to the lane change. Unfortunately, measurement noise and each driver's lane position fluctuation makes this option difficult because it becomes challenging to differentiate between a large fluctuation in lane position and an intentional deviation from their typical lane position to start/end a lane change procedure. For example, **FIGURE 7** extracts the distance to the right lane marking from FIGURE 5, where there are lane changes at the nearly-vertical segments near time = 380 and time = 720. The data shows that this driver's lane position undergoes relatively large fluctuations after making the first lane change, making it difficult to identify when the lane change ends.

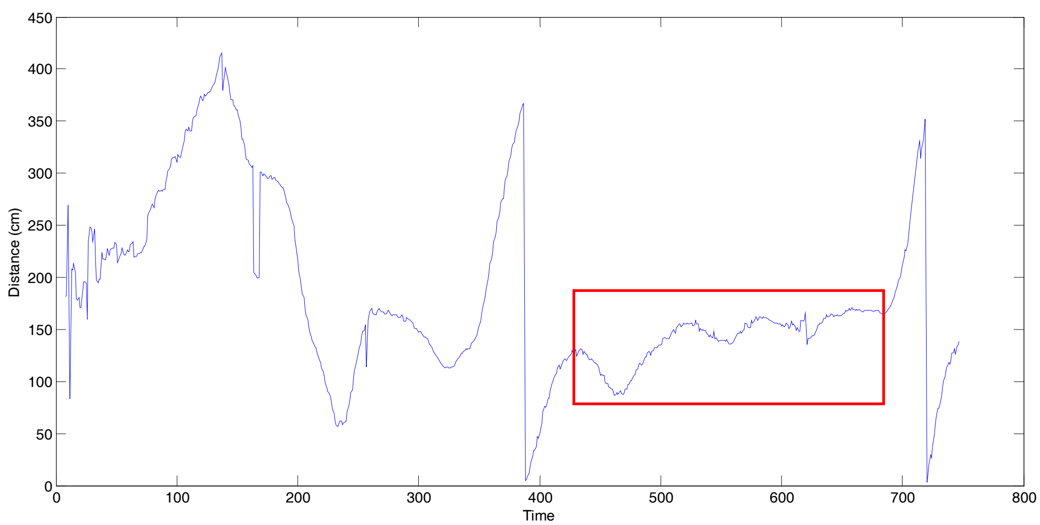


FIGURE 7 Distance from Vehicle Center to Right Lane Marking, Extracted From Figure 5, Showing Significant Variations in Lane Position After First Lane Change Near Time = 380 (Highlighted by the Red Rectangle).

The solution suggested in this research is to find a behavioral threshold indicating when a lane change maneuver starts and ends, a threshold which is unique to each trip and thus each individual driving situation. This threshold is established by estimating the typical second-to-second variation in the lateral lane position along the entire vehicle trajectory, and identifying when the vehicle's change in lateral lane position exceeds its range of typical fluctuations. The algorithm devised to accomplish this function uses the following procedure.

First, the algorithm calculates the change in the distance to the lane markings over one-second intervals (i.e., change in lane marking distances recorded one second apart). This appears to capture the magnitude of fluctuations in lateral lane position relatively well while filtering out the effects of most measurement noise. **FIGURE 8** shows the estimated lane position fluctuation captured from the data plotted in **FIGURE 7**. Next, the algorithm calculates the average value of this fluctuation over all available timestamps. This provides an initial estimate of the typical second-to-second variation in lane position over the entire trip (shown by the black line in **FIGURE 8**). However, this initial estimate also captures the variation(s) associated with lane change events, which stand out as outliers. As a result, this overestimates the average lane position variation during periods with no lane change maneuvers. The algorithm removes the effect of the lane change maneuvers by taking the average over all lane position fluctuation values less than the initial average lane position fluctuation. This new value represents an estimate of the average lane position variation without the effect of lane change maneuvers (shown by the red line in **FIGURE 8**).

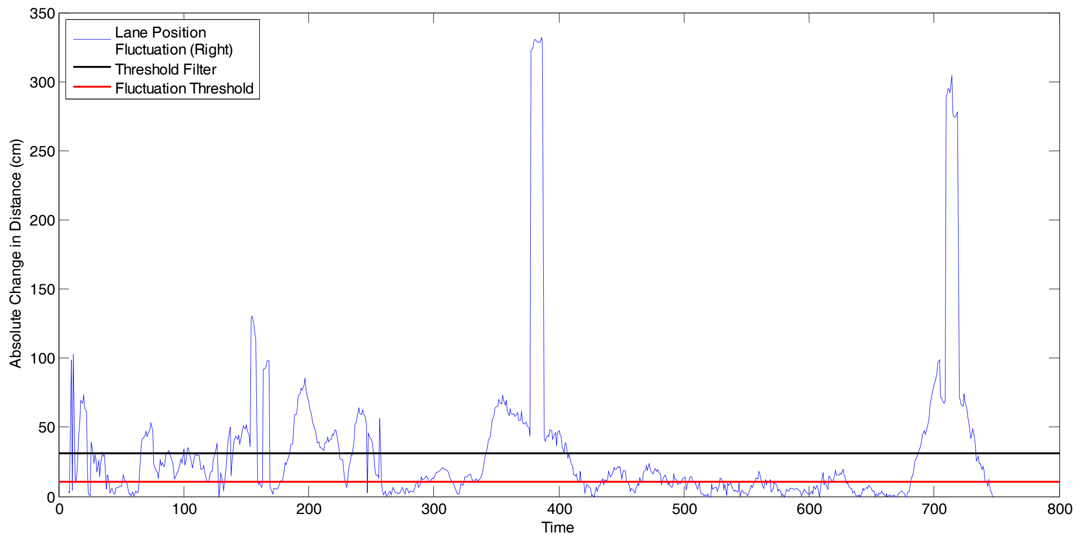


FIGURE 8 Second-to-Second Lane Position Fluctuation Estimated from the Lane Position Data in Figure 7 Showing Significant Increases in Variation Before and After Lane Change Maneuvers Near Time = 380 And Time = 720.

This new estimate becomes a threshold value for determining when the lane change maneuver begins and ends. When the fluctuation in lane position exceeds the threshold, the lane change maneuver is determined to have begun, and the maneuver is assumed to have completed when the fluctuation returns below the threshold. This is equivalent to defining the start and end of a lane change maneuver as the time at which the variation in the lane position exceeds the average variation during lane keeping.

5.3.1 Lane Change Duration Results

FIGURE 9 compares the estimated lane change duration distributions for lane changes observed along the weaving segments at all study locations, focusing on the presence of auxiliary lanes and the ramp spacing. Lane change durations were much shorter at sites that had no auxiliary lane and a ramp spacing shorter than 2000 feet. Longer (more gradual) lane changes were more frequent at sites which had an auxiliary lane and a ramp spacing longer than 2000 feet. Interestingly, the lane change duration at other sites were relatively similar in their distributions.

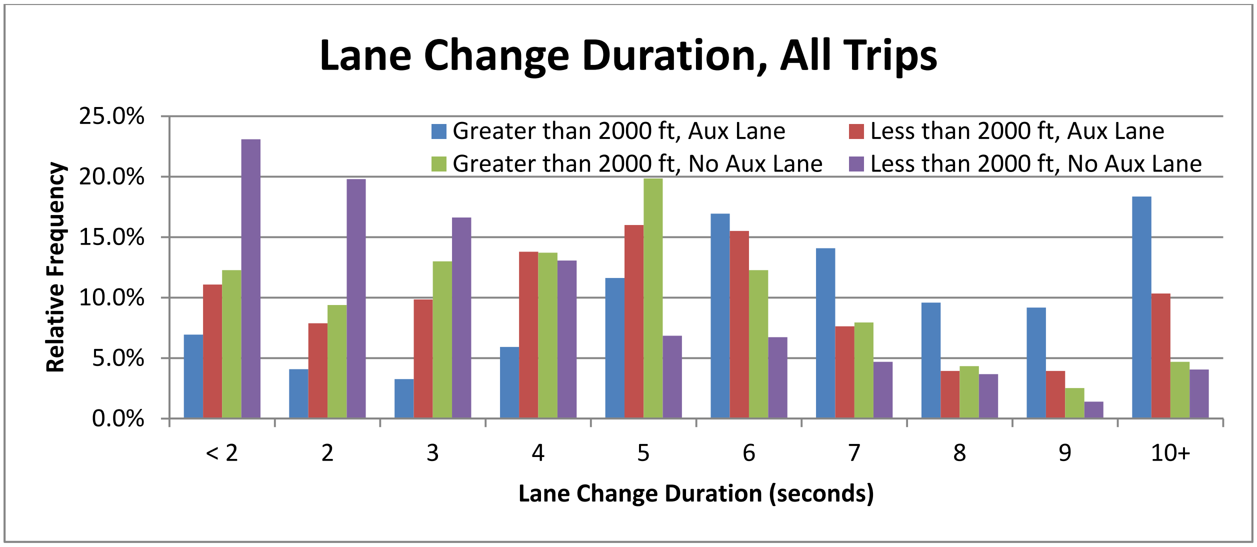


FIGURE 9 Relative Frequency Histogram for Duration of All Lane Changes Observed Between Physical Gores at All Study Locations, with Varying Weaving Segment Lengths and Auxiliary Lane Presence.

5.4 Merging and Diverging Speed Differentials

Speed differentials between the instrumented vehicle and nearby vehicles while entering/exiting the freeway is an expected safety surrogate in weaving areas due to the potential for hard braking/acceleration events during the merge/diverge maneuver. Since other vehicles are not instrumented, the NDS radar range rate data are the best option for estimating the speed of nearby vehicles along the trip trajectory. To do this, an algorithm was developed to process the available radar data and calculate nearby vehicle speeds during the subject vehicles merge/diverge.

The available radar data includes the range (i.e., distance to target) and range rate (i.e., target speed relative to the instrumented vehicle) for up to eight nearby objects. The speeds of nearby vehicles can be calculated by combining the instrumented vehicle's estimated speed at any given timestamp with the range rate. Since the data resolutions are often different for different data sources, interpolation is used to estimate the instrumented vehicle speed over all timestamps with vehicle speed available. After calculating the speeds of nearby vehicles, this data is combined with detected lane change timestamps to estimate the average speed of nearby vehicles during the lane change maneuver of interest (i.e., merge or diverge). This function involves iterating through all nearby vehicles with speed data available, determining that the vehicles are moving in the same direction as the instrumented vehicle, and then calculating the average of their speeds within ±0.5 seconds of the instrumented vehicle crossing the lane marking that separates the ramp from the mainline.

5.4.1 Merging and Diverging Speed Differential Results

The distributions in **FIGURE 10** show the speed differentials between the entering vehicles and nearby vehicles during merging maneuvers, where negative speeds indicate that the instrumented vehicle is traveling slower than nearby traffic. It appears that the speed differential does not vary much depending on ramp spacing or auxiliary lane presence. Further investigation may help identify other roadway attributes (e.g., ramp type, ramp length, etc.) more closely associated with merging/diverging speed differentials.

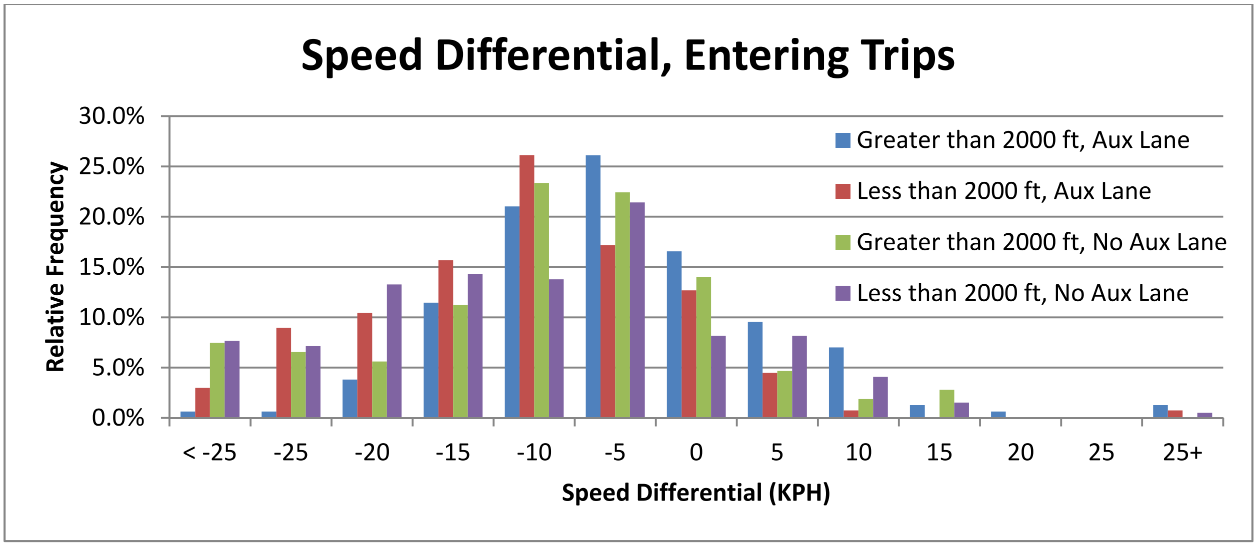


FIGURE 10 Speed differential relative frequency histogram for entering vehicles at all study locations, with varying weaving segment lengths and auxiliary lane presence.

5.5 Distraction Effects

Cell phone distraction-related data in this study is based on observing video footage from the driver-facing interior camera. Data were coded by VTTI staff. The driver's actions were observed when passing the entrance and exit ramps, and recorded separately based on their interaction with a cell phone or hands-free device, as well as any interactions with other passengers in the vehicle. The coded distraction data indicates that approximately 10% of sample trips at the study locations involved some form of cell phone usage near the entrance and exit ramps, and 15%-20% involved talking to a passenger. There were two clearly reported instances in which the driver is reported to have put down their cell phone before approaching the weaving area. This indicates that it is possible to detect when drivers self-regulate their cell phone usage while driving, which is one of the secondary research questions for this study.

5.6 Sequence of Events Leading to Near Crashes

Only two near-crash events were included in the Phase 1 sample trip data. Both events occurred in Washington on Interstate 5 between Northgate Way and 130th Street. In one case, the instrumented vehicle was cutoff by a vehicle quickly changing lanes in front of them while traffic ahead starts slowing down abruptly. The instrumented vehicle brakes hard, the instigating vehicle departs the lane, and the instrumented vehicle continues slowing down to meet the speed of nearby traffic. Driver distraction-related data indicates that the driver of the instrumented vehicle may have been manipulating their cell phone near the end of this trip segment.

The second case involves the instrumented vehicle traveling in the right-most lane with a relatively long headway to the next vehicle ahead. The trip occurs during rainy conditions with wet roads, and the vehicle ahead of the instrumented vehicle begins to decelerate. The instrumented vehicle begins to close the distance with the vehicle ahead and brakes hard to avoid a collision. No clear driver distraction-related information was available for this portion of the trip segment.

5.7 Lessons Learned

Upon starting the project, one of our biggest concerns was about data quality and data availability. We are taking a slightly different approach from other event-based analyses, so we were first concerned about whether the available time-series data would be of sufficient accuracy and resolution to answer our research questions. Additionally, there was some question as to which data sources would be available. There were notes on the InSight website about radar data availability, and we knew that not all vehicles could provide access to vehicle network data. We tried to ask for redundant time-series data (e.g., speed from the GPS and speedometer) to try to accommodate data availability issues. We also asked VTTI about missing data when selecting trips for our sample, but found that metrics about missing data were generally not available or not easily produced. In this regard, the only major metric that influenced sampling was the availability of GPS data due to privacy concerns.

After receiving the data from VTTI, initial analyses indicated some potential issues regarding both data quality and data availability. As expected, several variables collected from the vehicle network (i.e., steering wheel position, brake/gas pedal states) had relatively high rates of missing data. Approximately 73% of the sample trips had no steering wheel position data, and approximately 23% had no pedal state data. Approximately 20% of the trips had no radar data available, whether this was due to having no data or just observing no nearby vehicles during the trip. Roughly 5% of the sample trips had no lane position data (i.e., distances to lane markings). Among the trips with lane position data, nearly 13% of those trips showed no variation in the lane position data, indicating that they contained no useful information. GPS coordinates were unavailable for approximately 5% of the sample trips, but GPS speed data was almost always available. Interestingly, speedometer data was unavailable for approximately 3% of trips, but it was found that nearly 15% of the remaining trips had simply replaced the speedometer data with the GPS speed. Some of these findings are summarized in **TABLE 1**.

TABLE 1 Summary of Data Availability and Measurement Variability

Variable Name	Percent of Trips with Missing Data	Percent of Trips with No Variance
GPS - Position	5.1%	0.0%
GPS - Speed	0.2%	0.0%
Speedometer	3.3%	0.1%
Steering Wheel Position	73.0%	0.0%
Brake Pedal State	22.8%	34.7%
Gas Pedal State	22.9%	1.9%
Head Position Data	2.4%	0.0%
Radar Data	19.9%	0.0%
Lane Position Data	5.0%	12.8%

Several of these "lessons learned" will influence the way in which Phase 2 data are requested, including upstream and downstream boundaries for the vehicle traces through the study sites, larger sample than what is needed to account for missing data rates, and a large cross section of potential study sites to capture enough crash and near crash events.

6.0 FUTURE DIRECTION

This section describes the intended research outcomes that would result if the research were to continue into Phase 2, considering lessons learned during Phase 1. It includes a brief discussion of potential outcomes and future directions for the research, including the process by which the research will lead to the development of implementable countermeasures (e.g., changes in design criteria, signing, and markings as well as other promising countermeasures) that could lead to reductions in crash frequency and/or severity.

6.1 Research Outcomes

There will be six potential primary outcomes and two potential secondary outcomes at the conclusion of Phase 2. The expected primary outcomes are:

- Methodologies and performance measures for quantifying driver behavior and performance using SHRP2 NDS data in areas near consecutive freeway interchanges, where an entrance ramp is followed by a downstream exit ramp;
- Estimated differences in driver behavior and performance in areas with various EN-EX ramp spacing values;
- Estimated effects on driver behavior and performance of an auxiliary lane between entrance and exit ramps;
- A recommended subset of the driver behavior and performance measures that represent "safety surrogates" that have been verified using near-crash and crash events from the NDS data combined with comparisons to patterns in expected crash frequencies;
- A set of crash and near-crash *causal types*, which will group the NDS crash and near-crash events based on common predisposing factors, precipitating events, and target groups; and
- A recommended set of alternative countermeasures that are linked to the crash and near-crash *causal types*.

Based on preliminary success with working in cooperation with VTTI to obtain variables linked to driver distraction during Phase 1, a set of related secondary outcomes is also expected:

- Estimated effects of cell phone use and other secondary activities on driving behavior and performance in areas near consecutive freeway interchanges, where an entrance ramp is followed by a downstream exit ramp; and
- Greater understanding of if and how drivers adjust their cell phone usage depending on driving demands (e.g., volumes, speeds, gap availability, weaving intensities) (i.e., self-regulation).

6.2 Addressing Crash Causality and Implementable Countermeasures

Identifying crash causality and related countermeasures is a very difficult task that has challenged road safety researchers and practitioners for some time. Phase 2 of this research will implement a multifaceted approach to exploring crash causality and potential countermeasure effectiveness that incorporates various insights gained from the research outcomes identified in Section 6.1. An overview of the proposed Phase 2 process that will lead to a set of alternative, implementable countermeasures is provided in **FIGURE 11**. Additional details on the related methodologies and data needs are provided in Section 7.0 of this report.

The process outlined in **FIGURE 11** shows that we will first extract a number of different measures of driver behavior and performance at the study locations, which will continue to focus on the scenario of an entrance ramp followed by a downstream exit ramp, with or without an auxiliary lane. We have demonstrated our ability to process the data and extract behavior and performance measures during Phase 1. We have also learned about various limitations in the NDS data that will ultimately influence the set of behavior and performance measures that will be considered. Each of these measures will be further assessed as possible safety surrogates.

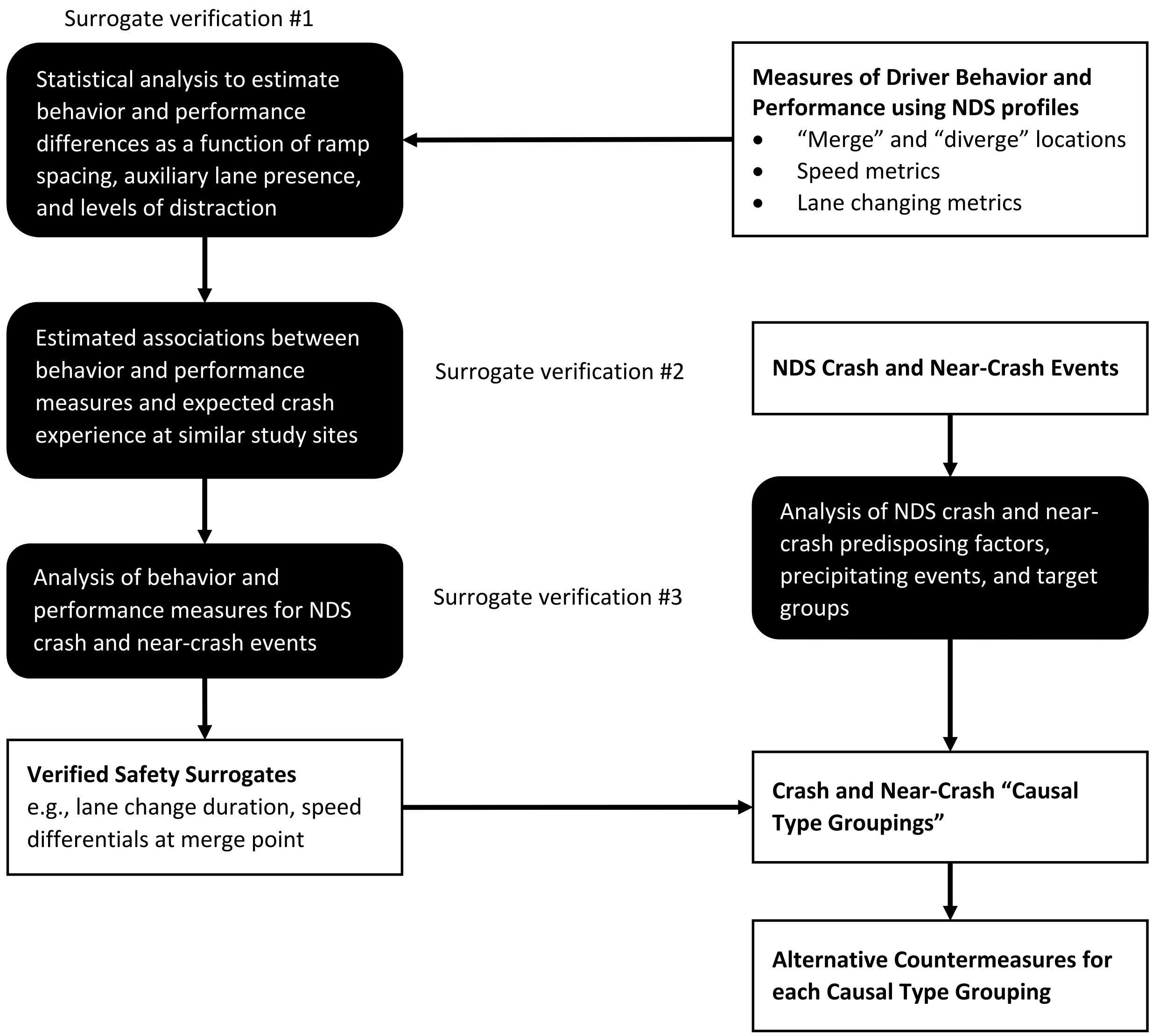


FIGURE 11 Overview of Process to Address Crash Causality and Identify Implementable Countermeasures.

Three different levels of verification are proposed for each measure of driver behavior and performance to determine if they have the potential to be informative safety surrogates. For this study, "verified safety surrogates" will be measures of driver behavior and performance with one or more of the following characteristics:

- Sensitive to ramp spacing, auxiliary lane presence, and levels of driving distraction (surrogate verification #1 in **FIGURE 11**);

- At an aggregate level, will be related to expected crash frequencies and/or severities at similar study locations (surrogate verification #2 in **FIGURE 11**); and
- Will vary in expected directions across the different NDS driving event classifications: crash, near-crash, and baseline driving (surrogate verification #3 in **FIGURE 11**).

In parallel to these safety surrogate efforts, Phase 2 of the research will also include a more clinical, in-depth analysis of NDS crash and near-crash events at a selected number of study locations. The "predisposing factors," "precipitating events," and "target groups" for each of the crash and near-crash events will be assessed, documented, and reviewed by the multi-disciplinary research team that has been formed for this effort (additional detail is provided in Section 7.0).

The research team will then assess the "verified safety surrogates" in combination with the summaries of "predisposing factors," "precipitating events," and "target groups" for each of the crash and near-crash events and propose a set of crash and near-crash "causal type groupings." The hope is that by determining these "causal type groupings" through the microscopic safety surrogate and clinical analysis that has been conducted, corresponding treatments or countermeasures can be identified, developed, and implemented in more cost-effective ways than if more traditional crash typologies are used (e.g., rear-end, sideswipe same direction).

7.0 PHASE 2 PROPOSAL

This section outlines how the Utah research team proposes to proceed in Phase 2. It includes an overview of research approach/methods, data needs, total cost (including data acquisition cost with VTTI), proposed schedule, and an approach to management and risk mitigation.

7.1 Phase 2 Research Approach/Methods

Section 6.0 included a description of the process by which the research will lead to the development of implementable countermeasures. This process included various steps ranging from statistical analysis of vehicle trace data to in-depth, clinical analysis of crash and near-crash events. The following subsections briefly describe the research approach and methods corresponding to each of these steps.

7.1.1 Estimating Measures of Driver Behavior and Performance from NDS Profiles

This step will directly build on the Phase 1 work by developing automated ways to extract measures of driver behavior and performance from the NDS data at a "large scale" and process the data for analysis. This report demonstrated successful algorithms for extracting merge and diverge locations, lane change characteristics, and speed differentials during merging and exiting movements, as well as a successful attempt to categorize driver distraction in the study segments. We will carry these same measures forward, and also explore head position (including rotation), number of rapid accelerations/decelerations, time-to-collision, and a more refined driver distraction variable, coded every second.

7.1.2 Estimating Sensitivity between Driver Performance Measures and Ramp Spacing

This analysis will take the measures of driver behavior and performance from Section 7.1.1 and identify which ones are most sensitive to ramp spacing and auxiliary lane presence using descriptive, graphical, and statistical and econometric analysis methods. Continuous variables will be summarized using means and standard deviations. If a variable's distribution is highly skewed we will use medians and interquartile ranges instead. Categorical variables will be summarized using frequencies and percentages. As many of these variables will take the form of traces while the vehicle passes through the study section of roadway, we will also use graphical methods, such as time plots or side-by-side box plots taken at fixed intervals, to understand how these measures vary over the vehicle's route. We will overlay graphs relating to merging, exiting, and through drivers to identify differences between these activities. To estimate differences in driver behavior and performance at locations with various ramp spacing and auxiliary lane arrangements, we will employ time series analysis methodologies.

7.1.3 Exploring Associations between Driver Performance Measures and Crash Experience

The introduction of this report noted that CMFs for ramp spacing and auxiliary lane presence have already been developed by the University of Utah research team. This portion of the study will further leverage the data used to develop those CMFs to determine if there are associations between the measures of driver behavior and performance from Section 7.1.1 and expected crash experience as a function of ramp spacing and auxiliary lane presence. First, we will refine the CMFs at more disaggregate levels of crash groupings that correspond to each of the potential surrogates identified from the NDS data. For example, speed differentials during the merge movement likely correspond to rear-end and same direction sideswipe collisions. After estimating these more disaggregated CMFs, we will examine the relative changes of both the CMF and the candidate safety surrogate as ramp spacing and auxiliary lane presence changes. If a surrogate is potentially useful, we would expected similar relative changes in both the surrogate and the CMF (e.g., as ramp spacing changed from 2500 feet to 1500 feet, we would expect the relative differences in the CMF for these two spacing values and the relative changes in the surrogate for these two spacing values to be relatively similar).

7.1.4 Exploring Differences in Driver Performance Measures for Crash, Near-Crash, and Baseline Events

This analysis will take the measures of driver behavior and performance from Section 7.1.1 and identify which ones differ the most, and in the expected direction, across three main NDS driving event types: crash, near-crash, and baseline events. The general analysis principles described in Section 7.1.2 also hold for this analysis.

7.1.5 Identifying Predisposing Factors, Precipitating Events, and Target Groups for Crash and Near-Crash Events

This analysis will involve an in-depth examination of precipitating events, predisposing factors, and target groups for crash and near-crash events in the freeway study segments, where:

- <u>Precipitating events</u> are the specific nature of the failure in the function/event sequence that led to the collision;
- <u>Predisposing factors</u> are the specific environmental, human, or vehicle variables that influenced the function failure; and
- <u>Target groups</u> are human populations and/or kinds of vehicle types involved in the crash type.

The crash and near-crash events will then be grouped into "causal type groupings" based on having similar sets of precipitating events, predisposing factors, and target groups. It is expected that this analysis will also be greatly informed by the surrogate verification efforts described in the previous sections by helping to define what "surrogate condition" may signify the start of a "collision course." There have been successful applications of similar approaches to pedestrian and bicyclist safety research of the 1970's, and there has been renewed interest recently in these types of analyses as researchers continue to identify challenges with relying solely on statistical associations developed at an aggregate level (see, for example, ongoing FHWA project DTFH61-12-C-00033, Understanding the Causative, Precipitating, and Predisposing Factors in Rural Two-Lane Crashes).

7.2 Phase 2 Data Needs

Data needs corresponding to each of the eight research outcomes identified in Section 6.0 will include the same Phase 1 data elements (see Section 4.0) for a larger sample of data, plus the additional elements summarized below:

- Head rotation and turn signal use (from the vehicle time series data);
- Driver distraction code as a more refined time series variable through the study segment (to be coded by VTTI);
- All available data and video on crash and near-crash events (to be accessed by the University of Utah both remotely and at the VTTI/FHWA secure data enclave); and
- A similar set of fully defined study segments (EN-EX with and without auxiliary lanes) and corresponding crash data to support surrogate verification #2 (we will leverage data already collected as part of NCHRP 3-88 and follow-on research).

7.2.1 Phase 2 Sample Size Discussion

This pilot study utilized NDS data from eight freeway segments, with 240 trips per segment (80 exiting, 80 entering, and 80 through trips). In order to 1) further estimate measures of driver behavior and performance from NDS profiles, 2) estimate sensitivity between driver performance measures and ramp spacing, and 3) explore measures between driver performance measures and expected crash experience during Phase 2, we are proposing to expand the sample to 40-60 segments, with a similar target of 240 trips per segment (80 entering, 80 exiting, 80 through). Based on Phase 1 experience, this means we will need to request 300 trips per segment (100 for each movement). This expands our sample from what was 1,920 trips during Phase 1 to between 12,000 and 18,000 trips.

Based on Phase 1 experience, we would expect this sample across 40-60 study segments to contain only 10 to 15 crash or near-crash events (i.e., about one crash or near-crash event for every four sites). This will not be a large enough sample to execute analysis described in Section 7.1.4 (exploring performance measure differences between crash, near-crash, and baseline events) or conduct the parallel in-depth analysis of predisposing factors and precipitating events. We will need to define anywhere between 600-800 additional sites and ask VTTI only for the crash and near-crash data at these sites. This will require us to expand our dataset beyond North Carolina and Washington to at least one or two more additional states.

7.4 Phase 2 Schedule

The proposed Phase 2 work will be carried out over a performance period of 24 months. We would expect the first 6 months to be devoted to identifying all needed data and also refining the CMFs for the analysis described in Section 7.1.3. The following 8 months will then be used for the analysis described in Sections 7.1.1 through 7.1.5. Three months will then be used to develop/confirm the crash and near-crash "causal type groupings" and identify associated countermeasures. The final three months will be used for report preparation and meeting with the FHWA and AASHTO safety task force.

7.5 Management Approach and Risk Mitigation

The proposed Phase 2 work will be managed from the Civil and Environmental Engineering Department (CVEEN) at the University of Utah, with Dr. Porter serving as PI. Financial, deliverable, and milestone tracking for the project will also be managed from CVEEN. Grants and Contracts at the University of Utah will administer the contract and will work with VTTI subcontractor invoices, and the accounting office at the Utah Department of Transportation. The University of Utah expects to conduct regular progress reporting with FHWA (Quarterly Reports), Utah Department of Transportation (Quarterly Reports and In-Person Meetings), and AASHTO.

The most likely risks for Phase 2 will be related to: 1) getting the needed data elements; 2) finding enough crash and near-crash events; 3) identifying relevant surrogates; and 4) successfully translating the research results into implementable countermeasures. These same risks likely apply to most early research involving the NDS datasets. Early during Phase 2, we propose to assemble a risk spreadsheet that identifies potential risks for all major activities of the project. This registry will require constant updates, as the project evolves. Every risk element will be ranked with respect to potential risk impact to the project (low, medium, high) and the potential for occurrence. Risk mitigation and contingency planning will be performed in close conjunction with FHWA, AASHTO, and UDOT project liaisons.

7.6 Addressing PII

As with Phase 1, we do not expect to house any PII at the University of Utah. Much like Phase 1, most portions of the University of Utah analysis would be considered IRB exempt since VTTI staff will code the driver distraction variables. We do, however, expect to have to get IRB approval for Phase 2 since University of Utah researchers will likely access cab/face videos at either the VTTI or FHWA secure data enclave to collect the data needed for the analysis described in Section 7.1.5 (predisposing factors, precipitating events, and target groups). The University of Utah team has extensive experience with human subjects research and protection of PII and will apply that knowledge to needed IRB approval for Phase 2.

APPENDIX A: REFERENCES

Abdel-Aty, M., Pande, A., Lee, C., Gayah, V., and Dos Santos, C. Crash Risk Assessment Using Intelligent Transportation Systems Data and Real-Time Intervention Strategies to Improve Safety on Freeways. In *Journal of Intelligent Transportation Systems*, 11(3), 2007, pp. 107-120.

Bonneson, J. and Pratt, M. *Calibration Factors handbook: Safety Prediction Models Calibrated with Texas Highway System Data*. Publication FHWA/TX-08/0-4703-5, Texas Transportation Institute, College Station, TX, 2009.

Chiu, M. Robinson, J.L., Boychuk, R., and Smiley, A. Evaluating the Road Safety Effects of Interchange Spacing: A Multidisciplinary Approach. *Proceedings of the Annual Conference of the Transportation Association of Canada*, Quebec City, Quebec, 2004.

Fazio J., Holden, J., and Rouphail, N. Use of Freeway Conflict Rates as an Alternative to Crash Rates in Weaving Section Safety Analyses, In *Transportation Research Record*, No. 1401, Transportation Research Board of the National Academies, Washington DC, 1993, pp. 61-69.

Fitzpatrick, K., Porter, R.J., Pesti, G., Chu, C.L., Park, E.S., and Le, T.Q. "Guidelines for Spacing between Freeway Ramps," In *Transportation Research Record, Journal of the Transportation Research Board No. 2262*, 2011, pp. 3-12.

Golob T.F., Recker, W.W., and Alvarez, V.M. Safety aspects of freeway weaving sections. In *Transportation Research Part A*, 38, 2004, pp. 35-51.

Golob, T.F., Recker, W., and Pavlis, Y. Probablistic models of freeway safety performance using traffic flow data as predictors. In *Safety Science*, 46, 2008, pp. 1306-1333.

Hidas, P. Modeling vehicle interactions in microscopic simulation of merging and weaving. In *Transportation Research Part C*, 13, 2005, pp. 37-62.

Le, T.Q. and Porter, R.J. "Safety Evaluation of Geometric Design Criteria for Spacing of Entrance-Exit Ramp Sequence and Use of Auxiliary Lanes," In *Transportation Research Record, Journal of the Transportation Research Board No. 2309*, 2012, pp. 12-20.

Lord, D., Manar, A., and Vizioli, A. Modeling crash-flow-density and crash-flow-v/c relationships for rural and urban freeway segments. In *Accident Analysis and Prevention*, 37, 2005, pp. 185-199.

Normann, O.K. Operation of Weaving Areas. In Highway Research Board Bulletin 167, Transportation Research Board of the National Academies, Washington DC, 1957, pp. 38-41.

Pesti, G., Chu, C.L., Fitzpatrick, K., Porter, R.J., and Le, T.Q. "Microscopic Simulation of Weaving Traffic between Freeway Ramps," *Compendium of Papers from the 90th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 23-27, 2011.

Shea, M.S., Le, T.Q., and Porter, R.J. "A Combined Crash Frequency-Crash Severity Evaluation of Geometric Design Decisions: Entrance-Exit Ramp Spacing and Auxiliary Lane Presence," In *Transportation Research Record: Journal of the Transportation Research Board* (accepted), 2015.

Skabardonis, A., Cassidy, M., May, A.D., and Cohen, S. Application of Simulation to Evaluate the Operation of Major Freeway Weaving Sections. In *Transportation Research Record*, No. 1225, Transportation Research Board of the National Academies, Washington DC, 1989, pp. 91-98.