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Geo-Locating and Identifying Wrong-Way Driving Entrance Points in Bexar County Highways by Implementing Mathematical Modeling and Land-Use Impact Assessment

Md Farman Mia, Samer Dessouky *, Jose Weissmann, Hatim O. Sharif and Khondoker Billah

Department of Civil and Environmental Engineering, University of Texas at San Antonio, San Antonio, TX 78249, USA; mdfarman.mia@my.utsa.edu (M.F.M.); jose.weissmann@utsa.edu (J.W.); hatim.sharif@utsa.edu (H.O.S.); khondoker.billah@utsa.edu (K.B.)

* Correspondence: samer.dessouky@utsa.edu; Tel.: +1-210-458-7072

Abstract: Wrong-way driving (WWD) leads to high severity crashes and is a major concern for transportation managers. This study aims to identify WWD entry points of urban highway ramps and develop an analysis methodology using basic knowledge of WWD occurrences. The methodology examines the origin and driving behavior of impaired drivers by utilizing a land-use impact assessment (alcohol-serving establishments (ASE) proximity to exit ramps) and analyzing three distinct mathematical models: wrong-way driving events excluding 911 call analysis, wrong-way driving events including 911 call analysis, and 911 calls without wrong-way driving crashes. Data were collected and implemented from Google Maps, the 911 call database, wrong-way crash database, ASE location database, and a video camera database of a recent WWD study. Out of a total 543 exit ramps, 213 exit ramps are associated with approximately 98% of total WWD entries. The hotspots analysis of WWD entrance locations have found four major hotspots locations in Bexar County, Texas study area: 410 Loop near Culebra Road and Jackson Keller Road, 1604 Loop near US-281 highway, and IH-10 near the Medical Drive area. Outcomes of this study include a methodology for determining WWD entry locations of regional highways.

Keywords: wrong-way driving; countermeasure; land-use impact; alcohol serving establishment

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1. Introduction

Wrong-way driving (WWD) events are infrequent on highways but often lead to severe injury and/or fatalities [1–3]. The safety of highway motorists is jeopardized by drivers who make wrong-way entries on highways. According to a study in Illinois, the impaired drivers, who might be intoxicated or visually restricted, take the wrong way entrance ramp to enter the highway and more than 50% of the WWD events happened due to the drivers getting impaired by alcohol consumption [4]. Upon entering the highway, they either correct themselves by turning around, or continue to drive in the opposite direction until they crash with incoming traffic unless they are forced to stop by law enforcement. The unpredictability of WWD behavior leaves no specific information for decision-makers to identify the exact geo-locations of the entrances unless there is any detection system exist [5]. Due to the unavailability of dedicated automated detection systems of WWD on highway aside from conventional traffic cameras and video surveillance that oversee traffic operation [6], there is a time lag in issuing warnings to other drivers after hearing 911 call from other motorists and dispatch law enforcement to mitigate WWD severe crashes.

This study used data from 2012 to 2018, and only the highways inside Bexar County highway system were considered in the analysis. According to the database, a total of 232 wrong-way crashes (WWC) occurred within the study period and resulted in 82 fatalities, which shows the severity level of this phenomenon. On the other hand, approximately 62,027 accidents occurred in total on Bexar County highways and only 207 people died during those occasions. Even though the proportion of WWD events is very small in total accidents, the severity of WWD events enforces the authority to find the solution of this problem and implement the countermeasures for safety of people.

The Arizona Department of Transportation (ADOT) and the Florida Department of Transportation (FDOT) implemented two real-time WWD countermeasures [6,7] which inspired the authors to conduct a WWD entrance location identification study for the Bexar County highway system to assist the authority to detect WWD events on highways. Many organizations intend to examine the characteristics of WWD events and reduce WWC frequency on highways by adopting historically validated countermeasures. Although the reduction rate of WWD events after the application of countermeasures is significant in specific regions, the overall WWD counts have not been reduced in general with respect to total number of crashes [8–10]. A monitoring system which detects all potential WWD entries and inform the motorists coming from opposite direction about the upcoming hazard is the most significant solution to this problem [6]. Although the cost of these systems is a concern for the DOT, implementing these systems in the hotspots where 90% or more of these WWD events occur is expected to substantially reduce severe crashes [6]. The outcome of this research could be utilized to improve motorists' safety against WWD, to identify the potential hotspots of WWD within a specific region (such as the Bexar County, Texas area) and to prioritize allocation of limited resources in the implementation of monitoring systems leading to countermeasures to warn motorists in avoiding collisions with WWD.

2. Literature Review

Since the mid-twentieth century, pioneering studies on WWD events have been conducted in California, Michigan, Missouri, Virginia, Indiana, Washington, Georgia, and Illinois as part of discovering convenient solutions such as spike barriers, wrong-way signs, and markings against WWD on roadways [11–23]. These studies discussed the nature of WWD events, where mostly the visually impaired and intoxicated drivers take the wrong way to enter the highways. Moreover, these studies also explored the associated countermeasures such as signs, marking, arrows design, and installation to prevent the access of vehicles driving in the wrong way. Prevention and detection of WWD events were explored by Caltrans study, where prevention included modification of geometric details and structure of roadway such as placing warning signs, signals, physical restrain (strikes), and red reflector pavement arrows which reduced 40% WWD events [18,19]. Generalizing the left lane of the exit ramps, location signs, size of the letter of symbols, intersection geometry modification, and aid program for mentally impaired drivers have been initiated by the Virginia highway resource council [20,21] to mitigate WWD events. Small signal frame cameras have been installed to find some hotspots, where about 50 to 60 WWD events occur each month, to put the "Do Not Enter" sign lower than the regular height to mitigate WWD events [17]. One of the major conclusions of these studies [16–18] is that off-ramps are solely responsible as the entrances of WWD events into the highways. On the other hand, recent studies focus on the applications of countermeasures such as technological sensors, cameras, dedicated detection systems (reduce 90% of WWD events), innovative management, and observational analysis to discuss the pattern of WWD events. Two studies [8,9] were performed on Texas highways to study state-of-the practice on safety, issues, and countermeasures of WWD. The recommended practices from this research were installing "reflectorized wrong-way pavement arrows" on left-side exit ramps, and this left-side exit ramps should be avoided during future freeway construction. Approximately 14% of WWD events resulted in a crash, about 10% of WWD events witnessed by the participants were reported to law enforcement or agencies, and almost 50% of WWD were considered as high-risk events in Florida [10], indicating the severity and damage associated with WWD events. A comprehensive study conducted by the ADOT analyzed the global and statewide opportunities to apply sensor detection system countermeasure for the betterment of roadway safety in Arizona [6] ended up with nearly 90% success rate in mitigating the WWD events in study area. Another study in Alabama used 5 years of data incorporating 18 explanatory variables to identify the most significant variables associated with WWC [24] and found that the intoxication and impairment of drivers to be the most significant variables for WWD events. Another study on Illinois highways attempted to identify the characteristics of WWC to rank the locations according to vulnerabilities to WWD entries and the results indicate that approximately 58% of all WWD events occurred when the driver was driving under influence (DIU), 80% events involved urban areas, and 70% WWD involved vehicles were passenger cars [25]. Two intelligent transportation systems (light-emitting diode signs and rectangular flashing beacon signs) were compared in place of "wrong-way" signage to evaluate the effectiveness of both countermeasures on the highway in a study which identified a reduction of WWD events by 48.1% and 69.4%, respectively, when intelligent transportation systems were used [26].

In Bexar County, Texas, the most recent work focused on the assessment of WWD countermeasures inside the city and provided an explicit comparison of the situations before and after the installation of countermeasures against WWD events [27] has found 30% less WWD events after the installation of countermeasures. More recently, extensive research on WWD has been performed in Florida [10,28–31] focusing on the countermeasures (LED light, retro reflective light), survey analysis, investigation, and management operational approach. WWD scenarios on a tolled road in Florida were studied to identify WWD hotspots that might need additional countermeasures by considering a multifactor risk-based model for Florida interstates and toll facilities [32].

However, only two studies [28,33] were focused on locating the entry points of WWD on highways. A comprehensive study [28] was conducted to identify the location of hotspots in the Florida highway system using two approaches (the first approach included a Poisson regression model that predicted the WWD frequency, and the second approach was based on operational data collected by traffic management centers). The linking of the WWD entrance points with specific segments and associated ramps becomes difficult in this approach since the driver involved in the WWD event might drive to another segment from the access point segment by the time the first 911 call is being logged by the authorities. The second study applied a model based on the 911 reports of WWD events where the caller identified intersections, ramps, and surrounding conditions as impact factors that can lead to WWD events and applied this model to prioritize countermeasures on a specific location [33].

No study has been conducted to identify the exact geo-location of WWD entries, such as the intersection point coordinates of highways and ramps where the WWD involved driver access the highway towards the wrong direction. This study intends to find out the exact geo-locations of WWD entrances on highways inside Bexar County to help the authorities to install appropriate and effective countermeasure to reduce WWD events.

3. Methodology

This research identifies WWD entry points with geolocations to assist state DOTs and county authorities in the implementation of their limited resources for effective countermeasure installation at WWD entry points. Historically, 911 calls have not been proven to be an indisputable countermeasure to avoid (WWC) as the first responder are often provided with insufficient time to act. This situation demands a system to alarm the existing motorists who might be the potential victims of WWD events that are independent of 911 calls. The installation of automated systems of potential WWD hazard in a highway system demands significant investment from road authorities. Moreover, installation of such monitoring systems throughout the county is impractical unless exact locations or road segments which require implementation are identified. This study assumes exit ramps are the entry points where WWD events are initiated. Considering the Bexar County freeway system, 543 exit ramps need sensors/cameras to detect WWD events (an expensive and unfeasible investment scenario). Identification of the WWD entry hotspots would facilitate effective allocation of funds to implement pertinent countermeasures. The methodology presented in this paper could be utilized by the other DOTs and cities to determine the potential WWD entry hotspots.

The proposed methodology applies the impact assessment of alcohol-serving establishments (ASE) (e.g., bars, restaurants, wineries, etc.), and mathematical models to analyze traffic data, crash records, and 911 calls. The outcome from these analyses was used to determine the risk factor which is found to be a parameter of hotspot intensity. The following chart (Figure 1) summarizes the methodology:

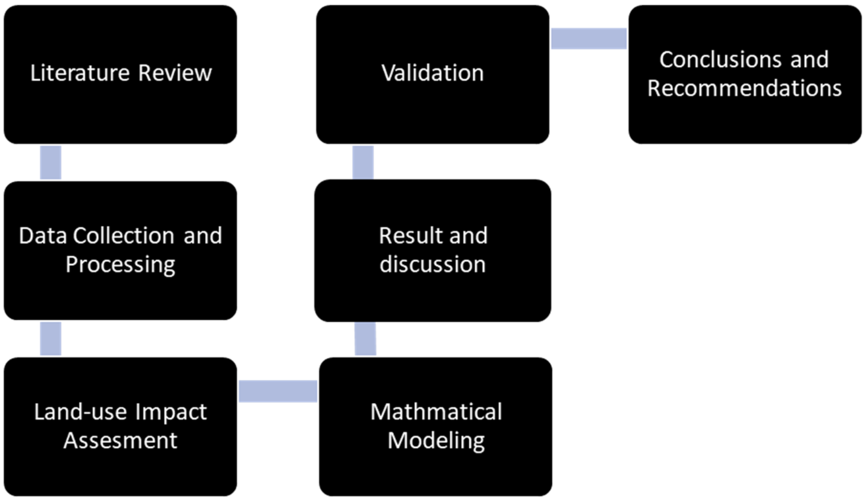

Figure 1. Flow chart of study process.

3.1. Data Collection and Processing

The Crash Record Information System (CRIS) database from the Texas Department of Transportation (TxDOT), ASE location database from Texas Alcohol Beverage Commission (TABC), hourly traffic volume data from TxDOT, 911 call database from San Antonio Police Department (SAPD), and Google Open Resources database were used for this research. During data processing, 4.9% of total incidents lacking geolocation (latitude and longitude) and database information that does not match with map information were excluded from analysis. Alcohol-serving establishments that are not within 2000 feet of highways were excluded from analysis under the assumption that these establishments might not have significant impact on highway WWD events. The assumption was made by analyzing the data collected from ADOT which suggests that any ASE located on the exit flow path of off-ramp has the highest entrance of WWD whereas any ASE located more than 2000 feet away from the exit ramp has negligible influence on the entrance of WWD (about 92% of WWD entries on highways based on ADOT data have ASE within 2000 feet of exit ramps).

Google Maps was used to identify exit ramps' geo-locations manually and later the database was validated on a generated exit ramp locations from the city of San Antonio maps to ensure that all 543 exit ramps were being considered in the analysis.

3.2. Land-Use Impact Assessment

The ADOT has implemented a highly successful operation to prevent WWD events in IH-17 by installing cameras to detect entries of WWD [6]. The camera provided continuous data for WWD entry and location of these events that have been used for studying the characteristics of these events. The ADOT installed thermal camera sensors on potential hotspots' entry points and detected over 90 WWD events during the study year. This research utilized recorded WWD detection footage from ADOT on IH-17 to investigate the significance of land use and the exit ramp geometry on WWD events with the purpose of adapting the results in support of the modeling of WWD events for the Bexar County highway system. Analysis of these data suggests that intersection geometric characteristics and exit ramp locations of ASE close to highway exit ramps are contributing factors to WWD events. The locations of all exit ramps in Bexar County highway system with locations of exit ramps that have ASE nearby are shown in Figure 2. Those ASE in proximity to exit ramps are potential entrance points of WWD based on land use impact assessment.

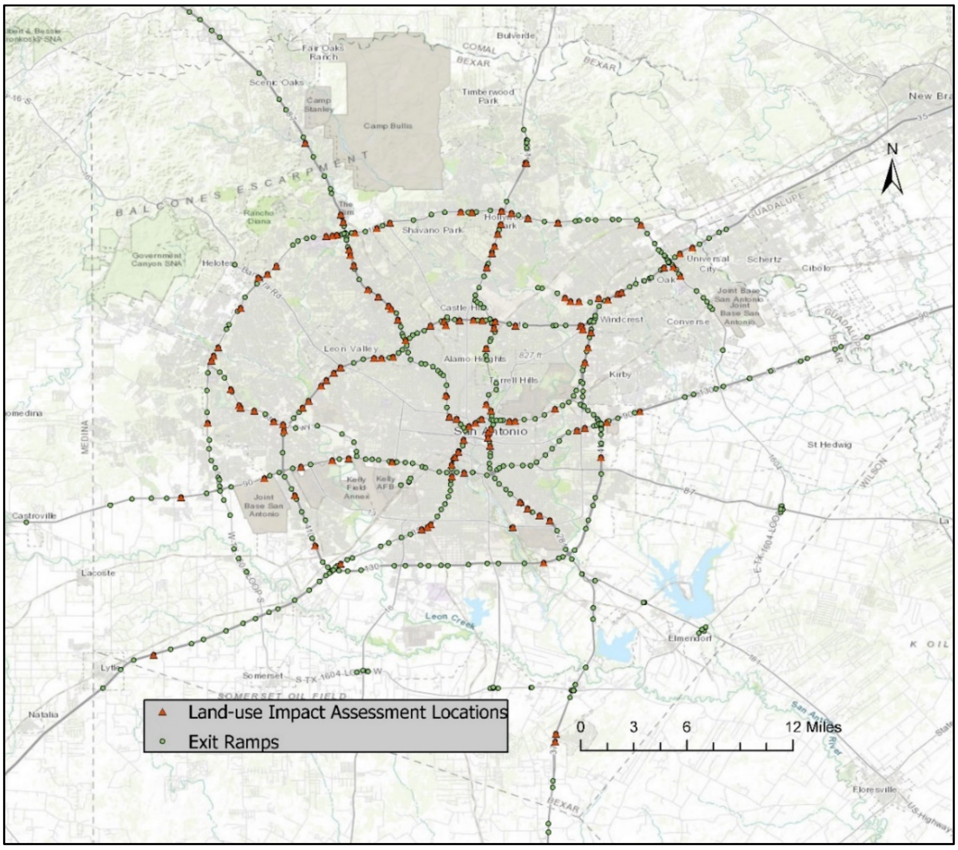

Figure 2. Exit ramps and land-use impact assessment entrance locations in Bexar County highway.

Data from TABC shows that a total of 2033 ASE have obtained permits to serve alcohol on-premises within the Bexar County area. The TABC database which includes the zip codes and street addresses of these ASE was utilized to geolocate the exact positions of these establishments. Data from TABC also include the active period of all ASE during study time, and this study only considered the ASE which were active during the study period. This research also georeferenced 543 highway exit ramps in Bexar County using maps, and the georeferenced database was visually validated by using GIS maps of San Antonio roadways alignments. Combined observation of georeferenced data shows that 141 exit ramps are within 2000 ft from registered on-premises ASE, which might act as the entrance locations for potentially intoxicated drivers (Figure 2). Considering the influence of ASE on WWD events, this study has considered these 141 exit ramps as potential hotspot entry points of WWD.

3.3. 911 Calls and Crash Data Analysis

The study analyzed highway-related WWD data over a seven-year period (2012–2018) from the TxDOT CRIS database. The 911 calls from the SAPD database include the reported location and time of WWD events. The time in this database is accurately reported by timestamp, but the location of the WWD on the highway is based on the verbal description provided by the caller.

After the initial data processing, three different mathematical analyses were conducted, namely WWC involved no recorded 911 call, WWC involved 911 call, and 911 call involved no recorded WWC.

3.3.1. Hotspot Analysis

This study adopted the hot spot analysis which uses the Getis-Ord Gi* statistic to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots) given a weighted set of data points (total frequencies for each exit ramp) [34]. Clusters of points having significantly higher or lower values compared to the expected values from random choices could be further classified based on confidence level. In other words, this tool looks at the value of each feature within the context of the values of the neighboring features and compares the local sum of the values of a cluster to the sum of the values of all features. In this study, hot spots and cold spots obtained from hot spot analysis respectively refer to high-risk and low-risk exit ramps. In this method, an output feature (containing a z-score, p-value, and confidence level bin) is obtained for each input feature. The local statistic of Getis-Ord Gi* is defined as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \quad (1)$$

where x_j is the attribute value (total frequency) for feature j, w_{ij} is the spatial weight (based on distance) between feature i and j, and n is the total number of features, the average of the observed values, $\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n}$, and the standard deviation, $S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\overline{X}\right)^2}$.

The hot-spot analysis assumes complete spatial randomness. When the z-score (represents standard deviation) is relatively high/low and associated with a very small p-value (represents the probability of randomness in clustering), the assumption of complete spatial randomness is rejected as these cases indicate statistically significant clustering or dispersion of features. In other words, it is very unlikely for a cluster to be a product of random distribution when it is associated with a very small p-value and a very high/low z-score. Selection of an excessive large/small search bandwidth results in a very smooth/spiky density pattern, and prior studies suggest a trial-and-error approach to overcome this limitation [34–36]. The total frequencies for each ramp obtained from 911 calls, land use, WWC with 911 calls, and WWC without 911 calls were used in the hot-spot analysis.

3.3.2. WWC Analysis Involved No Recorded 911 Call

In this scenario, the WWD involved vehicle might crash with the first vehicle encountered close to the endpoint of exit ramps on the highway. For this scenario, 911 calls are unavailable to report the WWD due to the short time between entering the highway and the occurrence of the crash. Therefore, the crash that happens on exit ramps or with the closest encountered cars (which will not allow other motorists to make 911 calls) on the highway will be considered under the analysis of the WWC involved no recorded 911 call model.

The schematic diagram of this scenario (Figure 3) reveals the collision between WWD and the closest encountered vehicle immediately close to the entrance location. The higher speed of vehicles on highways reduces the event response period, resulting in limited to no opportunity to make 911 calls by WWD observing motorists (C_1, C … C_n). The WWD vehicle which moves right to left (in the opposite of correct direction) has traveled a certain amount of roadway in the wrong direction before the crash (Figure 3). The exact location of crashes from the CRIS database and the anticipated traveled wrong-way distance have been applied to determine the entrance of specific WWD events in this model. Assuming that the highway traffic maintains a uniform deterministic gap, the value of the gap (g) was calculated by dividing the speed of vehicles (per hour) by the value of TxDOT hourly traffic volume.

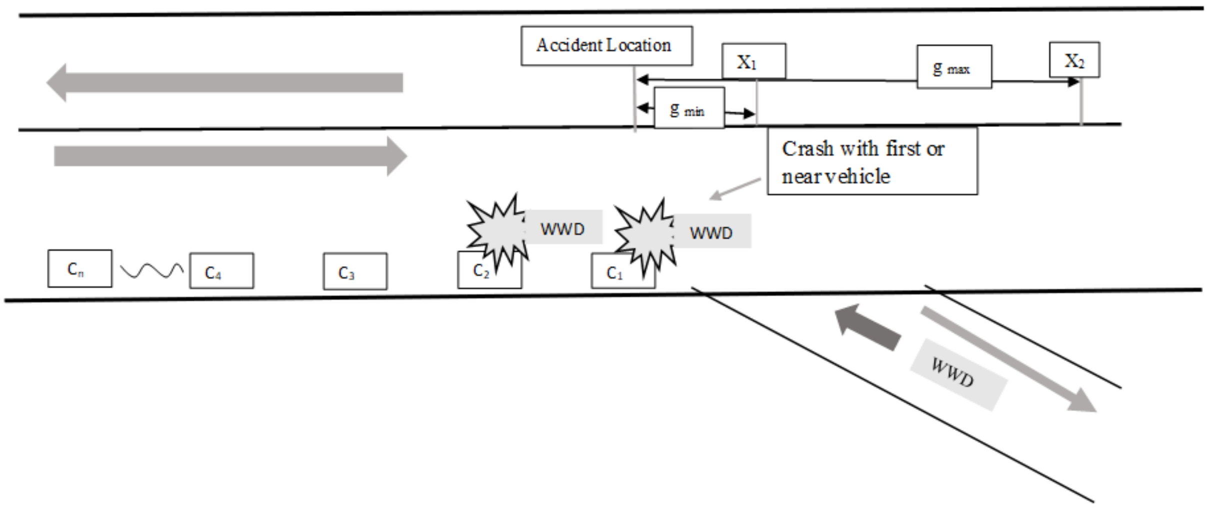

Figure 3. Schematic diagram of WWC involved no recorded 911 call.

The posted speed limit of a specific highway and the actual speed of vehicles on highways are not equal, and the model used the actual speed of vehicles involved in WWD on highways. All models of 911 call and crash data analysis considered the minimum possible speed to be 20 mph less than the posted speed limit (which is equal to 45 mph for Bexar County highways) and the maximum possible speed to be 80 mph (for a 65-mph speed limit highway) according to ADOT study [37] as 85th percentile of speed distribution. This research model calculates the g_{min} and g_{max} to geolocate the position of X_1 and X_2 from the map considering these speed limits. Here, X_1 indicates the possible earliest ramp location and X_2 Indicates the possible farthest ramp location for the entrance of WWD on the highway. The schematic diagram posits that exit ramps between X_1 and X_2 should be the potential entry point of that WWD event. The case of having zero ramps in-between X_1 and X_2 logically considered the immediate next exit ramp from the crash location as the entrance of the WWD assuming the fact that entrances should be very close to the crash location.

3.3.3. WWC Analysis Involved 911 Call

This model is proposed for a scenario different from the last model considering the facts that some motorists (C_1, C_2 … C_{n-1} from Figure 4) crossed the WWD without crashing and had made 911 calls to warn the authorities about the existence of a WWD on the highway. The WWC analysis involved 911 call model has been applied for cases where a crash event happened on the C_n location in Figure 4 and up to a maximum of (n−1) 911 calls have been generated by the motorists.

Geo-location of the crash from CRIS database and 911 calls geo-location from the SAPD database have been analyzed to determine the X_1 and X_2 locations from maps to identify the possible entrance in between these locations. Interval (ΔT) of T_1 and T_{n-1} is the time WWD involved driver drives on the highway after encountering the C_1 vehicle till the encounter of C_{n-1} vehicle before hitting the C_n vehicle. The value of g_{min} and g_{max}, and the distance between the first WWD encountered vehicle to the last encountered vehicle ΔD) have been calculated from assumed WWD speed (90 mph and 160 mph). The speed is double from the last model as opposite direction vehicles are passing each other and the resultant of speed is double of single vehicle's speed. Finally, the total distant g_{max} and g_{min} have been estimated by adding (d_{max}*2) and (d_{min}*2) with Δ, respectively. A factor of two for gap was considered due to the two gaps in this scenario: the gap between the exit ramp to the first vehicle and the gap between crash location to the C_{n-1} vehicle position. If it is not possible to guess the possible minimum and maximum speed on the highway, the posted allowable speed limit must be considered to calculate the value of g which will give

X_1 and X_2 (Figures 3–5) as the same location, and any ramps nearby this location will be considered as the entrance of this WWD event.

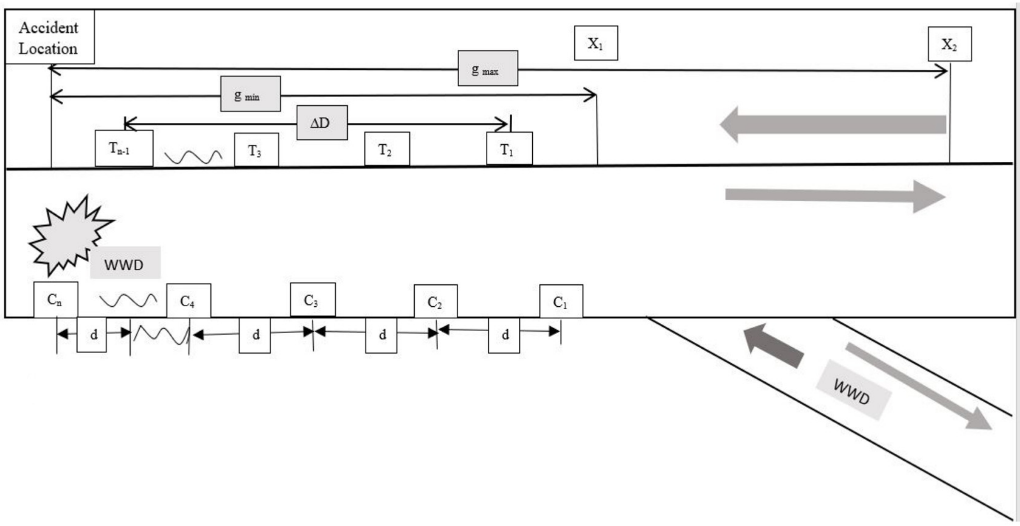

Figure 4. Schematic diagram of WWC involved 911 call.

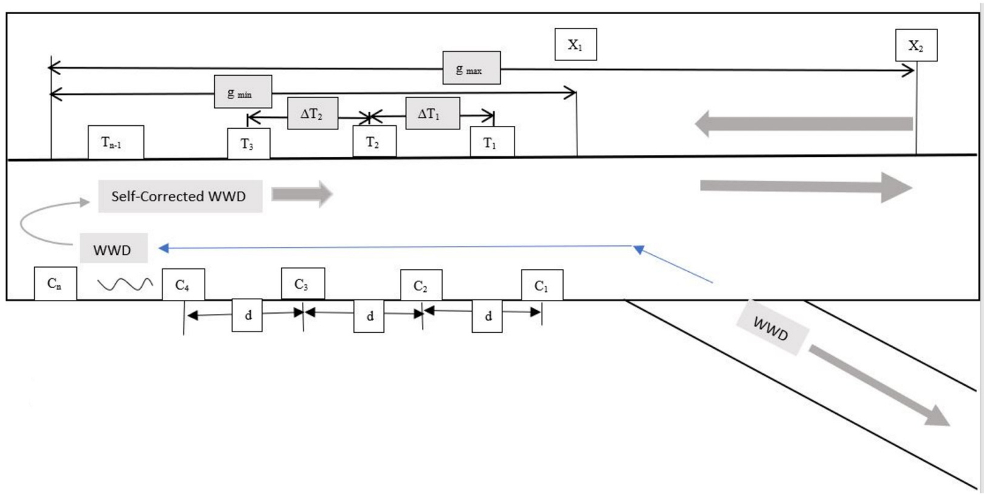

Figure 5. Schematic diagram of 911 call involving no recorded WWC.

3.3.4. 911 Call Analysis Involved No Recorded WWC

This model has been applied for the scenarios slightly different from the previous model. Here, the WWD involved driver recognizes the mistake after encountering a few vehicles and successfully makes a U-turn to correct the direction from the C_n location (Figure 5) or can exit the freeway using another ramp.

This phenomenon only contributes to 911 calls from motorists (C_1, C_2, C_3 … C_n) but fortunately not a crash on the roadway. The WWD events that produced only one 911 call were eliminated from the analysis due to the insufficient availability of information to identify the entrances of those WWD events. Geographic Coordinate System (GCS) of 911 call database was converted to Universal Transverse Mercator (UTM) coordinate systems to generate the distance between two callers to discover the actual speed of WWD involved vehicles. The areal distances have been validated from maps by observing the roadway geometry and corrections were applied if the roadway distance between two points is not straight. This distance (ΔD_1, $\Delta D_{2\ldots}$ ΔD_{n-1}) and time intervals between two callers (ΔT_1, ΔT_2 … ΔT_{n-1}) have been used to calculate the actual speed of WWD (V_1, V_2 … V_{n-1}) according to the information of callers. The acceptable speed, g_{max}, and g_{min} have been utilized to calculate the geolocations of X_1, X_2, and the entrance point of the specific WWD events.

4. Results and Discussion

This study adopted four distinct approaches (land-use impact assessment analysis, WWC analysis involving no recorded 911 calls, WWC analysis involving 911 calls, and 911 call analysis involving no recorded WWC events) to detect potential WWD entrances in the Bexar County highway system. The land-use impact assessment approach investigated 543 off-ramps in the Bexar County highway system to specify the ramps neighboring to an ASE to enforce the technique documented in the land-use impact assessment Section 3.2 of this manuscript. The exploration of land-use impact assessment suspected 141 exit ramps neighboring ASE as possible entryways for WWD. The analysis of WWC involving no recorded 911 (Section 3.3.2) calls have been performed over 199 WWC events during the study period and identified 132 exit ramps as possible entryways of WWD events. Moreover, 32 WWC were isolated to have 911 call records, and the analysis of WWC involving 911 calls (Section 3.3.3) identified 29 potential exit ramps responsible for the entrance of those 32 WWD events. Analysis of the 911 calls (Section 3.3.4) applied for 571 events has found 225 exit ramps to be potentially responsible for these WWD entrances. The summarized table of these four analyses posits that 213 ramps are possibly responsible for almost 98% entries of WWD for the data analyzed from 2012 to 2018. This study applied the total number of frequency parameter to rank the vulnerability of the ramps, where the sum of the counts from all four analyses was considered as the total frequency of WWD entries for each ramp.

The highest total frequency (13) has been found for the exit ramp denoted as "Point 213" in this study. Exit ramps where total frequency count is zero (a total of 242 exit ramps) are marked as "safe ramps". According to the validation of the study described in Section 5 of this study, no ramp from the above mentioned list was found to be a known entrance of WWD events and was the reason to consider them as safe ramps. The 88 exit ramps where the total frequency count is one are considered "less vulnerable ramps" as the total frequency is negligible. The remaining 213 exit ramps, where the total frequency is between 2 and 13, are denoted as "vulnerable ramps" as these exit ramps are responsible for all known WWD events. Limited availability of resources might make simultaneous installation of countermeasures in all 213 exit ramps uneconomical and impractical. The authors suggest allocation of resources based on exit ramp vulnerability (from total frequency count) while instilling countermeasures.

Table 1 represents the summarized final output of all associated exit ramps by analysis approach. Using the total frequency, statistically significant exit ramps with relatively high WWD events were identified through hotspot analysis (Figure 6). Physical inspection suggests that the identified hotspot locations (exit ramps) are within proximity of ASE and could be easily accessed by wrong way drivers who might be driving from the ASE. The results suggest that multiple exit ramps that are in proximity on the same roadway with substantial number of ASE close to the exit points of those ramps have significant influence on WWD entrance.

Table 1. Summary of four analysis with outcomes.

Analysis Type	Land-Use Impact Assesment Analysis	WWC Analysis—No Recorded 911 Call	WWC Analysis Involved 911 Call	911 Call Analysis—No Recorded WWC
Description	543 exit ramps with near proximity to ASE were examined. Those identified exit ramps have been considered potential entrance points of WWD to highways.	199 WWC from the database which has no 911 involved have been used in this analysis. WWD hits the first exit ramp proximate encountered vehicle on highway leaves no opportunity for other motorists to make 911 call before crash occurred. Approximate speed of the vehicle on highways is used to determine the maximum and minimum possible distance covered by WWD before crash to determine the location of exit ramps responsible for entrance of WWD.	32 WWC from the database with 911 calls from motorists in near proximity have been used in this analysis. Approximate speed of the vehicle in highways is used to determine the maximum and minimum possible distance covered by WWD before crash to determine the location of exit ramps responsible for entrance of WWD.	571 distinct events without WWC from 911 calls by motorists in near proximity was used in this analysis. Drivers somehow correct themselves or the authority was able to correct them crash occurred. Approximate speed of vehicles on highways has been used to determine the maximum and minimum distance covered by WWD before correcting the direction to determine the location of exit ramps responsible for entrance of WWD.
Number of ramps identified as entrance of WWD	141	132	29	225

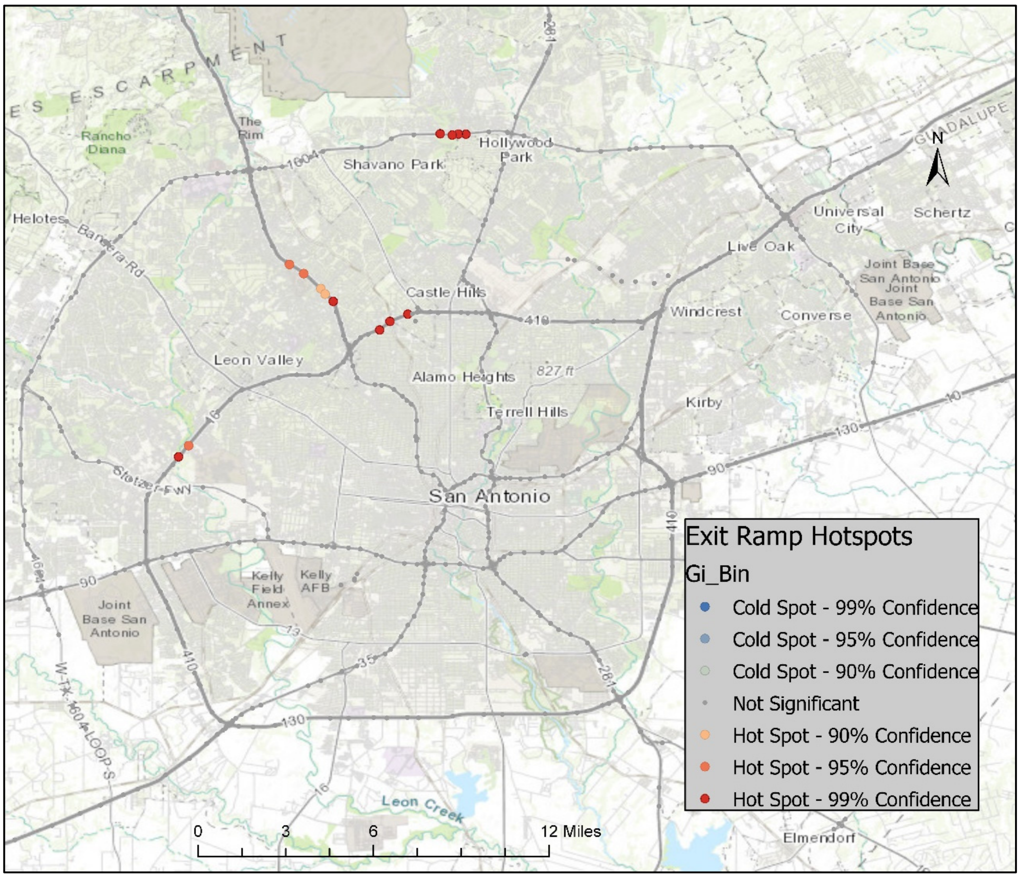

Figure 6. WWD entrance hotspots in San Antonio or Bexar County Area.

According to TxDOT crash data for the last two years, about 72% of WWC have resulted in at least one death. The yearly WWC frequency on highways inside Bexar County did not decrease since 2012 (Figure 7), implying the need of effective countermeasures on highways.

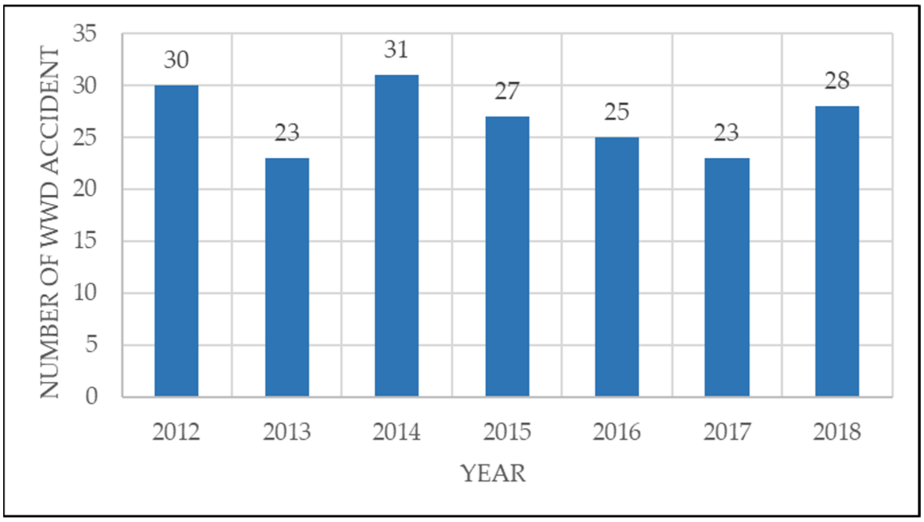

Figure 7. WWC in Bexar County highways (2012–2018).

Friday and the weekend period have the maximum WWD events (Figure 8). The increased activities at the ASE might be the potential reason. The hourly distribution of WWD events suggests relatively high WWC during late night hours (12:01 a.m.–3:00 a.m.). The peak of WWC is at 2:00 a.m. which is the accumulation of all WWC that have occurred between 1:01 a.m. and 2:00 a.m. (Figure 9). This peak of WWC coincides with the closing time of most ASE in San Antonio, implying that the proportion of intoxicated drivers on the streets might be relatively higher during this period.

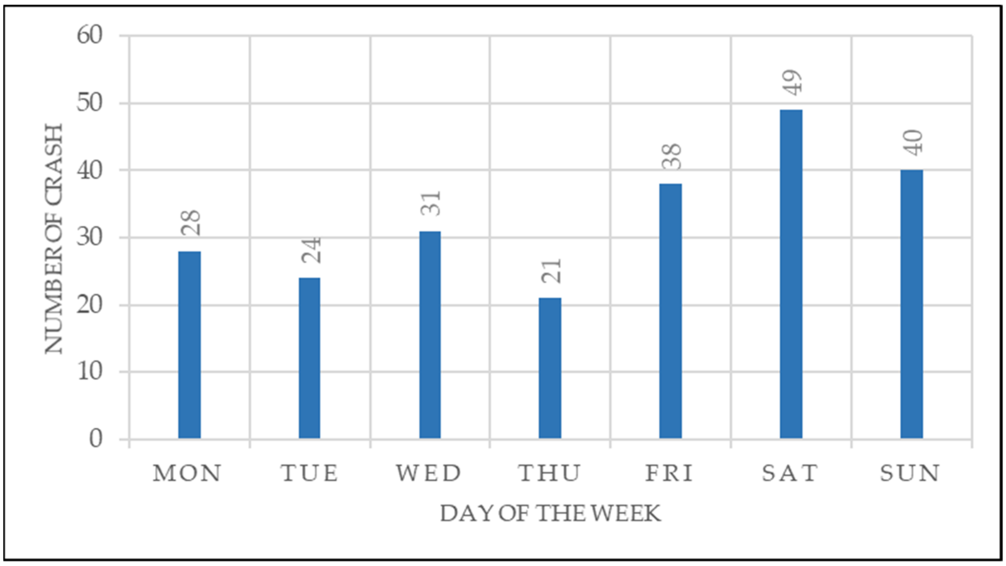

Figure 8. WWC in Bexar County highway by day of the week (2012–2018).

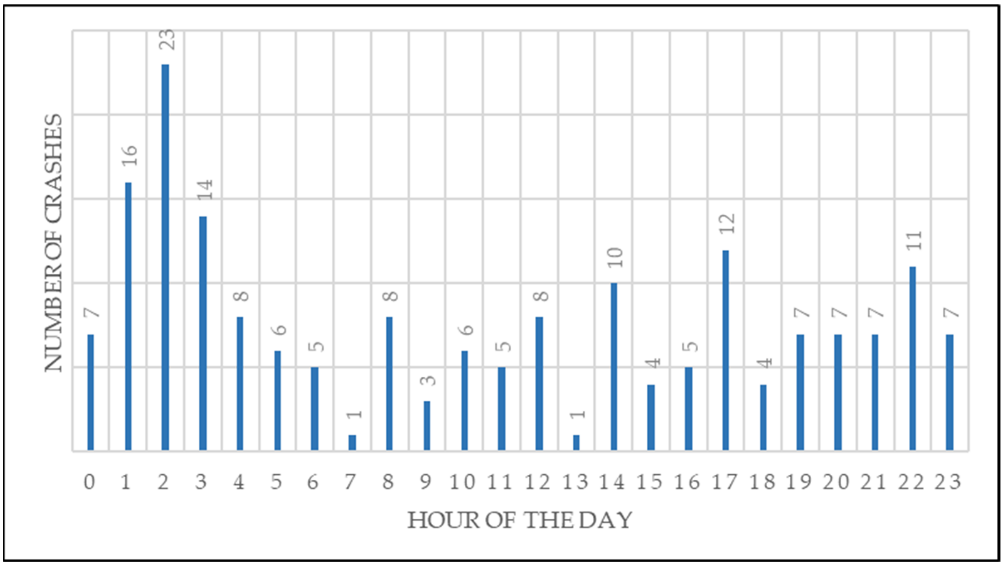

Figure 9. WWC in Bexar County Highway by hour of the day (2012–2018).

5. Validation

Validation of these outcomes were conducted from four different resources (crash database, court file report and site survey, 911 call database, and SAPD police investigation reports). Findings from the crash database analysis imply validity of our hypothesis about the impact of ASE on WWC. The court report files and field surveys have also supported the outcome of the study. Approximately 84.5% of SAPD 911 call entrances were within the outcome of the study and four out of five SAPD police investigation reports have been matched with the analysis result.

6. Conclusions

In summary, the ASE locations and the presence of residential area nearby the exit ramps appears to have a substantial influence on having WWD events (entering the highway while driving to home being intoxicated from ASE) [5]. Summarized outcomes of four analyses show the total frequency of all WWD entrance locations in the study area, which helped to classify ramps from the highest frequency to zero frequency. The validation from crash database, court file report and site survey, 911 call database, and SAPD police investigation reports indicate a relationship between the resultant frequency from the study and the known entrances of WWD events. As exit ramps which have a total frequency ranging from zero to one has no known entrances based on the validation, they are considered less vulnerable and would be eliminated at the beginning of future countermeasure's application. The 213 exit ramps where the total frequency ranges between 2 to 13 should be brought under consideration for applying relevant countermeasures.

As part of short-term plan and minimum investment, 41 exit ramps were identified which have higher total frequencies (carrying 32.8% of total entrances) and require prompt implementation of countermeasures. Suggested countermeasures in its simplest form include the installation of cameras, sensors, and adequate management of ramps. The precise real-time tracking of WWD will be possible if the authority installs a dedicated sensor system on each hotspot's ramps [5]. In future, effective countermeasures could also be provided on other vulnerable ramps to mitigate the WWD events in significant margin.

The study also found four major hotspots locations in the Bexar County, Texas study area: the 410 Loop near Culebra Road and Jackson Keller Road, 1604 Loop near US-281 highway, and IH-10 near the Medical Drive area. These hotspots area should be kept under surveillance to detect WWD events before other motorists are harmed.

The markings, signs, arrows, and WWD preventives must renovate and implement on dangerous hotspot locations to start mitigation of WWD events. According to a study, Light-

Emitting Diode sign and Rectangular Flashing Beacon signs of WWD identified a reduction of WWD events by 48.1% and 69.4% respectively, when intelligent transportation systems were used [28]. The assumed speed limits in this study are based on the previous studies and suggestions from TxDOT, but it is recommended to exercise survey investigation on actual vs. posted speed limits on all highways to estimate the minimum and maximum possible speed limit to conduct the analysis. The SAPD 911 call geolocations are not exactly accurate, so the improvement on 911 call data collections with more accurate geolocations might assist the methodology to be more precise and effective. If it is impossible to assign the possible minimum and maximum speed on the highway, the posted allowable speed limit must be considered to calculate the value of g which will gives X_1 and X_2 (Figures 3–5) as the same location, and any ramps nearby this location will be considered as the entrance of this WWD event.

The weekend period and the closing hours of ASE were associated with increased WWD events. The risk of bicycle and pedestrian crashes resulting in fatal and serious injuries also increased during this period in San Antonio, although the hotspots for pedestrian and bicycle crashes are different from the WWD hotspots [38,39]. This calls for the public encouragement of the use of ride sharing services after drinking and use of automatic emergency braking systems in vehicles in addition to increased law enforcement activity during this period. Future research may continue to improve the proposed methodology to find out the entrances of WWD events of non-highway systems. The regional and cultural impact of WWD can be expanded to reflect drivers' behavior.

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