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Research Article

Traffic Capacity of Interchange Circular Loops

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Abstract

The major objective of this research was to determine the capacity of circular loops at suburban interchanges. To achieve this objective, ten interchange loops with different radii were selected. Data on traffic operation variables at loop entrance, loop exit, and middle part of the loop (proper) were obtained using video camera. Also, data on loop geometric were obtained through field survey.

Results of analysis indicated that loop proper capacity under Jordanian conditions is significantly lower than those presented in the Highway Capacity Manual. Two loop proper capacity models were developed using loop radius or free-flow speed as determinate variable. The analysis also revealed that loop exit capacity is influenced by the traffic flow on the outer arterial lane. Using regression analysis, an exponential model was developed to estimate loop exit capacity. Furthermore, a linear model was recommended to estimate loop entrance capacity, using loop radius as determinate variable. Finally, results of the study showed that loop entrance and exit capacity values in Jordan are comparable with those presented in the literature, and the exit capacity is the critical value that determines the capacity of the loop ramp.

Keywords: Interchange; loop capacity; circular loop; exit; entrance; proper; regression

Introduction

Today with the increase in traffic congestion levels, many interchanges were constructed to eases traffic movements. Cloverleaf and trumpet interchanges are widely developed in rural and suburban areas. These highway facilities are normally made of ramps and loops. In fact, a loop is provided to handle left-turn movements and its capacity is a critical issue in selecting a specific interchange type. For example, American Association of State Highway Officials (AASHTO 2011) revealed that the maximum capacity of a loop, regardless of its width, varied from 800 to 1200 vph [1].

In Jordan, Highway Capacity Manual (HCM) is widely used in estimating capacities of highway facilities without any modifications to account for possible differences. These differences are anticipated and attributed to differences in driver's behavior, design factors, and traffic mix. Estimation of loop capacity and determination of influencing geometric or operational factors would be very crucial for traffic and highway engineers.

The objective of this study was to determine loop capacity under Jordanian local condition and identify design factors that influence the estimated capacity. The scope of this study included circular loops in urban and suburban interchanges. In fact, in Jordan most of loops are constructed as circular loops. Furthermore, loops in rural areas are rarely operated at/near capacity.

Background

The Highway Capacity Manual [2] defined the capacity as the maximum number of vehicles that can pass through a point or uniform section of highway lane per hour under prevailing roadway, traffic, and ambient conditions. An interchange loop consists of three distinct elements; loop entrance, proper, and loop exit. Thus, capacity should be estimated singularly for each element [3]. Several studies have indicated that loop exit capacity at merge areas limits the loop capacity to a value of 1000 – 1200 veh/hr/ln [4, 5]. For radius 45 – 75 m and design speed 40 -50 km/hr, the proper capacity was found to be varied from 1800 to 1900 veh/hr/ln [5, 6]. Also, the HCM [2] indicated that the capacity of a single lane ramp varied from 1800 to 2000 veh/hr. for free- flow speeds of 30 to 65 km/hr., respectively. However, these values are very large compared with findings of other studies. For example, Fang et al. [7] used simulation analysis and estimated loop proper capacity at 1500 pcu/hr./lane.

On the other hand, previous studies have provided valuable methodological issues that relevant to capacity estimation. Headway models, car-following, empirical, and simulation methods are widely used to estimate capacity of uniform highway section such as loop proper. For merge areas such loop exit, methods such as theoretical gap acceptance, empirical, and simulation may be used to estimate capacity of entering traffic. Although some studies concluded that the gap-acceptance concept provides unrealistic capacity values of non-priority traffic, Al-Masaeid [8] indicated that both empirical and gap-acceptance approaches yield reasonable and comparable capacity estimates for U-turn at median openings.

Methodology

To achieve the objective of this study, ten interchange loops located in Amman, the capital of Jordan, were selected. These loops are located at interchanges of major arterials in urban and suburban areas. The selected loops are subjected to high traffic volumes and operated at capacity during peak periods. At capacity operation is defined as the condition in which there is a stable and continuous queue of moving vehicles in the middle part of the loop proper section. While for loop exit or entrance, this condition is achieved if there is a continuous queue of vehicles in the approach of the loop exit lane or loop entrance lane.

Empirical approach using regression analyses was adopted to estimate capacity of the proper section, loop exit, and loop entrance. A multiple regression analysis was carried out to develop empirical relationship for estimating capacity and identifying variables that affect the estimated capacity.

Data Collection

Three independent data sets were collected in 2017 and 2018. The first data set was collected to investigate relationships between traffic flow variables, estimate proper capacity, and identify variables that affect the estimated capacity. While, the second and third sets were obtained to estimate loop exit capacity and loop entrance capacity.

The first set included data on traffic and loop proper geometric characteristics. Traffic related data; including traffic flow rates and average vehicle speeds, were obtained through field survey using video camera. Manual speed traps located at the middle part of each loop were used to extract speed data. Traffic flow and average vehicle speeds were obtained based on one-minute intervals. These data were collected during peak and off-peak periods to cover a wide range of traffic flow and speed conditions. Loop geometric variables were obtained by Mapper software and AutoCAD civil 3D and checked through field survey. Each selected loop has one lane with 4.5 m width and total paved shoulders of about 3.2 m. Also, speed limit was varied from 30 to 50 km/hr.

The second set included data on loop exit capacity and arterial traffic conditions at merge areas. Loop exit capacity is defined as the maximum number of vehicles, under queue condition, that can leave the loop exit and join the mainline arterial traffic. For each 1-minute interval, loop exit capacity and mainline traffic flow rates on the outer two lanes were obtained using video camera. Also, average speed of the mainline traffic was obtained using manual speed traps. It is worth mentioning that loop exit lane has a trapped type. The collected data consisted of 183 min. of at capacity operation.

The third data set was collected to develop loop entrance capacity. The data were obtained at the throat of each loop and it included entrance capacity under stable queued traffic conditions. For each 1-minute interval loop entrance capacity and traffic speed of entering vehicles were observed. However, it was noted that entering traffic speeds and capacities, under queued condition, had very low variability at each loop entrance, and as such 15 observations were recorded and the average value was considered for further analysis.

Finally, all vehicles on the loop proper, loop exit or entrance and mainline arterial traffic were converted into passenger car units (PCU). For conversion into PCU, headway principles were adopted [9]. In the selected sites, heavy trucks were not allowed and the percentage of light trucks was 2 to 5 percent.

Analyses and Results

Loop proper capacity

For each selected loop, the relationship between average speed and traffic flow was investigated. For illustration, Figure 1 shows the scatter plot of speed and traffic flow data for a loop having a radius of 55 m. The relationship had a parabolic form with maximum observed flow or proper capacity of about 1480 pcu/hr. For this loop, traffic density was computed from observed flow and speed data and the relationship between speed (u) and density (k) is shown in Figure 2. This figure indicates that the speed-density relationship is almost linear. Regression analysis was performed to develop the relation between traffic speed and density for the proper section:

$$u = 48.2 - 0.39\,k \quad (1)$$

Equation 1 was found to be significant at a 95 percent confidence level (N=32, R^2=0.92, F=321). This equation indicates that the free-flow speed (FFS) is 48.2 km/hr. and the free-flow speed to jam density ratio (FFS/Kj) is 0.39.

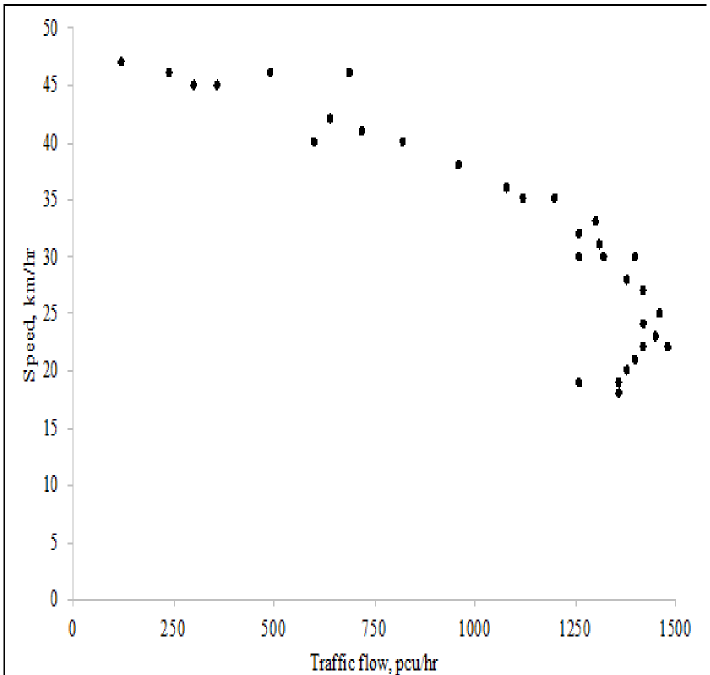

Figure 1: Scatter plot of traffic speed vs traffic flow for loop proper with radius of 55 m

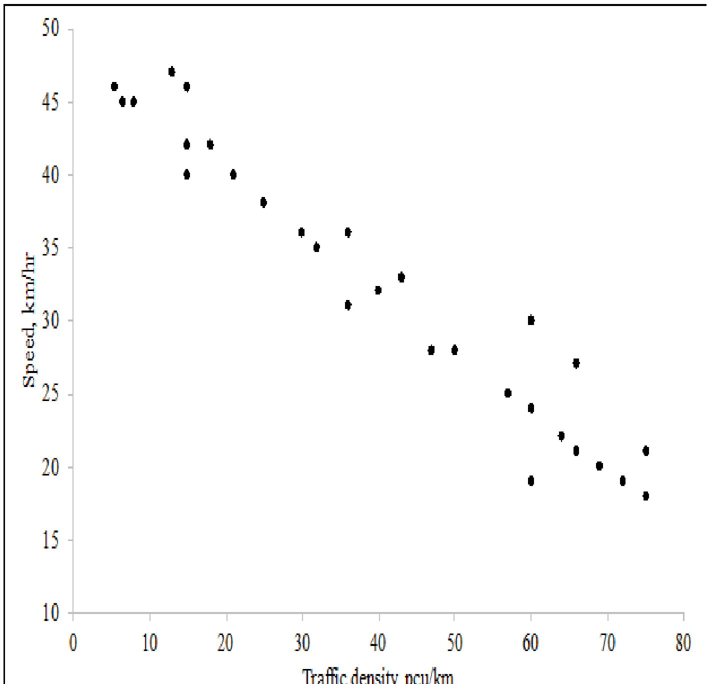

Figure 2: Scatter plot of traffic speed vs density for loop proper with radius of 55 m.

Also, this equation is similar to the Green shields' model which indicates that the relationship between traffic speed and density has a linear form. Based on this model form, Figure 3 presents the developed fundamental curves for loops having radii 45, 60, and 75 m. similar relationships were developed for all investigated loops and the results are presented in Table 1.

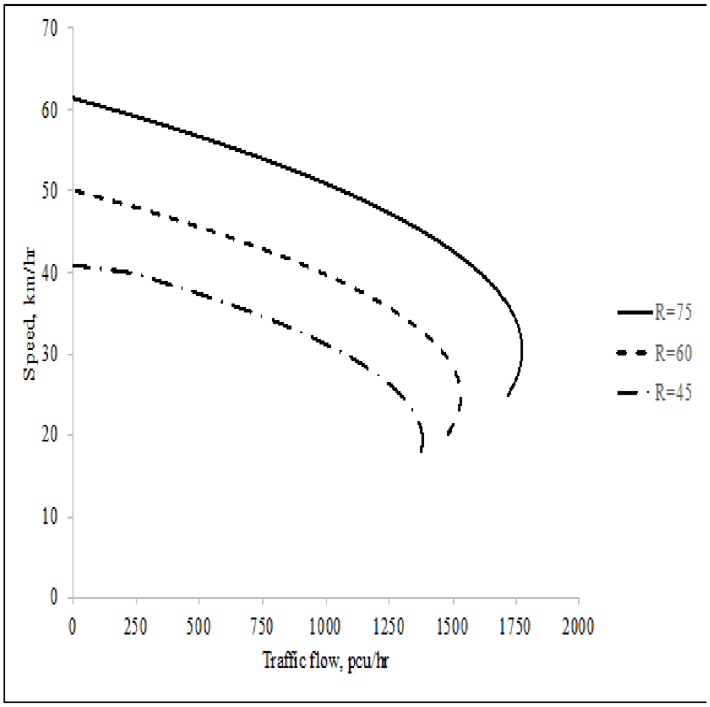

Figure 3: Relationship between traffic speed and flow on loop proper with different radii.

Investigation of Table 1 revealed that proper capacity varied from 1280 to about 1800 pcu/hr. for radius 25 to 75 m, respectively. Furthermore, correlation analysis showed that loop radius and FFS have a strong effect on the observed proper capacity. Also, the analysis revealed that loop radius is strongly correlated with the FFS. As such, two separate models were developed to estimate loop proper capacity. Based on the analysis, two regression equations were developed:

$$Cp = 492\ r^{0.29} \quad (2)$$

$$Cp = 188\ FFS^{0.54} \quad (3)$$

Where:

Cp = proper capacity, pcu/hr./lane, and

r = loop radius, m.

Equations 2 and 3 were found to be significant at a 95 percent confidence level. Although the use of radius (N=10, R^2= 0.83, and F= 46.2) and FFS (N=10, R^2= 0.95, F= 174.8) equations were found to provide reasonable fit to the observed capacity data, the use of FFS was the best from statistical point. However, the use of equation 2 is much more transparent from design perspective.

Finally, regression analysis was carried out to develop the relation between FFS and loop radius. Based on the analysis, the following regression equation was developed:

$$FFS = 5.65\ r^{0.54} \quad (4)$$

The regression parameters in Equation 4 was significate at a 95 percent confidence level (N=10, R^2= 0.92, and F = 103.4). This equation is similar to the one derived

Table 1: Observed proper capacity and the fitted speed-density relationship for different loop radii.

Radius, r (m)	Number of observations	Observed capacity (pcu/hr)	FFS (km/hr)	FFS/Kj	R^2
25	46	1280	34.3	0.28	0.90
30	44	1320	35.4	0.26	0.91
38	44	1380	37.2	0.3	0.91
45	52	1400	41.6	0.36	0.86
50	40	1400	42.6	0.34	0.89
55	32	1480	48.2	0.39	0.92
60	32	1560	49.5	0.43	0.94
65	30	1620	53.3	0.48	0.94
70	30	1720	58.6	0.54	0.91
75	34	1800	61.1	0.55	0.95

to estimate running speed on two-lane loop ramps [4].

Loop exit capacity

A correlation analysis was undertaken to identify the factors that influence loop exit capacity. The analysis indicated that loop exit capacity had strong correlation with the mainline traffic on the outer two lanes. The analysis also showed that the approach speed of the mainline traffic and traffic in the median lane did not have a strong effect on the loop exit capacity. Using regression analysis, two regression equations were obtained:

$$Cexit = 1097\, e^{-1.11\, F1/2000} \quad (5)$$

$$Cexit = 1163\, e^{-(0.99\, F1+0.18\, F2)/2000} \quad (6)$$

Where:

Cexit = loop exit capacity, pcu/hr./lane.

F1 = traffic flow in the first outer mainline lane, pcu/hr./lane, and

F2 = traffic flow in the second outer mainline lane, pcu/hr./lane.

Equations 5 and 6 were found to be significant at a 95 percent confidence level. Although traffic flow in the first outer mainline lane in Equation 5 (N=183, R^2= 0.87, and F = 1232.3) explained 87 percent of loop exit capacity variations, the addition of the traffic flow in the second outer mainline lane in Equation 6 (N=183, R^2= 0.88, and F = 689.1) improved the explained variations in the loop exit capacity by 1 percent only. For practical applications, thus, it is recommended to estimate loop exit capacity using Equation 5 with traffic flow in the outer mainline lane as the determinate variable. Clearly, Equation 5 illustrates that the maximum loop exit capacity is about 1100 pcu/hr./lane (see Figure 4).

Loop entrance capacity

Investigation of the empirical data indicated that the observed loop entrance capacity varied from 1700 to 1960 pcu/hr/lane for loop radius of 25 to 75 m, respectively. Data analysis revealed that the capacity is strongly related to the loop radius. Also, variations of traffic speed among investigated loops were relatively low; thus traffic speed had weak correlation with observed capacity. Two regression models were developed to estimate loop entrance capacity with loop radius as determinate variable, as follows:

$$Cent = 1566 + 5.1\, r \quad (7)$$

$$Cent = 1106\, r^{0.13} \quad (8)$$

Where; Cent represents loop entrance capacity, pcu/hr./lane. Both of the above equations were statistically significant at a 95 percent confidence level. Although both equations explained large variations in the estimated capacity, Equation 7 (N=10, R^2=0.89, and F= 64.95) had better statistical characteristics than Equation 8 (N=10, R^2= 0.88, and F = 59.55). Therefore, Equation 7 was recommended for practical applications.

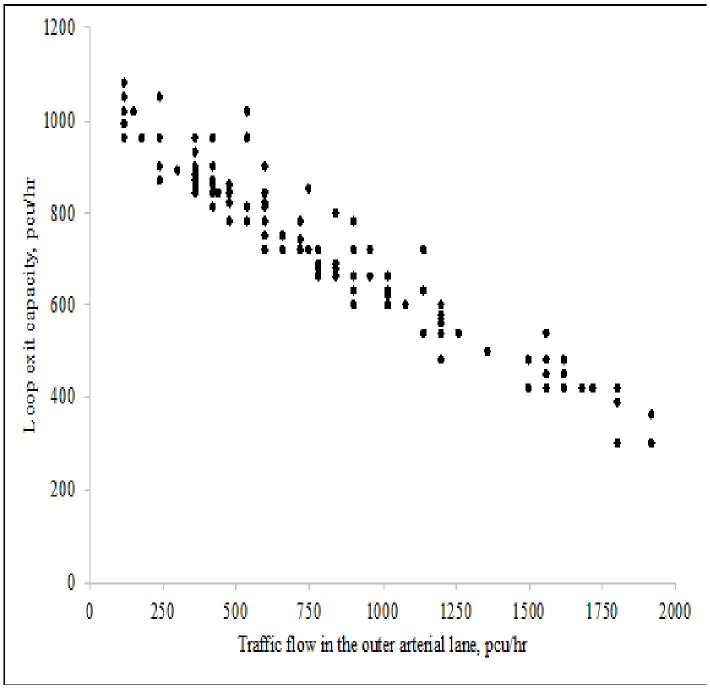

Figure 4: Scatter plot of loop exit capacity and traffic flow

Discussion

This study was undertaken to estimate the capacity of proper and exit sections of circular loops at urban and suburban interchanges. Empirical approach using regression analysis was adopted to develop capacity models. For loop proper, the analysis revealed that the capacity would be estimated based on loop radius or free-flow speed. Other geometric variables, such as speed limit, superelevation, and grade, were not found to be strongly correlated with the estimated capacity.

For the investigated loops with radii ranged from 25 to 75 m and the corresponding estimated FFS from 34 to 61 km/hr., the observed capacity was found to vary from 1280 to about 1800 pcu/hr./lane, respectively. These values are relatively low compared with some cited literature. For example, Bonneson et al. [5] and the HCM [2] indicated that proper capacity of loops varied from 1800 to 2000 veh/hr./lane for a FFS of 30 to 65 km/hr. However, Fang et al. [7] estimated loop proper capacity at 1500 pcu/hr./lane for a FFS of 35km/hr. Although traffic operation on loops and outer connection ramps are different, Leisch [10] showed that the capacity of circular proper of outer connection ramps ranged from 1250 to 1900 pcu/hr./lane at ramp free-flow speed of about 30 to 80 km/hr. Thus, the results of this study are not unreasonable.

For loop exit section, one exponential model was recommended to estimate loop exit capacity with traffic in the outer mainline arterial lane as the determinate factor. The analysis showed that the maximum capacity of the loop exit is nearly 1100 pcu/hr./lane. This value is consistent with the results of previous studies, which indicated that the capacity of loop exit is 1000 – 1200 pcu/hr./lane. Although high traffic speed on the mainline traffic would reduce merging rate, results of the study did not confirm this effect on the estimated loop exit capacity.

Analysis of loop entrance capacity showed that the observed capacity varied from 1700 to 1960 pcu/hr/lane for loop radius 25 to 75 m, respectively. These values are consistent with the results of the previous studies [11, 12], which indicated that the capacity of tapered right-turn ramp varied from 1600 to 1900 pcu/hr/lane.

Finally, results of this study revealed that proper capacity or loop entrance capacity is larger than loop exit capacity for each investigated loop. Also, this result is compared favorably with findings of previous studies. Thus, loop exit capacity controls the loop ramp capacity.

Conclusions

Based on the results of this study, the following points were concluded:

1. Loop proper capacity was found to be significantly affected by the loop radius and free-flow speed. The best predictive capacity model, using loop radius or free-flow speed, had a power form.

2. Results of this study revealed that loop proper capacity values in Jordan are significantly lower than those presented in the HCM especially for loops with small radii.

3. Although both traffic flows in the outer two lanes of the mainline arterial were found to be influenced the loop exit capacity, arterial flow in the outer lane was explained the major part of exit capacity variations. Using traffic flow in the outer lane as determinate variable, an exponential model was developed to estimate loop exit capacity.

4. Analysis indicated that loop entrance capacity is strongly and linearly related to loop radius. The results showed that the obtained capacity is compared favorably with values presented in the literature.

5. The results of this study were consistent with previous literature, which indicated that the loop exit capacity limits the loop ramp capacity.

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