Jordan Journal of Civil Engineering, Volume **15**, No. **1**, **2021**

Consistency and Performance of Interchange Loops

Hashem R. Al-Masaeid[1)*], Mohammed Taleb Obaidat[2)] and Ahmad S. Hjouj [3)]

[1)] Professor, Civil Engineering Dept., Jordan University of Science and Technology, Irbid, Jordan.
E-Mail: hashem@just.edu.jo, * Correspondent Author.
[2)] Professor, Civil Engineering Dept., Jordan University of Science and Technology, Irbid, Jordan.
E-Mail: mobaidat@just.edu.jo; Currently: in leave at Jadara University; President, mobaidat@jadara.edu.jo
[3)] Civil Engineering Dept., Jordan University of Science and Technology, Irbid, Jordan.
E-Mail: ahmadhjouj86@yahoo.com

ABSTRACT

The objective of this study was to investigate drivers' behavior, including traffic speed and vehicle lateral placement, as well as accidents at interchange loops. Twenty seven loops located in rural and suburban areas were investigated. For different vehicle classes, loops were evaluated using four measures; speed profile, speed consistency, vehicle lateral placement and traffic accidents. Data on loop characteristics, traffic speed and lateral placement of vehicles was obtained through field measurements.

Analysis results revealed that entrance, exit and the middle part of the loop are critical locations. Loop entrance and exit exhibited speed inconsistency and experienced a large number of collision accidents. The use of circular curve with a radius of more than 70 m may eliminate this problem. At the middle part of the loop, vehicles were found to get closer to the inner edge of the pavement and this location experienced considerable loss-of-control accidents. Results also indicated that passenger car is the critical vehicle for a consistent design.

KEYWORDS: Interchange loops, Speed profile, Consistent design, Lateral placement, Accidents.

INTRODUCTION

Nowadays, with the increase in traffic volume, many interchanges are constructed to release traffic congestion and improve safety. Interchanges are among the most complex and expensive components of highway facilities. Loops and ramps are prominent in the cloverleaf, partial cloverleaf, trumpets and other interchange designs. Despite the fact that interchanges are widely used, information on operational performance and safety of loops is limited (Farah et al., 2018; Lee et al., 2018). Thus, it is necessary to ensure that successive geometric elements of a loop are coordinated in a manner to produce harmonious driver performance without surprising events, such as traffic turbulence around discontinuities or lane change.

An interchange loop consists of loop entrance, ramp proper and loop exit (see Figure 1). In the design of these elements, the designer should provide a consistent design to achieve an effective and safe traffic operation. Consistency is defined as the degree to which highway systems are designed and constructed to avoid hazardous driving maneuvers, which may lead to accident risk (Al-Masaeid et al., 1995). Others defined design consistency as the conformance of highway geometry with drivers' expectancy (Gibreel et al., 1999; Hassan, 2004; Ng and Sayed, 2004) or drivers' workload (Sadia and Polus, 2013). Drivers' workload is defined as the rate of time at which drivers perform a given amount of driving tasks. However, this method is much less used than other methods because of its higher measuring difficulty (Hassan, 2004; Sadia and Polus, 2013). Therefore, the lack of consistency at successive highway elements may be considered a major cause of improper speed adaptation, unsafe driver maneuver and accident occurrence, especially under adverse weather conditions (Lamm et al., 1994; Al-Masaeid et al., 1999; Al-Masaeid, 2002; Ng and Sayed, 2008). Thus, the consistency in geometry evaluates the highway design issues, including speed, safety and performance (Castro et al., 2008; Farah et al., 2008; Anitha Jacob et al., 2013).

Received on 4/9/2020.
Accepted for Publication on 3/12/2020.

In fact, the concept of speed consistency has been implemented in the design guidelines of a number of some developed countries. Up to the authors' knowledge, all previous studies on consistency focused on two-way, two-lane highways and none of them tackled the issue of consistency at interchange loops.

The objective of this study was to investigate drivers' behavior and accident occurrence at interchange loops and explore possible recommendations for engineers and planners in this domain. The developed recommendations will take into account speed profile, speed consistency, vehicle placement and traffic accidents along interchange loops. In this study, different vehicle classes were considered, including cars, light trucks and trucks. The class of light trucks includes pick-up trucks, mini-bus, mini-van and cargo van. Also, interchange loops at rural and suburban areas were investigated.

METHODOLOGY

Four measures were used to evaluate interchange loop design performance, including speed profile along a loop, speed consistency, vehicle lateral placement along the loop and traffic accidents. Vehicle speed profile was considered to investigate how drivers negotiate and behave along the loop. This measure was used by several studies (Himes et al., 2011; Easa and Mehmood, 2007; Farah et al., 2017). The reduction in free-flow vehicle speeds between successive points along the loop was considered as a measure of speed inconsistency (Al-Masaeid et al., 1995; Al-Masaeid et al., 1999; Jacob et al., 2013; Al-Masaeid et al., 2020b). A vehicle is considered to travel at free-flow speed if the time headway exceeds 6 sec (Al-Masaeid et al., 1995). McLean (1978) indicated that the operating speed, represented by the 85th percentile speed, exceeded the design speed in low-speed environment. Also, several studies concluded that the use of operating speed for evaluating design consistency tended to underestimate speed reduction (Hirsh, 1987; McFadden and Elefteradou, 2000; Misghi, 2003; Pork and Saccomanno, 2006; Ben Nie, 2006). Thus, the speed reduction was computed as the difference between the averages of free-flow speeds on successive points along a loop.

Vehicle lateral placement along the loop was investigated to explore possible steering reversal to avoid shoulder encroachment or lateral guardrail. Also, lateral placement of a vehicle may be considered as a surrogate measure of traffic safety. Finally, traffic accident distribution was investigated to indicate critical hazard points along interchange loops.

According to AASHTO, loop horizontal alignment is designed as simple curve radius, flat-sharp-flat compound curve radii or sharp-flat-sharp compound curve radii (AASHTO, 2011). Although flat-sharp-flat compound curve is preferred in the design, most loops in Jordan are constructed as simple circular curve radius. It is worthwhile mentioning here that using composite curves including spirals and ramps in Jordan is not common; therefore, it is not included in this study. Field observations indicated that free-flow speed was not constant along the loop; therefore, points having maximum or minimum free-flow speeds were identified for detailed speed measurements. As such, free-flow speed measurements were taken for different vehicle classes at six points, as shown in Figure 1. The first point was taken on the tangent to the loop entrance. The second point was on the entrance of the loop, the third point was taken on the first quarter of the loop. The fourth point was on the middle of the loop. The fifth point was on the third quarter of the loop and the sixth point was on the exit of the loop. These points were considered to explore drivers' behavior along loops and to determine speed reduction, as a measure of speed inconsistency, along successive points on the loop.

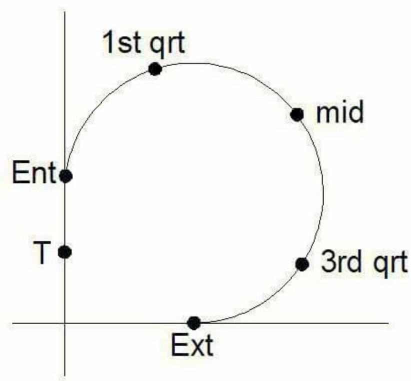

Figure (1): Points of measuring vehicle speeds

Vehicle placement along the loop was also considered in this study. It is worth mentioning that each loop has only one traffic lane with provision of over-passing. The pathway of the vehicle is normally represented by the outer-front wheel and the inner- rear wheel. In the field, it was difficult to determine the pathway of the frontal wheel because of the difficulty of determining its position by the car following method. In fact, the path of frontal wheel is not important, because drivers can control it, but they may not control the inner-rear wheel pathway. Therefore, the inner-rear wheel pathway is the one which affects the possibility of encroachment of shoulders or roadside obstacles as guardrail and thus dangerous situation may be created. As stated before, each loop has only one lane; thus no other conflicts are expected, since the investigated vehicle is traveling under free-flow condition. Using the car following method under free-flow condition, it was possible to get the actual pathway of the rear wheel, by using a video camera fixed on the tablue of the following vehicle and oriented towards the observed vehicle. Only vehicles under free-flow condition were considered in the data collection; therefore, sheltering effect of the investigated vehicle was not present. Five video images were taken at the same points where vehicle speeds are measured except at the tangent point. The images were analyzed to determine vehicle placements along the loop by using AUTOCAD, Version 2013 and image processing program. Knowing the width of the pavement at each investigated point, each image was imported to the AUTOCAD and scaled to determine the distance from the inner-rear wheel path and the inner edge of the pavement. All the images were analyzed by the same method to obtain the behavior of the drivers along the interchange loop.

DATA COLLECTION

Twenty seven loops were selected, of which fourteen loops were in rural areas and thirteen loops were in suburban areas. All selected loops were located at cloverleaf, partial cloverleaf and trumpet interchanges. Free-flow speeds data was measured for different vehicle classes, including passenger cars, light trucks and trucks. Twenty five passenger cars, fifteen light trucks and fifteen trucks were randomly selected and their free-flow speeds were measured on each of the specified points along each selected loop. The numbers and percentages of trucks and light trucks were very low in suburban areas, specifically under free-flow condition. Therefore, it was difficult to conduct speed measurements for a large number of light trucks and trucks. For each vehicle class, the average free-flow speed was computed on each point. However, for vehicle lateral placement along each loop, only ten vehicles under free-flow condition were selected for each vehicle class. The lateral placement study was limited to ten obsevations, because measurements extracted through cameras were more precise than speed measurements using car-following method. Moreover, for each vehicle class, the average lateral position of the inner-rear wheel was observed and measured at marked points on the pavement of loop roadway. The selected points were the same ones used for speed measurements.

Car-following method was used to collect speed data on the specified points along each selected loop. The global position system (GPS) tracking and video recording methods failed to provide accurate measurements. The GPS tracking method failed, because the Internet network coverage was not accessible in most of the selected rural areas. Thus, this method was abandoned. A video camera was used to record vehicles while passing along the loop. However, this method failed because of the inability of the video camera to record vehicle pathway along the whole loop completely. Finally, car-following technique was adopted, which provided accurate data (Hjouj, 2016). This method was performed by following vehicles on the loop with approximately constant space headway and the vehicle speeds were obtained from the following vehicle speedometer at the specified points. Clearly, the responsibility of the following driver was just to follow the leading vehicle at constant space headway, while the accompanied observer was to record the speed at the specified points. The free-flow speeds were recorded at each of the six marked points at every loop, which could form a speed profile for the followed vehicle.

Loop geometric design elements were obtained through field measurements and Google map (2016) surveys. These elements included loop radius, loop length, road intersecting angle subtending the loop, longitudinal slope of the loop, grade of the loop, bridge clearance elevation of the interchange, superelevation rate and posted speed limit. It is worthwhile mentioning here that all investigated loops have the same loop width of 10 m. The 10 - m width is fully paved, including inner shoulder, one traffic lane and outer shoulder.

Furthermore, lane and shoulder markings were not available or visible on most of the investigated loops. According to AASHTO (2011) specifications, the included loops are one-lane loops with the provision of passing.

As mentioned before, 27 loops and three classes of vehicles were investigated (81 observations). Table 1 illustrates the statistical characteristics of the collected geometric variables. As shown, loop radius varied from 25 to 85 m, while the speed limit on these loops varied from a minimum of 30 km/hr to a maximum of 40 km/hr. All investigated loops were super-elevated, with an average value of 5.6 %. Road intersecting angle which subtended the loop varied from 40 to 140 degrees with an average value of 90 degrees (for more detailed data, see Hjouj, 2016).

Traffic accident data for twenty of the selected loops was obtained from Traffic Department, Public Security Headquarters. Accident information included type of accident and its location of occurrence according to global positioning system, GPS. At the start of 2015, Traffic Department in Jordan had implemented the GPS system in accident records, which defined the exact position of accidents. Thus, accident history for only one year was available to be used in this study. It is known that accident records of two to three years are generally preferred (Al-Masaeid and Sinha, 1994). In this cross-sectional study, the use of accident history for one year is not unsound. Unfortunately, Annual Average Daily Traffic Volumes (AADTs) on the selected loops were not available.

Table 1. Statistical characteristics of the collected data

Variables	N	Mean	Std. Deviation	Range
Loop radius, *R* (m)	81	52	15.8	25 – 85
Loop length, *L* (m)	81	208	80.6	80 – 405
Road intersecting angle, *A* (degrees)	81	90	27.6	40 – 140
Longitudinal loop slope, *S* (%)	81	0.03	0.012	1.4 – 6.3
Superelevation rate, *e* (%)	81	5.6	1.9	3 – 8
Bridge clearance, *BC* (m)	81	5.5	0.66	5 – 6.5
Longitudial grade, *G*	81	0.59	0.49	Up or down
Location, *Loc*	81	0.56	0.5	Rural or suburban
Speed limit, *SL* (kph)	81	38.5	3.57	30 – 40

ANALYSES AND RESULTS

Vehicle Speed Profile

For each vehicle class, Figure 2 shows the speed profile along a loop with a radius of 45 m. This figure indicates that speed profiles of trucks and light trucks are almost similar, with a few differences. On this loop, the average free-flow speeds for passenger cars, light trucks and trucks were 42, 35.6 and 34.6 km/hr., respectively. Also, the standard deviations of speeds for passenger cars, light trucks and trucks were found to be 2.2, 1.9 and 1.8, respectively. Compared with speed standard deviations on rural or suburban roads, the speed standard deviations on interchange loops were relatively low.

For each vehicle class, the speed on tangent is higher than that at the interchange loop entrance and the vehicle speed becomes higher at the middle point of the loop and then decreases till reaching loop exit. Irrespective of the magnitude of speed reduction or increase, this behavior is consistent for all loops having a radius of less than 70 m. In contrast, no significant speed variations were observed along the investigated points for all loops with a radius greater than 70 m.

At the entrance of a loop with a small radius, drivers are very cautious or find difficulty to adopt to loop curvature; therefore, they negotiate the loop at relatively low speed, after which they increase their speeds nearly at the middle of the loop. The reverse behaviors were observed at the third quarter of the loop and at the exit. At the exit of the loop, drivers may face the same difficulty in eliminating the effect of curvature and negotiate the intersecting road. As such, they reduced their speeds at the loop exit to merge with traffic at the main road. Clearly, drivers may find difficulty in maneuvering and speed adaptation at the entrance and exit of the loop. Thus, speed consistency at loop entrance and exit should be further investigated. It is worth mentioning that speed on main roads varied between 80 and 100 km/hr; i.e., almost twice the loop speed.

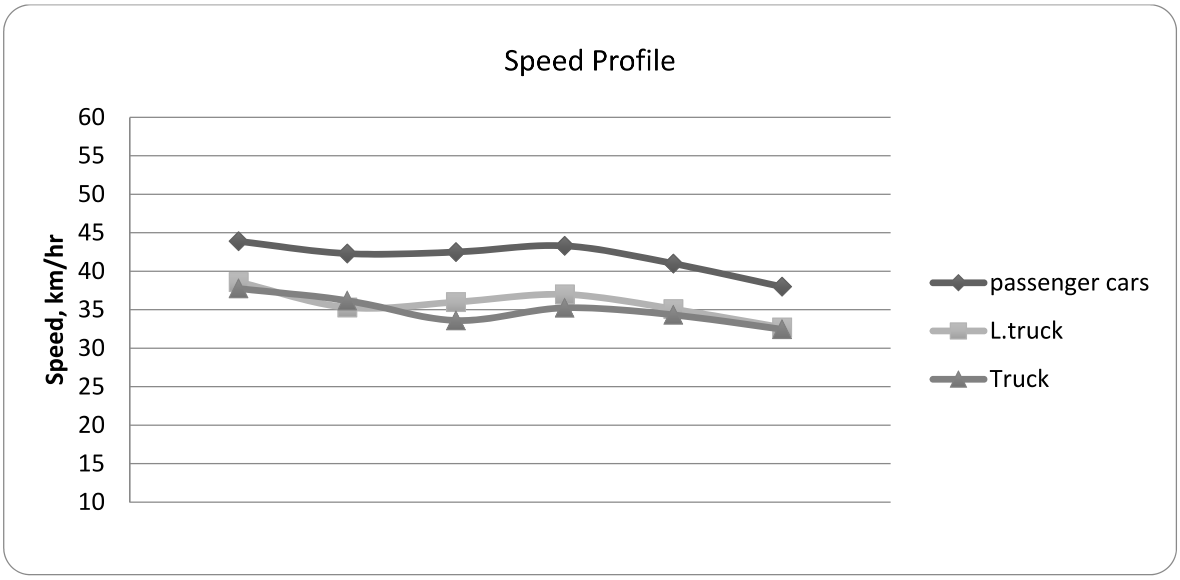

Figure (2): Speed profile for different vehicle classes along a loop having a radius of 45 m

Speed Consistency

Speed reduction between successive components of the loop was considered as a measure of inconsistency in the design. For all classes of vehicles, speed reductions between tangent and loop entrance, between the 3rd quarter of the loop and the loop exit and between the middle point of the loop and the loop exit should be investigated. Sections between these points exhibited noticeable reductions in speeds as observed in Figure 2, specifically for small loop radii. These reductions are:

$$\Delta V1 = Vt - Ven \quad (1)$$

$$\Delta V2 = V3rd - Vex \quad (2)$$

$$\Delta V3 = Vmid - Vex \quad (3)$$

where:

ΔV1: speed reduction between tangent and loop entrance.

ΔV2: speed reduction between 3rd quarter of the loop and loop exit.

ΔV3: Speed reduction between middle of the loop and loop exit.

Vt, *Ven*, *Vmid*, *V3rd* and *Vex* are the average of free-flow speeds at tangent, loop entrance, middle of the loop, 3rd quarter of the loop and loop exit, respectively.

For the included loops, Figure 3 illustrates the relationship between speed reduction of passenger cars and loop radius at the loop entrance, *ΔV1*. The figure indicates that the relationship is almost linear, especially for relatively small loop radii. Although the departure from linearity is relatively small, its effect will be discussed at two levels. First, any estimation of speed reduction must be done within the range of the empirical data; thus, the asymptotic issue is not prevailing. And second, the aptness of modeling or the need for any independent variable transformation will be highlighted in the subsequent paragraphs.

As shown in Figure 3, the maximum speed reduction is about 7 km/hr for a loop with about 25 m radius. However, for a loop radius of 65 m or more, the speed reduction is approximately zero. For a radius greater than 70 m, empirical observations indicated that drivers tend to increase their speeds a little bit, since they find that the loop radius is large enough to keep their speeds at a high level.

For passenger cars, Figure 4 shows the relationship between speed reduction and loop radius at loop exit, *ΔV3*. This figure shows that the relationship is almost linear. This behavior was almost the same as at loop entrance, but at loop exit, speed reduction values were slightly larger than at loop entrance, because vehicle speeds at loop exit were substantially lower than at loop entrance. For a loop radius of 25 m, the maximum speed reduction was 8 km/hr. However, for a loop radius more than 70 m, the reduction in traffic speeds from middle of the loop point to the loop exit was approximately equal to zero.

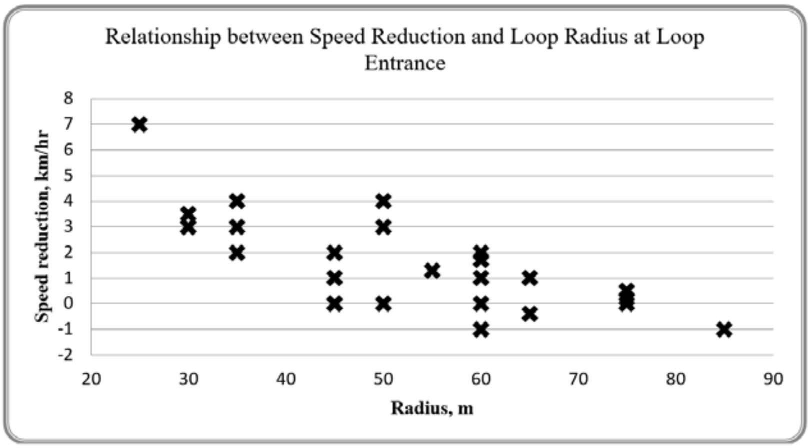

Figure (3): Scatter plot of passenger car speed reductions for different loop radii at loop entrance

Table 2 presents the correlation matrix among the included variables. Speed reductions *ΔV1*, *ΔV2* and *ΔV3* are strongly and negatively correlated with the loop radius and loop length. Also, there is a positive correlation between speed reductions and loop longitudinal slope. However, very strong multicollinearity was observed among radius, loop length and longitudinal slope, as shown in the table. In contrast, weak correlations were observed between speed reductions and each of super elevation rate, road intersecting angle or speed limit.

In modeling speed reduction, stepwise regression analysis was carried out including all potential independent variables. The curvature change rate (CCR) variable was excluded, because all its components, such as radius, deflection angle and loop length, were included as individual potential variables. Also, many researchers indicated that CCR cannot explain all speed or speed reduction variations (Ambros and Valentova, 2016; Obaidat et al., 1997).

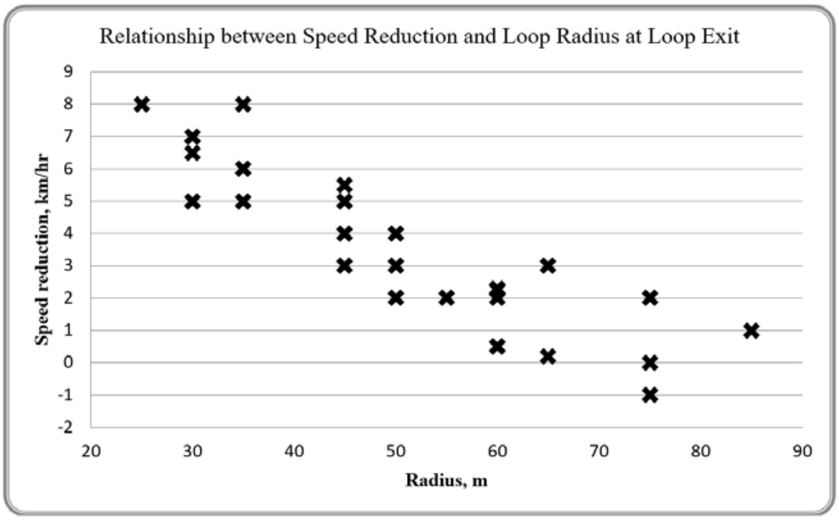

Figure (4): Scatter plot of passenger car speed reductions for different loop radii at loop exit

Using stepwise regression analysis, two statistical models were developed to estimate speed reduction at loop entrance and exit. Instead of fitting a separate model for each vehicle class, one model was adopted with one indicator variable. The indicator variable was introduced to distinguish between passenger cars and trucks and light trucks. Data for trucks and light trucks was pooled to form one population, since both trucks and light trucks had approximately the same speed profile pattern (see Figure 2).

The approach was adopted, because both populations had nearly the same error term and the use of one model with indicator variable would increase the power of testing model parameters, since more degrees of freedom will be associated with standard deviation of the model.

Table 2. Correlation matrix among the included variables

	R	***L***	***S***	***E***	***G***	***A***	***LOC***	***BC***	***SL***
DV_1	-0.79*	-0.76*	0.7*	0.24*	0.38*	-0.14	-0.53*	-0.62*	-0.18
DV_2	-0.72*	-0.73*	0.57*	0.14*	0.29*	-0.22*	-0.59*	-0.58*	-0.25*
DV_3	-0.68*	-0.68*	0.58*	0.17*	0.28*	-0.23*	-0.47*	-0.53*	-0.22*
R		0.96*	-0.84*	-0.28*	-0.35*	0.18	0.61*	0.67*	0.32*
L			-0.84*	-0.17	-0.40*	0.39*	0.56*	0.64*	0.39*
S				0.31*	0.38*	-0.45*	-0.28*	-0.40*	-0.10
E					0.09	0.07	0.14	0.17	0.21
G						-0.40*	-0.14	-0.15	-0.11
A							-0.15	-0.11	0.15
Loc								0.70*	0.43*
BC									0.20
SL									1.00

* p-value < 0.05.

For loop entrance, the following regression equation was obtained:

$$\Delta V1 = 8.6 - 0.08R - 0.59BC + 0.61G \quad (4)$$

where BC is the bridge clearance (difference in elevation between road pavement and the bottom of the bridge) in meters and G is the grade direction or direction of travel (for upgrade $G = 1$, downgrade $G = 0$). The above regression equation was significant at 95% level (N=81, R-square = 0.65, adj. R-square = 0.64, F =47.4, P < 0.0001). Furthermore, all regression parameters were significant at 95% confidence level. Loop radius, bridge clearance and loop grade direction were found to explain 42.1%, 13.1% and 9.7% of speed reduction variations, respectively. In the case of upgrade travel, speed reduction increased by about 0.61 km/hr compared with downgrade travel. For downgrade direction of travel and bridge clearance of 5.0 m, a zero-speed reduction could be obtained if a loop radius of 70 m is used. In the loop entrance model, vehicle class was found to be insignificant; therefore, the above equation is applicable to all included vehicle classes. The effects of loop length and longitudinal slope on speed reduction were found to be insignificant. This result is logical, because both variables are strongly correlated with the loop radius and the loop radius explained a large part of the variations in speed reduction. This supports our methodology of using individual variables rather than curvature change rate only, where loop length does not appear in the model.

The second model was developed for loop exit. Speed reductions from the middle or 3rd quarter of the loop to the exit were considered. The developed model was:

$$\Delta Vex = 13.72 - 0.10R - 0.75BC - 0.015A - 1.03VT + 1.15SEC \quad (5)$$

where:

ΔVex: speed reduction, km/hr.

A: angle between intersecting roads at which the loop is cited, degrees.

VT: vehicle class (for trucks and light trucks *VT* =1, for passenger car *VT* =0).

SEC: section type (for speed reduction between the middle of loop and exit *SEC* = 1, for speed reduction between the 3rd quarter and exit *SEC*=0).

The regression equation above was found to be significant at 95% confidence level (N=81, R-square = 0.56, Adj. R-square=0.55, F=39.57, P< 0.0001). All regression parameters were also significant at 95% confidence level. This equation indicates that speed reduction from the middle of the loop to the exit is greater than speed reduction from the 3rd quarter of the loop to the exit. Also, greater speed reduction is experienced by passenger cars compared with trucks or light trucks. Thus, the critical vehicle for a consistent design is the passenger car. Large intersecting angles reduced values of speed reduction. Drivers of light and heavy trucks are more cautious at loop exits more than at entrances because of merging of traffic at main roads and curiosity of accident involvement.

Correlations between speed reductions and the investigated variables for loop entrance and exit represented in Equations 4 and 5 are not unreasonable taking into account the variability of human behaviors among drivers.

Vehicle Lateral Placement along the Loop

The data collected for vehicle lateral placement was used to develop drivers' behavior along the interchange loop. Figure 5 shows the average distance from the pathway of inner-rear wheel to the pavement edge along the interchange loop for different vehicle classes. For this loop, the average distance for passenger cars, light trucks and trucks was 3.04, 2.36 and 2.44 m, respectively. Also, the standard deviations of these distances were 0.26, 0.27 and 0.25 m for passenger cars, light trucks and trucks, respectively. Figure 5 illustrates that the critical point along the interchange loop occurred at the middle point of the interchange loop. Therefore, this point should be considered as an important point in the interchange loop design.

Also, Figure 5 shows that there are different behaviors according to the vehicle class. In the case of passenger cars, drivers negotiate the interchange loop approximately at the middle of the entrance pavement, then they become closer and closer to the inner edge of the pavement until they reach the middle of the loop, then they drift away until they exit the loop at the middle part of the pavement. In the case of trucks and light trucks, the same behaviors were observed, except that the paths of the inner-rear wheel were closer to the edge of pavement compared to that of passenger cars. At the midpoint of the loop, light trucks approached the inner edge of the loop pavement more than trucks, because truck drivers keep the outer–front wheel closer to the outer edge of the loop pavement to keep the inner–rear wheel away of the inner pavement shoulder. In fact, light trucks are shorter than trucks; thus, light truck drivers do not worry about the inner shoulder encroachment.

At the middle point of the loop, vehicle placement data was used to estimate the minimum radius of the inner-rear wheel pathway. The minimum inner-wheel pathway radius, Rp, was computed as follows:

$$Rp = R - D \qquad (6)$$

where:

R: loop radius, m, and

D: distance from the center-line of the loop pavement to the path of the inner-rear wheel.

The following regression equation was developed to estimate the vehicle actual pathway radius of the inner-wheel at the middle point of the interchange loop:

$$Rp = -2.394 + 1.005R + 0.367VT \qquad (7)$$

where:

Rp : the pathway radius of inner-rear wheel,

R : loop radius, m, and

VT: vehicle type (for passenger cars *VT* = 1, for trucks or light truck *VT*= 0).

The above regression equation and all its parameters were found to be significant at 95% confidence level (N=81, R^2 = 0.99, Adj. R^2 = 0.98, F= 23649.063, P < 0.001). Clearly, the radius of the pathway of inner-rear wheel for passenger cars is larger than for trucks or light trucks by about 0.37 m. Furthermore, the distance between the center-line of the loop pavement and the path of the inner-rear wheel of trucks or light trucks is about 2.4 m, as shown in the equation above.

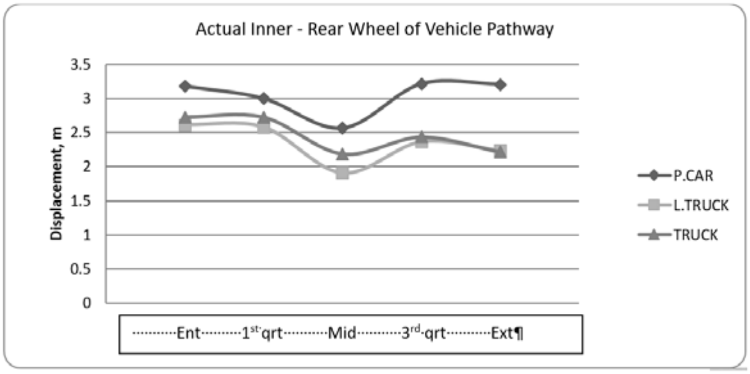

Figure (5): Vehicle placement for different vehicle classes along a loop having a radius of 45 m

Traffic Accidents

The distribution of the obtained accident data is shown in Figure 6. At each location of the loop, the three bars in Figure 6 represent the number of collision, turn over and pedestrian accidents, respectively. According to GPS accident data, traffic accidents were clustered at the loop entrance, at the middle part of the loop and at loop exit. This result is compatible with speed consistency and vehicle placement results. Bad speed adaptation, as indicated by speed reductions, at loop entrance and exit may contribute to collision accidents. On the other hand, drivers may raise their speeds near the middle of the loop and lose control over their vehicles as a result of centrifugal force. Consequently, turn over or loss-of-control accidents occurred. Also, drivers may get closer to the inner pavement edge near the middle of the loop; as such, they reverse their steering in the opposite direction and this sudden movement may create loss-of-control accidents. It is worth mentioning that pedestrian accidents occurred only at interchanges in suburban areas. Furthermore, fatal and injury accidents constitute about 1% of the total observed accidents.

In accident analysis, previous studies used a variety of models, such as Poisson regression (Jones et al., 1991; Al-Masaeid, 1997a), negative binomial regression (Bowman and Vecellio, 1995; Al-Masaeid et al., 1997) and regression analysis (Miaou, 1994; Al-Masaeid, 1997b). Poisson regression may result in biased model coefficients when the variance is greater than its mean (Bowman and Vecellio, 1995; Lord and Mannering, 2010). In this study, the mean, median and standard deviation of the observed accident data were 8, 7 and 4.8 accidents per year, respectively. As such, Poisson regression was excluded. Also, the use of negative binomial regression with small sample size probably creates dispersion-parameter estimation problem (Lord and Mannering, 2010). Furthermore, the computed coefficient of skewness for accident data was 0.2, which is close to zero. Therefore, the use of regression analysis is not unreasonable, since the distribution of accidents on the investigated loops is approximately normal.

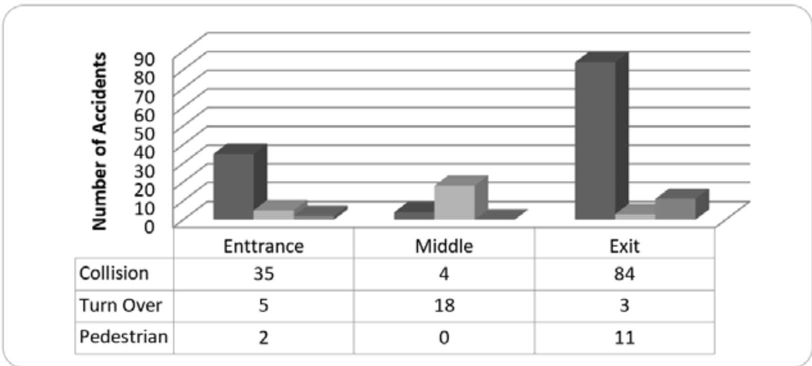

Figure (6): Distribution of traffic accidents at the included interchange loops

Using regression analysis, the following exponential equation was found to best fit the accident data for twenty loop sites:

$$NA = 42.10\ Exp(-0.037R\ ) \qquad (8)$$

In the equation above, NA is the expected number of accidents at a loop. The regression equation and all its parameters were found to be significant at 95% confidence level (N=20, R^2 = 0.85, Adj. R^2 = 0.84 F= 99.17, $P < 0.001$). This equation indicates that traffic accidents are exponentially related to loop radius. Again, the existence of multicollinearity between loop radius and loop length may force the loop length to be insignificant in the model equation above. Moreover, the unavailability of traffic volume, as an exposure measure, precluded the evaluation of the impact of this risk factor on accidents along the interchange loops.

DISCUSSION

Speed profile and speed reduction results for the investigated circular loops revealed that considerable speed reductions of 7-8 km/hr were observed at entrances and exits of loops having small radii. Thus, loop entrances and exits exhibited speed inconsistency. These locations also exhibited a large number of traffic accidents. This result is compatible with previous findings, which indicated that accident rates are significantly associated with inconsistent design elements (Polus and Matter-Habib, 2004; Ng and Sayed, 2004; Cafiso and Cava, 2009). This result shows the direct relationship between loop inconsistent design and occurrence of traffic accidents.

Previous studies that focused on design consistency of two-lane highways reported that good design can be achieved if speed reduction is less than 10 km/hr (Lamm et al., 1988; Al-Masaeid et al., 1995). Unlike two-lane highways, interchange loops being complex element with large curvature cannot provide drivers the possibility to accommodate such speed reduction within a relatively short distance. As such, entrances and exits of loops experienced large accidents at these locations as presented in this study. Most of these accidents were classified as collision accidents as rear-end collision at loop entrance and sideswipe in the same direction at loop exit. There were only yield signs at the loop exits with the existence of weaving condition at both the entrances and exits of loops. In fact, all investigated loops at cloverleaf interchanges were not provided with collector/distributor roads. Perhaps, weaving near on/off loop ramps contributes to these accidents. From safety perspective, the developed accident model revealed that loops with small radii are associated with relatively high accidents. Based on speed reduction results, it is recommended to use circular interchange loops with a radius of at least 70 m. This value is considered to be sufficient to avoid speed inconsistent design at loop entrance or exit and ultimately reduced traffic accidents. However, if radius can't be designed over 70 m, it is recommended to increase the bridge clearance, which will reduce speed reduction and provide better visibility and sight distance.

As shown in Figure 1, most drivers increased their speeds near the middle part of the loop. This increase in vehicle speed may increase the centrifugal force to an intolerable level and create turn-over accidents, particularly under rainy conditions (Al-Masaeid et al., 1999; Al-Masaeid, 2002). Empirical measurements and field observations indicated that most of drivers tried to cut the curve near the middle part of the loop, as shown in Figure 5 and this behavior may force the driver to drift his vehicle away to avoid encroachment of shoulder or guardrails; consequently, loss-of-control or turn-over accidents occurred as a result of this maneuver. This might happen, because drivers were trying to compensate for the centrifugal force. For each vehicle class, the lateral placement model indicated that the difference between loop radius and the inner-rear wheel radius is not largely sensitive to the loop radius, as shown in Equation 6. Thus, both loop curvature and drivers' behavior contributed to the concentration of accidents at the middle part of the loop. Therefore, traffic calming or warning measures might be sufficient to overcome this problem.

At loop entrance, speed reduction was not affected by the vehicle class. At loop exit, vehicle class affected the magnitude of speed reduction and the highest reduction is associated with passenger vehicles. Thus, passenger car is the critical vehicle for a conservative consistent design. This result is compatible with the results of previous studies conducted on two-lane highways (Al-Masaeid et al., 1995). Analysis of correlation and modeling indicated that speed reductions are not affected by the speed limit or superelevation rate. This result is logical, since speed limit and superelevation rate might affect the vehicle speed rather than speed reduction. Previous studies on geometric consistent design revealed that posted speed limit and super-elevation rate had no effect on speed reduction (Kanellaidis et al., 1990; Al-Masaeid et al., 1995). Also, interchange loop location, whether rural or suburban, did not influence the speed reduction. This result is consistent with the AASHTO policy that recommends using 50% of speed at main roads in loop design irrespective of the interchange location (AASHTO, 2011); i.e., the ratio of speed reduction between main road and loops is constant. Finally, the rear-wheel path of trucks determined the pavement width requirements.

Finally, traffic accidents were investigated in this study. Accidents are caused by several risk factors, such as drivers' errors, bad geometric design and vehicle conditions (Al-Masaeid, 2009; Mujalli, 2018; Al-Masaeid et al., 2020a). In this study, only risk factors related to geometric variables were explored in order to develop guidelines for safe interchange loops. The traffic accident model developed in this study indicates that accidents are exponentially reduced with the increase in loop radius. Empirical data and the developed model illustrated that loops with small radii experienced relatively large accident records. In fact, most of loops with small radii are located in suburban areas and some of these loops were subjected to heavy traffic volumes. A recent study conducted in Jordan (Al-Masaeid et al., 2020b) revealed that traffic accidents on interchange outer connection ramps are influenced by curve radius, traffic volume and ramp length. In this study, the unavailability of traffic volume data, as an exposure measure, precluded the evaluation of the impact of traffic volume on the level of accidents or possible confounding between traffic volume and loop radius. Thus, it is recommended to carry out further studies to highlight this issue. However, the results of this study clearly demonstrated that the use of loops with large radii may substantially reduce traffic accidents compared with loops with small radii.

CONCLUSIONS

The following points were the most significant findings and conclusions of this work:

1. Results of this study indicated that interchange loop entrance, exit and the middle part of the loop are the most critical locations. Compared with trucks or light trucks, passenger cars provided conservative consistent design values, so that they could be generalized as design vehicles in loops.
2. Small interchange loop radii exhibited a considerable speed inconsistency at loop entrance and exit. The use of circular loops with radii of 70 m or more may eliminate such speed inconsistent design and substantially reduce accidents.
3. At loop entrance, speed reduction was affected by loop radius, bridge clearance and traffic direction of travel (upgrade or downgrade). At loop exit, speed reduction was influenced by loop radius, bridge clearance, vehicle class and the value of the road intersecting angle subtending the loop.
4. At the middle part of the loop, vehicles were observed to get closer to the inner edge of the pavement. Findings indicated that the radius of the rear-inner wheel path depends on loop radius and type of vehicle. However, empirical and field observations indicated that most of drivers tried to cut the curve near the middle part of the loop.
5. The results indicated that traffic accidents at loop locations are exponentially reduced with the increase in loop radius.
6. Traffic accidents were found to be clustered at the entrance, middle part and exit of the loop. Collision accidents were concentrated at the entrance and exit, while turn-over or loss-of-control accidents were concentrated at the middle part of the loop.
7. When the variables investigated in this study are incorporated with traffic and accident data, this will open the door for a new framework and recommendations for loop design. It is recommended to conduct further studies to reach comprehensive loop design guidance, especially since traffic data was not included in this study and it was limited to circular loops with fixed cross-sections and shoulder widths.

REFERENCES

AASHTO (American Association of State Highway and Transportation Officials). (2011). "A policy on geometric design of highways and streets". Washington, DC, USA.

Al-Masaeid, H.R. (2009). "Traffic accidents in Jordan". Jordan Journal of Civil Engineering, 3 (4), 331-343.

Al-Masaeid, H.R. (2002). "Consistency of continuous horizontal curves under adverse weather condition." In: Proceedings of the 2nd International Conference on Safety on Roads, Bahrain, SORIC.

Al-Masaeid, H.R. (1997a). "The influence of block length on arterial accidents and traffic operation". Road and Transport Research, ARRB, 5 (3), 62-71.

Al-Masaeid, H.R. (1997b). "Impact of pavement condition on rural road accidents". Canadian J. of Civil Engineering, NRC, 24 (4), 523-531.

Al-Masaeid, H. R., Bazlamit, S. M., Al-Zedaneen, H., and Al-Mofleh, H. (2020a). "Impact of fasting on traffic accidents". Jordan Journal of Civil Engineering, 14 (3), 431-442.

Al-Masaeid, H.R., Hamed, M., Aboul-Ela, M., and Ghannam, A.G. (1995). "Consistency of horizontal alignment for different vehicle classes". Transportation Research Record, 1500, 178-183.

Al-Masaeid, H. R., Hammory, Kh., and Al-Omari, B. (1999). "Consistency of horizontal alignment under adverse weather conditions". Road and Transport Research, ARRB, 8 (3), 55-67.

Al-Masaeid, H.R., Magsi, T.M., and Almasaeid, H.H. (2020b). "Consistency of interchange outer connection ramps." Canadian J. of Civil Engineering, NRC, doi: 10.1139/cjce-2019-0828.

Al-Masaeid, H.R., Obaidat, M.T., and Gharaybeh, F. (1997). "Pedestrian accidents along urban arterial midblocks". J. of Traffic Medicine, 25 (3-4), 65-77.

Al-Masaeid, H.R., and Sinha, K.C. (1994). "Analysis of accident reduction potential of pavement markings". J. Transportation Engineering, ASCE, 120 (5), 723-736.

Ambros, J., and Valentova, V. (2016). "Identification of road horizontal alignment inconsistencies: A pilot study from Czech Republic". The Baltic J. of Road and Bridge Engineering, 11 (1), 62-69.

Ben Nie, B. (2006). Effect of horizontal alignment on driver speed behavior on different road classifications". MSc Thesis, Carleton University, Ottawa, Canada.

Bowmen, B., and Vecellio, R. (1995). "Vehicle and pedestrian accident models for median locations". J. of Transportation Engineering, ASCE, 121 (6), 531-537.

Cafiso, S., and Cava, G. (2009). "Driving performance, alignment consistency and road safety". Transportation Research Record, 2012, 1-8.

Easa, S.M., and Mehmood, A. (2007). "Establishing highway horizontal alignment to maximize design consistency". Canadian J. of Civil Engineering, NRC, 34 (9), 1159-1168.

Farah, H., Daamen, W., and Hoogendoorm, S. (2018). "How do drivers negotiate horizontal ramp curves in system interchanges in the Netherlands?". Safety Science, 119 (Nov. 2019), 58-69.

Farah, H., Mattar-Habib, C., and Polus, A. (2008). "Further evaluation of the relationship between enhanced consistency model and crash-rates of two-way rural roads in Israel and Germany". European J. of Transport and Infrastructure Research, 8 (4), 320-332.

Farah, H., Van Beinum, A., and Daamen, W. (2017). "Empirical speed behavior on horizontal curves in ramps in system interchanges in the Netherlands". Transportation Research Board 96th Annual Meeting, 17-02032, Washington, DC.

Gibreel, G.M., Easa, S.M., Hassan, Y., and El-Dimeery, I.A. (1999). "State-of-the-art of highway geometric design consistency". J. of Transportation Engineering, ASCE, 125 (4), 305-313.

Google Maps. (2016). "Map of Easterhouse churches". https://www.google.co.uk.

Hassan, Y. (2004). "Highway design consistency refining the state of knowledge and practice". Transportation Research Record, 1881, 63-71.

Hassan, Y., Sayed, T., and Tabernero, V. (2001). "Establishing practical approach for design consistency evaluation". J. of Transportation Engineering, ASCE, 127 (4), 295-302.

Himes, S., Donnell, E., and Porter, R. (2011). "New insights on evaluations of design consistency for two-lane highways". Transportation Research Record, 2262, 31-41.

Hirsh, M. (1987). "Probabilistic approach to consistency of highway alignment". J. of Transportation Engineering, ASCE, 113 (3), 268-276.

Hjouj, Ahmad S. (2016). “Speed consistency of interchange loops with different vehicle classes on rural highways”. MSs Thesis, Civil Engineering Department, Jordan University of Science and Technology, Irbid, Jordan.

Jacob, A., Dhanya, R., and Anjaneyulu, M. (2013). “Geometric design consistency of multiple horizontal curves on two-lane rural highways”. Procedia – Social and Behavioral Sciences, 104, 1068-1077.

Jones, B., Janssen, L., and Mannering, F. (1991). “Analysis of frequency and duration of freeway accidents in Seattle”. Accident Analysis and Prevention, 23(4), 229-255.

Kanellaidis, G., Golias, J., and Efstathiadis. (1990). “Drivers’ speed behavior on rural road curves”. J. of Traffic Engineering and Control, 31 (8), 404-435.

Lamm, R., Choueire, E., and Paluri, A. (1988). “Possible design procedure to promote design consistency in highway geometric design on two-lane rural roads”. Transportation Research Record, 1195, 111-122.

Lamm, R., Steffen, H., and Guenther, A.K. (1994). “Procedure for detecting errors in alignment design and consequences for safer redesign”. Transportation Research Record, 1445, 64-72.

Lee, T., Choi, Y., Kho, S., and Kim, D.K. (2018). “Multilevel model for ramp crash frequency that reflects heterogeneity among ramp types”. KSCE J. of Civil Engineering, 22 (1), 311-319.

Lord, D., and Mannering, F. (2010). “The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives.” Transportation Research, Part A: Policy and Practice, 44 (5), 291-305.

McFadden, J., and Elefteriadou, L. (2000). “Evaluating horizontal alignment design consistency of two-lane rural highways: Development of new procedure”. Transportation Research Record, 1737, 9-17.

McLean, J. (1978). Speed on curves: Regression analysis”. Internal Report 200-3, Australian Road Research Board, ARRB, Australia.

Misaghi, P. (2003). “Modeling operating speed and speed differential for design consistency evaluation”. MSc Thesis, Carleton University, Ottawa, Canada.

Mujalli, R.O. (2018). “Modeling risk of road crashes using aggregated data”. Jordan Journal of Civil Engineering, 12 (1), 45-60.

Ng, J.C.W., and Sayed, T. (2004). “Effect of geometric design consistency on road safety”. Canadian J. of Civil Engineering, NRC, 31 (2), 218-227.

Obaidat, M.T., Al-Jayyousi, O., and Al-Masaeid, H.R. (1997). “A new methodology for geometric performance of highways.” Highway Res. Bulletin, Indian Roads Congress, 57, 1-20.

Park, Y., and Saccomanno, F.F. (2006). “Evaluating speed consistency between successive elements of a two-lane rural highway”. Transportation Research, Part A: Policy and Practice, 40 (5), 375-385.

Polus, A., and Matter-Habib, C. (2004). “New consistency model for rural highways and its relationship to safety.” J. of Transportation Engineering, ASCE, 40 (3), 375-385.

Sadia, R., and Polus, A. (2013). “Interchange complexity model and related safety implications.” J. Transportation Engineering, ASCE, 139 (5), 458-464.