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Research Article

Evaluation of Throughput Changes In Merging Bottlenecks Based on on-Ramp Traffic Flow Ratio_Case Study Tehran

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Abstract

When congestion occurs in a traffic flow, the throughput downstream of a bottleneck tends to decline from the maximum throughput in the free-flow state. Fluctuation in traffic circumstances affect the maximum throughput in the free-flow situation for the same research location. Ramp-metering can prevent or lessen traffic congestion if we can accurately forecast the maximum throughput depending on traffic conditions. The relationship between maximum throughput and on-ramp ratio is investigated in this study. It turns out that there is a convex quadratic-polynomial relationship between changes in the on-ramp ratio and the maximum throughput of each research site. The results of this investigation demonstrate that capacity loss and traffic congestion can be successfully avoided by regulating the on-ramp ratio.

Keywords: Bottlenecks; Traffic congestion; Throuput flow rate; On-ramp ratio

Introduction

The bottleneck usually activates at a merging point in a continuous traffic flow, such as freeway [1-5]. Due to competition between mainline and on-ramp traffic, the merging bottleneck becomes congested as on-ramp traffic ratio increases. When a bottleneck causes congestion, the throughput downstream of the bottleneck often declines from its maximum in the free-flow state [3,6-7]. The difference between the maximum pre-queue flow and the discharge rate can be used to calculate the capacity decrease. Numerous researchers, including Oh and Yeo [8], estimated the amount of capacity drop by looking at the discharge rate and defined capacity as the highest throughput. To visually represent flow fluctuations at several measurement locations, they employed an N-curve [9-10]. Yet, a number of studies [11,10] have discovered that capacity is typically underestimated when using the traditional approach of capacity assessment.

Additionally, it is known that, for the same research site, traffic flow changes affect the maximum throughput in the free-flow state [12-15]. Usually, the flow of traffic changes from being free-flowing to crowded as vehicles on ramps join into the mainline in the shoulder lane [16-17]. Here, the center lane does not attain its maximum flow; instead, it moves at free-flow speed. As the travel speed drops and the shoulder lane is crowded, vehicles in it attempt to merge into the center lanes. This results in a decrease in speed and a shift in the mainline flow to queue-discharge circumstances. The middle lane may not reach the maximum flow rate even if the maximum throughput is achieved because it may abruptly transition from 1) free flow, which has a flow rate below the maximum flow rate, to 2) queue-discharge. Even in circumstances where there is unrestricted flow, some lanes might not permit the maximum flow rate to be reached [11] . Maximum throughput in the free-flow scenario needs to be maintained in order to delay the onset of congestion [18,19]. Understanding the impact of on-ramp traffic on maximum throughput is essential to developing an efficient on-ramp management strategy [20,21]. We can either prevent or reduce traffic congestion if we can accurately forecast the maximum throughput. The purpose of this study is to investigate the relationship between maximum throughput and the on-ramp traffic flow ratio, a critical component in bottleneck operation mergers.

Data Collection and Estimation

Study Sites

We investigated the relationship between on ramp ratio and maximum throughput by analyzing traffic data from five distinct merging sections on Tehran highways. The average vehicle mix for each research location is displayed in (Table 1).

Table 1: Average vehicle composition of each selected study site.

Average vehicle composition				
#	Study site	Passenger car	Trucks and buses	Total
1	Hakim EW at Shaghayegh	96.11%	3.89%	100%
2	Hakim EW at Haghani	90.58%	9.42%	100%
3	Hakim EW at Payambar	88.61%	11.39%	100%
4	Hemmat EW at Tavanir	84.30%	15.70%	100%
5	Hemmat EW at Shariati	96.85%	3.15%	100%

Data Collection and Screening

For the analysis, data was gathered over a nine-month period. Every thirty seconds, basic data like as volume, occupancy, and speed are recorded by the recorders at the mainline and on-ramp. To investigate the independent influence of on-ramp traffic in the merging bottleneck, only traffic data for congested traffic was employed.

Congestion Identification

The amount of congestion brought on by on-ramp traffic was computed by calculating the fastest speed for a minute at each observation point. When congestion event happens, certain lanes slow down while other lanes maintain their free-flowing speeds. In this situation, the mainline's average speed can be decreased. Conversely, if the top speed of every lane drops, we can presume that every lane is clogged. “Traffic congestion” refers to the condition where all mainline lanes are moving at or below critical speeds in this study; hence, the maximum speed was used as a congestion indicator instead of the mean speed. The relationship between the on-ramp ratio and maximum throughput is the main subject of this investigation. As a result, the analysis was limited to the specific cases of congestion caused by on-ramp traffic at a certain bottleneck. Thus, we chose data that demonstrated a pattern of speed reduction at the bottleneck and recovery after it was passed through. These conditions were removed from the study because, in the event that the downstream speed is less than the upstream speed or the mainline vehicle speed does not increase after crossing the bottleneck, they could indicate an incident or traffic spillover from the downstream.

Maximum Throughput

With an increase in mainline and on-ramp traffic flow, throughput flow usually increases. As traffic demand rises, a bottleneck's throughput approaches capacity for a few minutes before transitioning from a free-flow to a congested condition. Although the Transportation Research Board defines capacity as the maximum flow sustained for 15 minutes, prior research has shown that the maximum throughput is not maintained for longer than 15 minutes [2,15,22]. Numerous studies have shown that while the traffic flow rate remains near capacity for roughly five minutes, five minutes is a sufficient amount of time for study when monitoring the maximum throughput [8,12,23]. In this study, the throughput value in the free-flow scenario, which does not include the bus priority lane, was selected for continuous monitoring of the 5-min throughput fluctuation. A 5-min moving-average throughput was created by aggregating the previous 10 30-s raw data every minute (Equation (1)). Using the moving average is a simple method of keeping an eye on a continuous data trend throughout the course of an analytical time unit.

$$Q_i^{5MA} = \frac{1}{5}\sum_{i}^{i+9} Q_i^{30s} \quad (1)$$

Q_i^{5MA} = 5-min moving-average throughput at time step i (veh/min)

Q_i^{30s} = 30-s throughput raw data at time step i (veh/30 sec)

Calibration of Time Lag

According to the traffic conservation law, the total number of vehicles on the mainline and the on-ramp adds up to the downstream traffic flow [24]. Consequently, the passing time lag between the upstream and downstream should be taken into account while computing the on-ramp ratio. Equation (2), where the downstream recorders' distance is l and the upstream speed is Vu, gives the passing time lag between the upstream and downstream detectors. Equation (3) calculates the on-ramp ratio for the 5-min maximum-throughput phase.

$$\tau = \frac{1}{V_u} \times 60 \qquad (2)$$

τ = Passing time lag (min)

V_u = Upstream speed (km/h)

l = Distance between upstream and downstream (km)

$$\phi = \frac{Q_{r,(t-\tau_r)}}{Q_{u,(t-\tau_u)} + Q_{r,(t-\tau_r)}} \qquad (3)$$

$Q_{r,t}$ = On-ramp traffic flow at time t (veh/5 min)

$Q_{u,t}$ = Upstream traffic flow at time t (veh/5 min)

t= Time

φ = On-ramp ratio

τ_u = Passing time lag between upstream and downstream

τ_r = Passing time lag between on-ramp and downstream

Constraints of On-Ramp Ratio

Think of a bottleneck that is forming a merge with Nm mainline lanes, Nr on-ramp lanes, and (Nm + Nr -1). The maximum throughput downstream is f(φ), a function that is contingent on the on-ramp ratio. The maximum downstream throughput f(φ) is made up of on-ramp traffic and mainline traffic, which are represented as φ × f(φ) and (1−φ) × f(φ), respectively. These numbers need to be lower than the mainline and on-ramp's combined capacity. Equations (4) and (5) display the correlations, and the on-ramp ratio needs to satisfy these equations.

$$(1-\phi) \times f(\phi) \le N_m \times C \qquad (4)$$

$$\phi \times f(\phi) \le N_r \times C \qquad (5)$$

C= Capacity per lane (veh/5 min-lane)

F(φ) = Maximum throughput (veh/5 min)

N_m = Number of mainline lanes.

N_r = Number of on-ramp lanes.

φ = On-ramp ratio

Analysis Results

For every research site, empirical observations yield 13-22 data points that illustrate the relationship between the on-ramp ratio and the maximum throughput. (Figure 1) illustrates the connectivity for each study location graphically. The data points for each study came from a unique case of traffic congestion at each research site. The on-ramp ratio and maximum throughput exhibit significant diversity, according to the empirical results. Equations (4) and (5) are satisfied by all observed on-ramp ratios, as Table 2 demonstrates. The maximum throughput at research site #1 decreased until the on-ramp ratio got to 0.26, after which it increased and reached the local minimum point. At the other study sites, convex quadratic polynomial forms were also discovered. At research locations #2, the local minimum on-ramp ratios for maximum throughput.

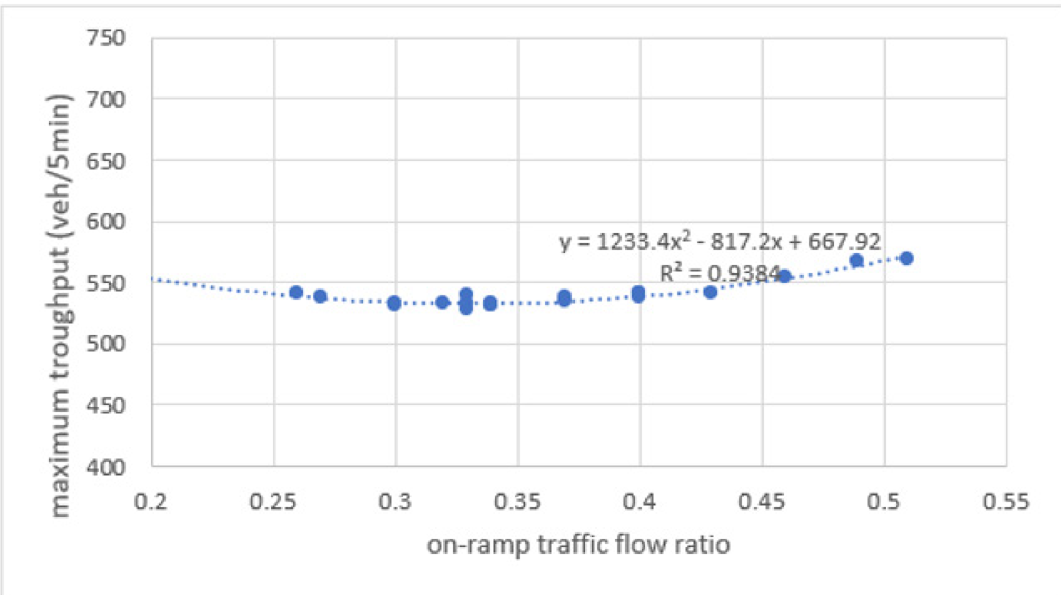

Figure 1a: Relationship between On-Ramp Ratio and Discharge Rate: (a) Study Site #1, Hakim EW at Shaghayegh.

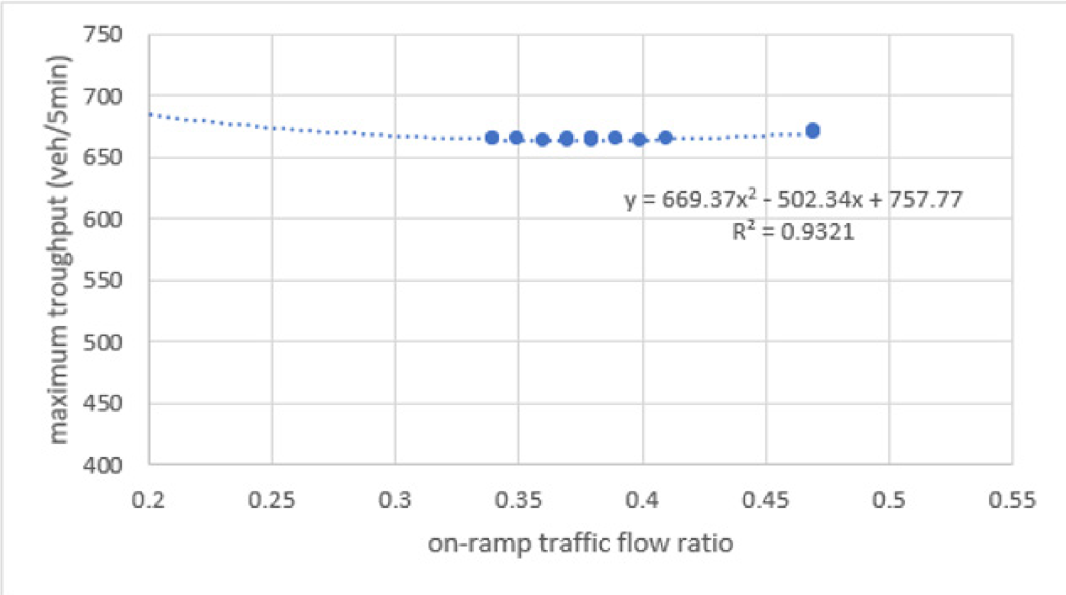

Figure 1b: Relationship between On-Ramp Ratio and Discharge Rate: (b) Study Site #2, Hakim EW at Haghani.

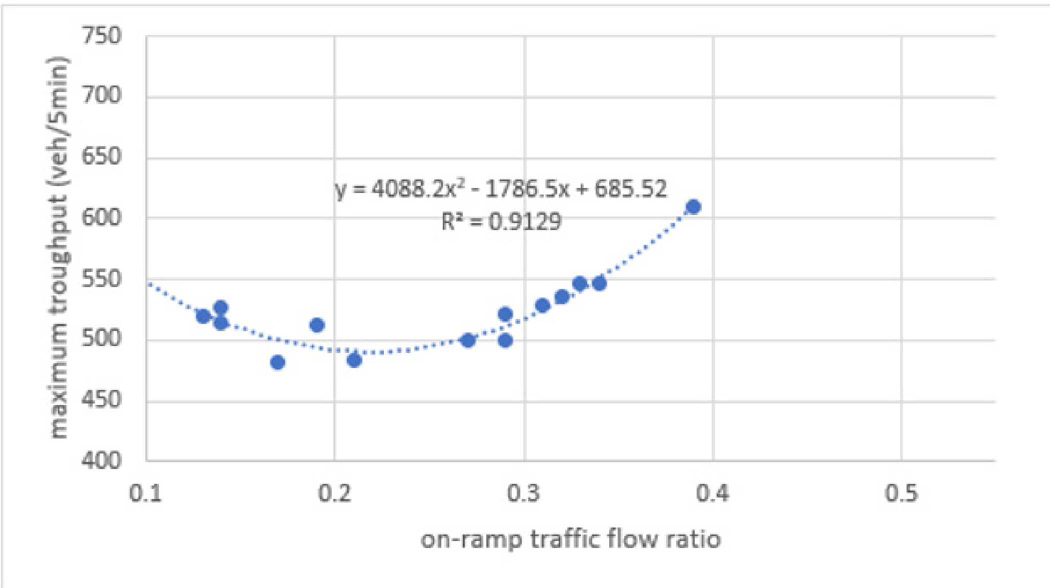

Figure 1c: Relationship between On-Ramp Ratio and Discharge Rate: (c) Study Site #3, Hakim EW at Payambar.

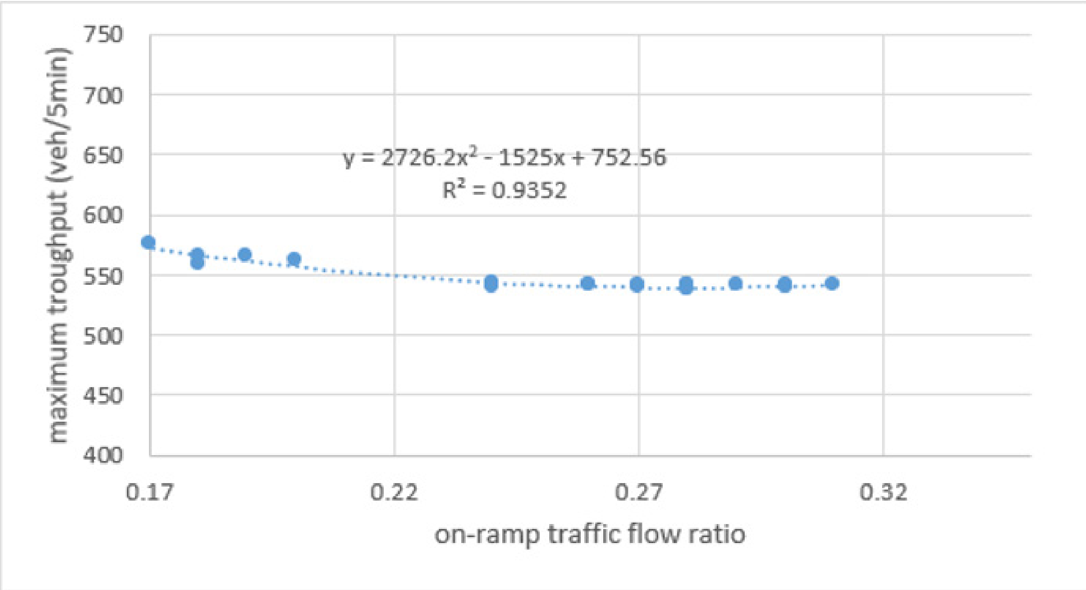

Figure 1d: Relationship between On-Ramp Ratio and Discharge Rate: (d) Study Site #4, Hakim EW at Tavanir.

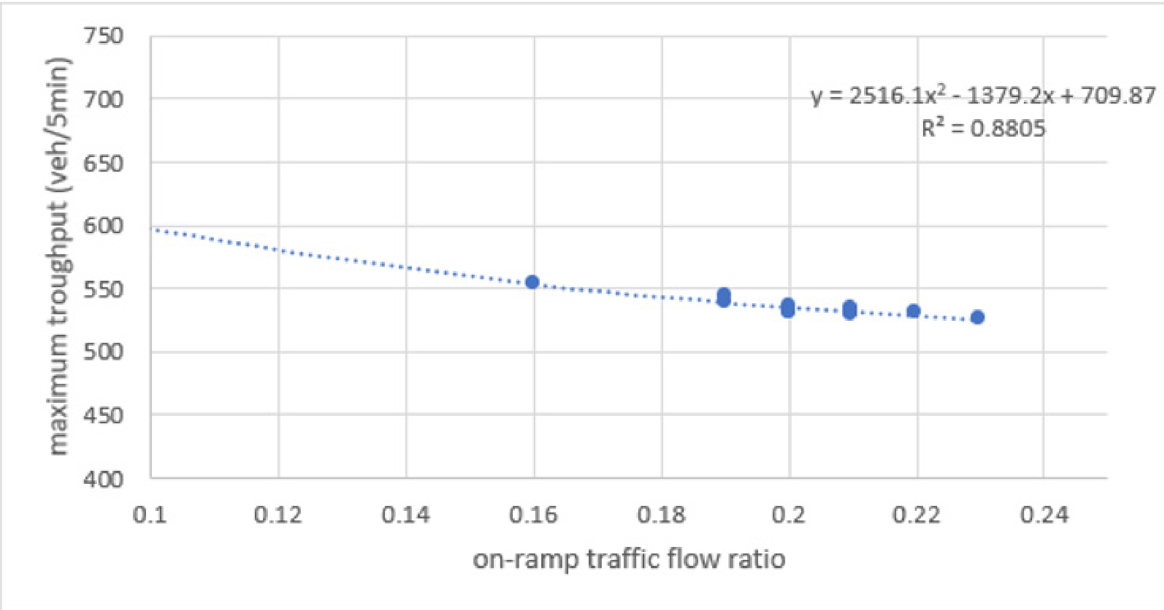

Figure 1e: Relationship between On-Ramp Ratio and Discharge Rate: (e) Study Site #5, Hemmat WE at Shariati.

The maximum throughput dropped to the local minimum value at a specific on-ramp ratio and then began to increase at each research location once it passed the local minimum on-ramp ratio. This is explained in the way that follows. The fight for space between mainline and on-ramp cars is so fierce at the local minimum on-ramp ratio that it causes an increase in the time headway of mixed traffic. When the on-ramp ratio is less than or larger than the local minimum value and the time headway in combined traffic is reduced, mainline/on-ramp traffic prevails in the merging conflict. To determine how the on-ramp ratio affected maximum throughput, a convex quadratic polynomial function was fitted to the empirical data. The convex quadratic polynomial function could account for 95% of the variation in the maximum throughput with respect to the on-ramp ratio for each research site where the correlation coefficient (r) was more than 0.95. On the right side of Figure 1, the regression functions for every research site are shown.

The second-order derivative, $f''(\varphi)$, can be used to calculate the elasticity of the maximum throughput, a sensitivity indicator for the on-ramp ratio (Table 2).

Table 2: Empirical Analysis Results for Relation between On-Ramp Ratio and Maximum Throughput.

Study site id	Range of on-ramp ratio from Eqs.(4) and (5)		Range of on-ramp ratio from empirical observation		Number of lanes		Acceleration lane length (m)	Throughput elasticity depending on on-ramp ratio ($f''(\phi)$)	Local minimum on-ramp ratio
	from	to	from	to	Mainline	Ramp			
1	0.08	0.61	0.26	0.51	3	2	101	2466	0.32
2	0.002	0.52	0.34	0.47	4	2	66	1339	0.36
3	0.13	0.57	0.14	0.39	3	2	64	8176	0.21
4	0.09	0.31	0.17	0.3	3	1	68	5452	0.46
5	0.11	0.31	0.16	0.23	3	1	217	5032	0.23

The comparison results point to potential influences from geometric highway design elements, such as the number of bus priority lanes, on-ramp lanes, and mainline lanes. The study locations with the highest and lowest elasticity were #3 and #2, respectively. The maximum throughput's elasticity decreased as the number of lanes increased. These geometric roadway design-dependent maximum throughput elasticity findings closely resemble other findings from current studies. Lane length and free-flow speed don't really affect acceleration, according to new studies [25]. There was a negative correlation between the number of lanes and the frequency of breakdowns and a positive correlation with ramp flow speed.

Statistical Validation

Residual Analysis

Table 3: Statistical Results.

	Kolmogorov-Smirnov			Shapiro-Wilk			Durbin- Watson		df	Sum of squares	Mean square	F	Sig.
Study site	Statistic	df	P-value	Statistic	df	P-value							
1	0.238	20	0.192	0.976	20	0.702	1.824	Regression	1	2239.113	2239.113	30.316	0.000031
								Residual	18	213.837	11.879		
								Total	19	2452.95			
2	0.226	14	0.2	0.912	14	0.452	1.754	Regression	1	57.002	57.002	22.629	0.000467
								Residual	12	4.194	0.350		
								Total	13	61.214			
3	0.155	14	0.2	0.889	14	0.078	1.954	Regression	1	12919.231	12919.231	71.485	0.00008
								Residual	12	407.698	33.975		
								Total	13	13326.929			
4	0.108	22	0.2	0.961	22	0.502	2.04	Regression	1	2614.956	2614.956	39.344	0.00002
								Residual	20	87.044	4.350		
								Total	21	2702.000			
5	0.198	13	0.175	0.891	13	0.1	1.993	Regression	1	595.078	595.078	66.928	0.000005
								Residual	11	51.230	4.657		
								Total	12	646.308			

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Using observable data, the ordinary least squares method is often used to develop regression models. However, as can be seen in (Figures 2(a), 2(c), 2(e), 2(g), and 2(h)), the residual scatter plots of the linear-regression model for the study locations indicated nonlinearity (i). The residual scatter plot of the quadratic polynomial models, which stayed within 2, showed homoscedasticity for each study site (Figures 2(b), 2(d), 2(f), 2(h), and 2(j)). As a result, the quadratic polynomial model, with homoscedastic residuals, accurately matched the data. The Shapiro-Wilk and Kolmogorov-Smirnov tests were used to determine the normality of the residuals (Table 3). The Kolmogorov-Smirnov statistic computes the difference between the sample's empirical distribution function and the normal distribution's cumulative distribution function in order to assess the normality assumption.

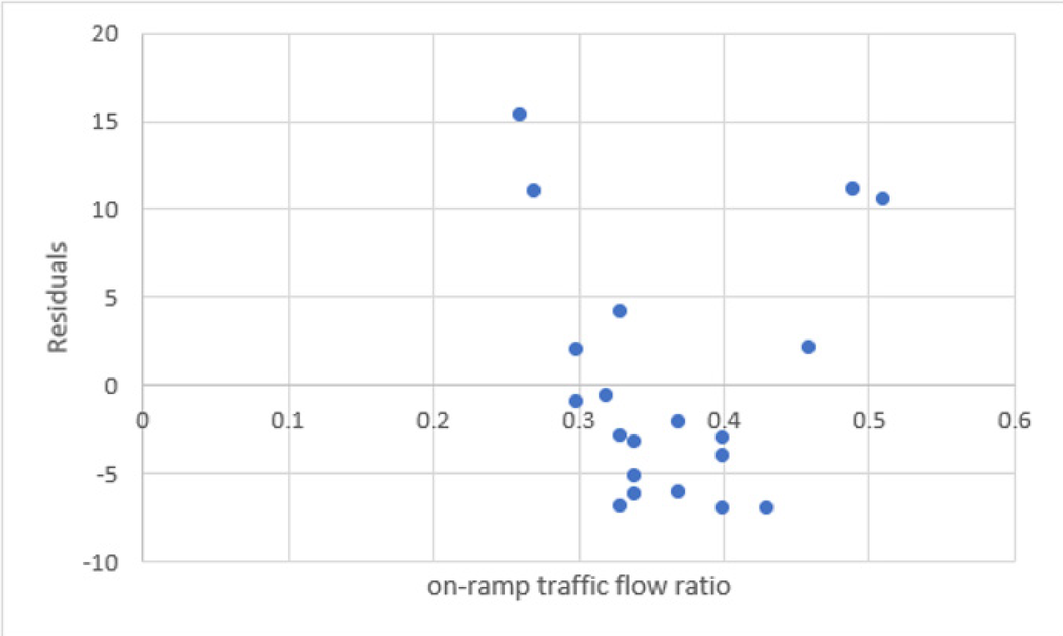

Figure 2a: Residual Scatter Plots: (a) Study Site #1 (Linear Regression Model).

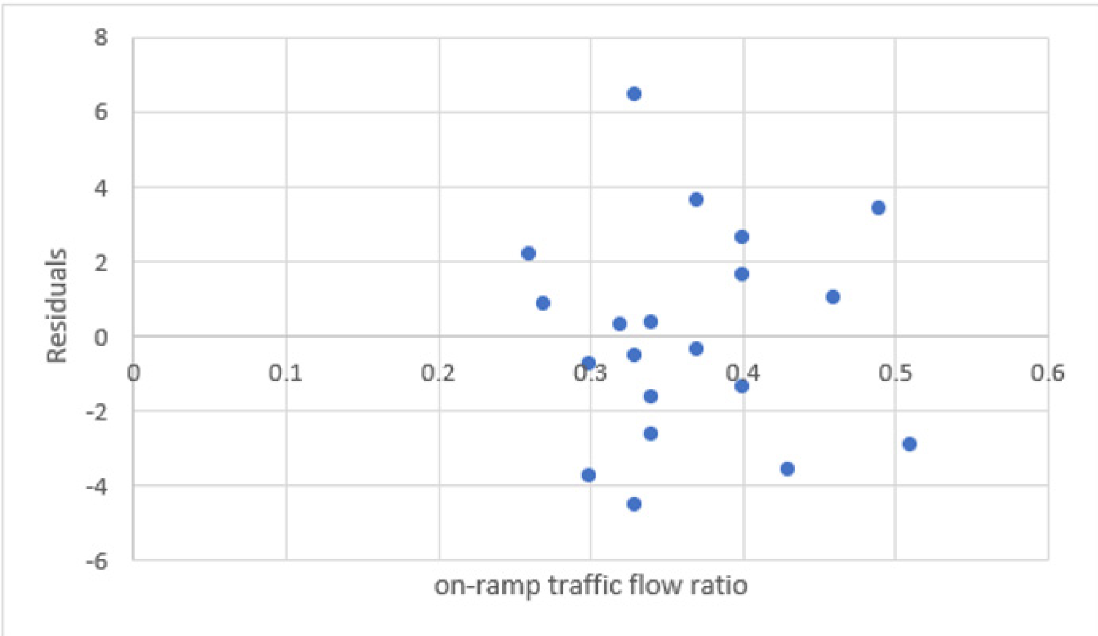

Figure 2b: Residual Scatter Plots: (b) Study Site #1 (Quadratic Polynomial Model).

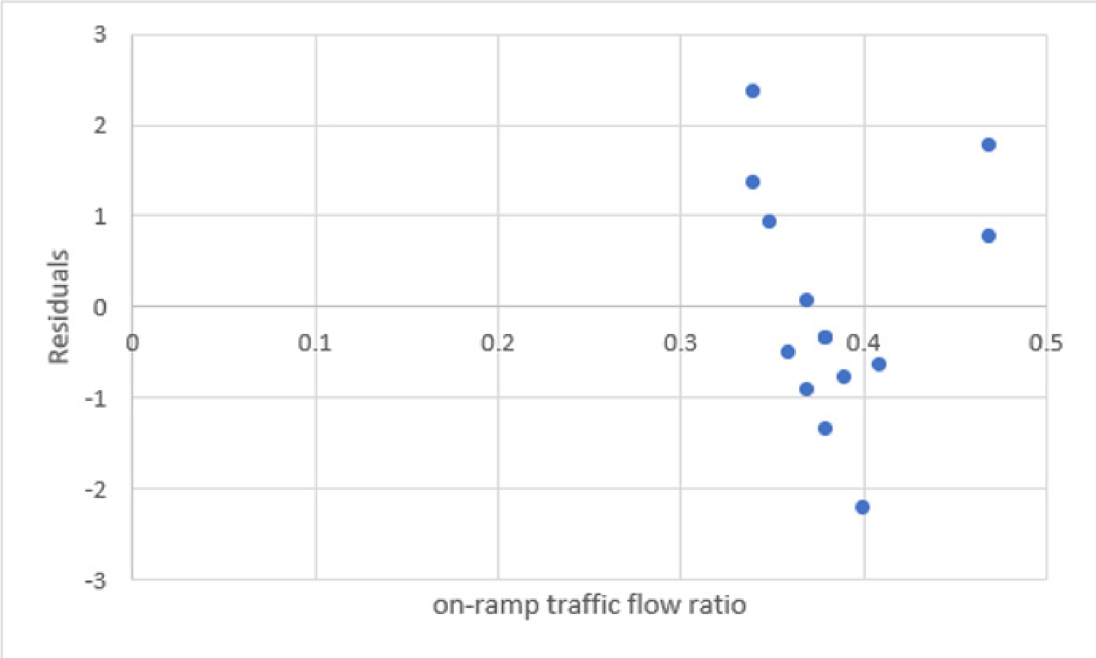

Figure 2c: Residual Scatter Plots: (c) Study Site #2 (Linear Regression Model).

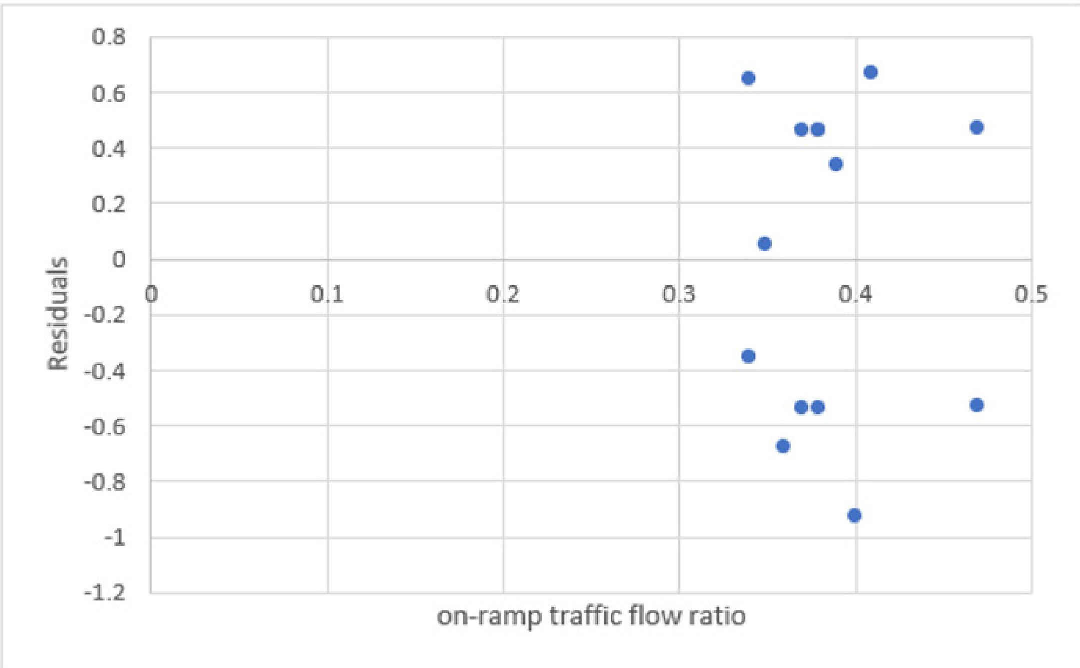

Figure 2d: Residual Scatter Plots: (d) Study Site #2 (Quadratic Polynomial Model).

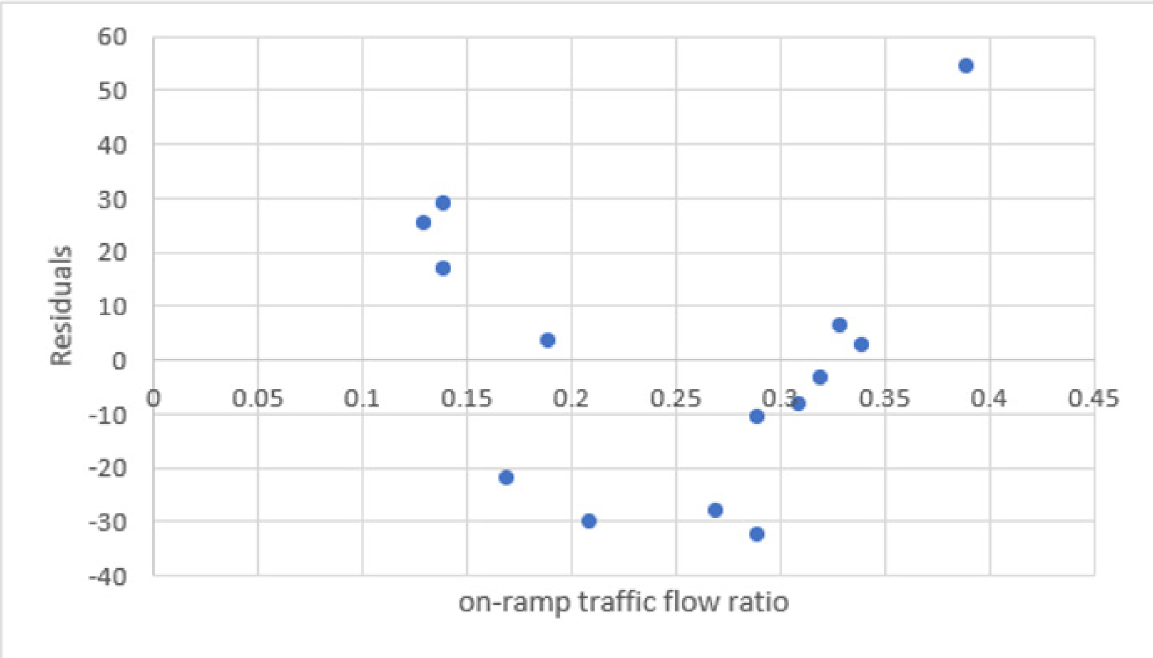

Figure 2e: Residual Scatter Plots: (c) Study Site #3 (Linear Regression Model).

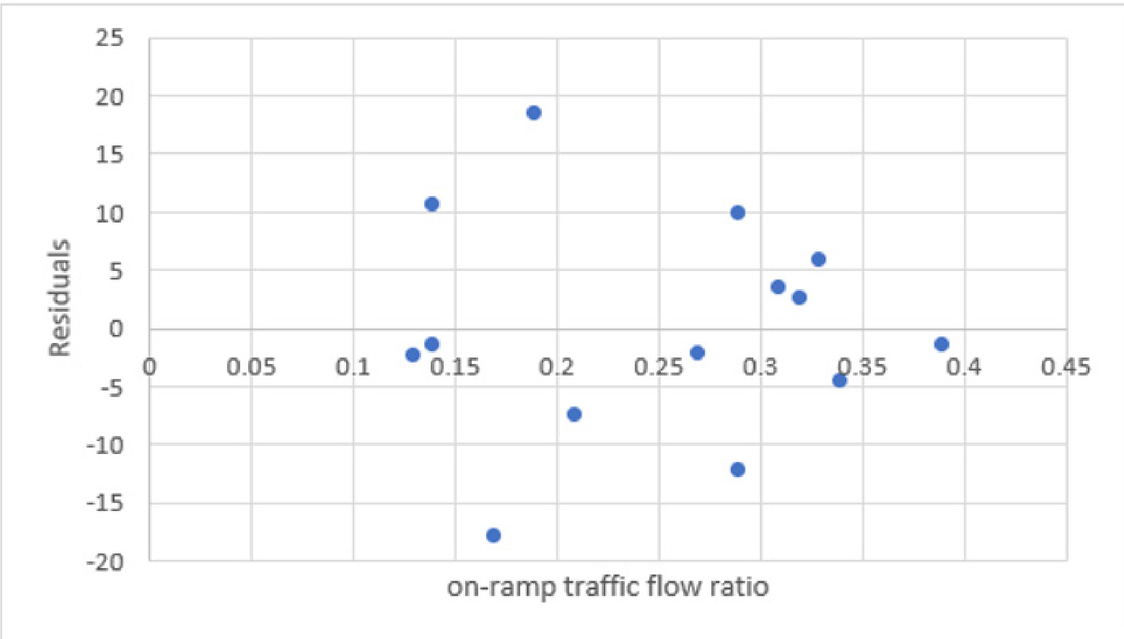

Figure 2f: Residual Scatter Plots: (f) Study Site #3 (Quadratic Polynomial Model).

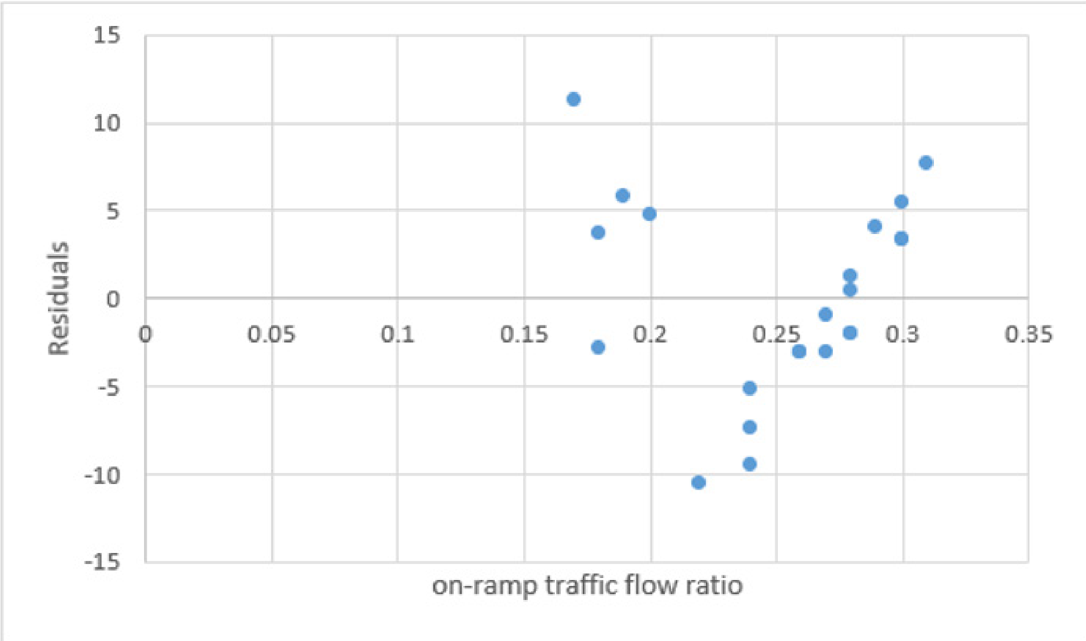

Figure 2g: Residual Scatter Plots: (g) Study Site #4 (Linear Regression Model).

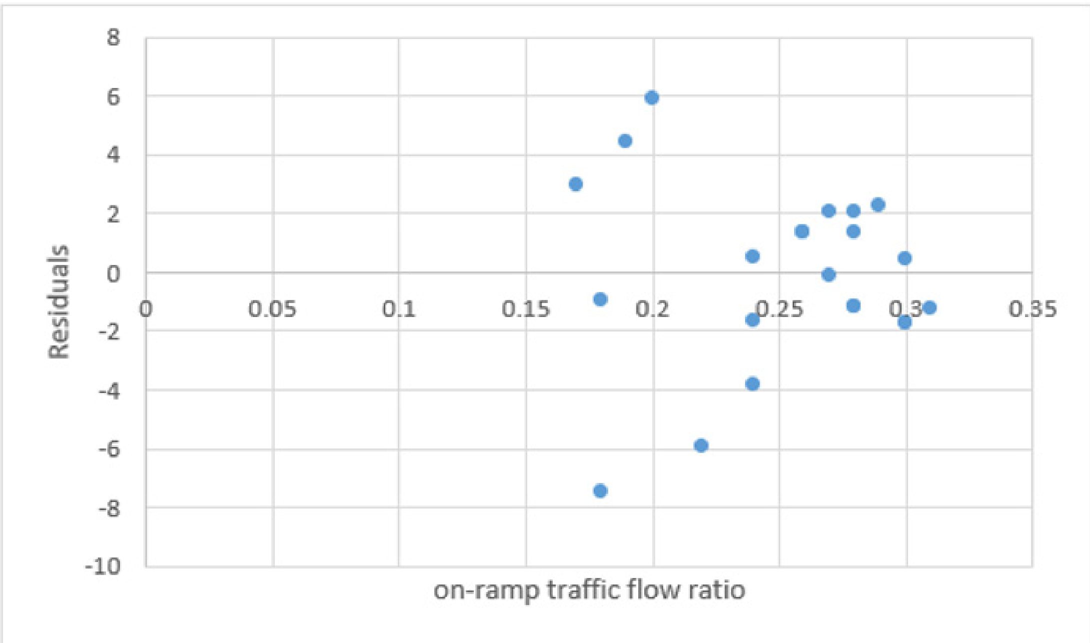

Figure 2h: Residual Scatter Plots: (h) Study Site #4 (Quadratic Polynomial Model).

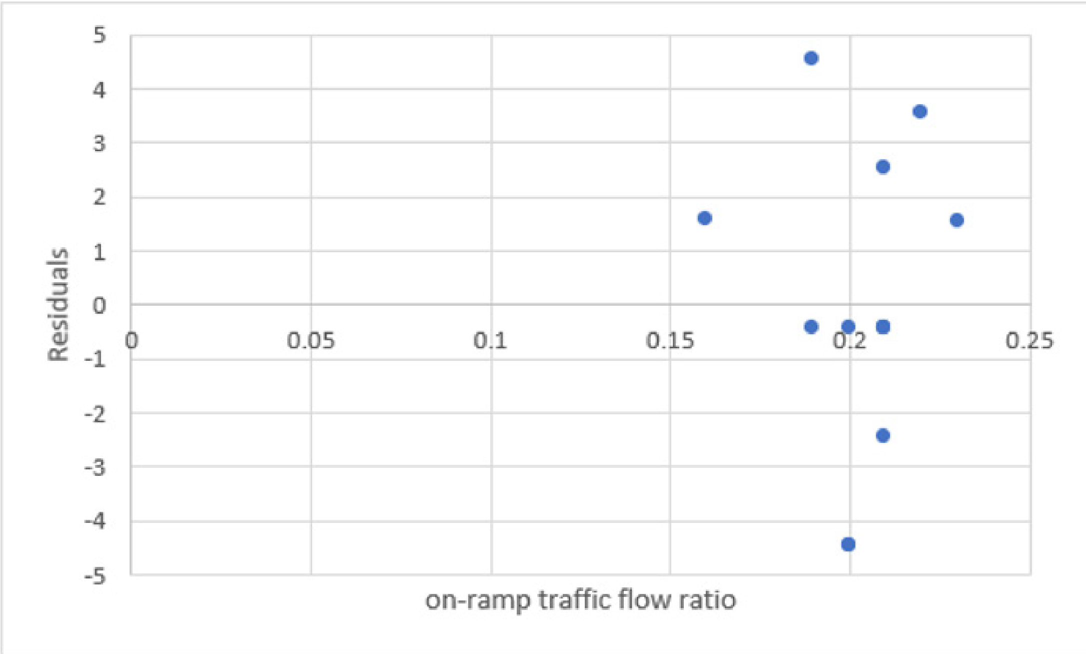

Figure 2i: Residual Scatter Plots: (i) Study Site #5 (Linear Regression Model).

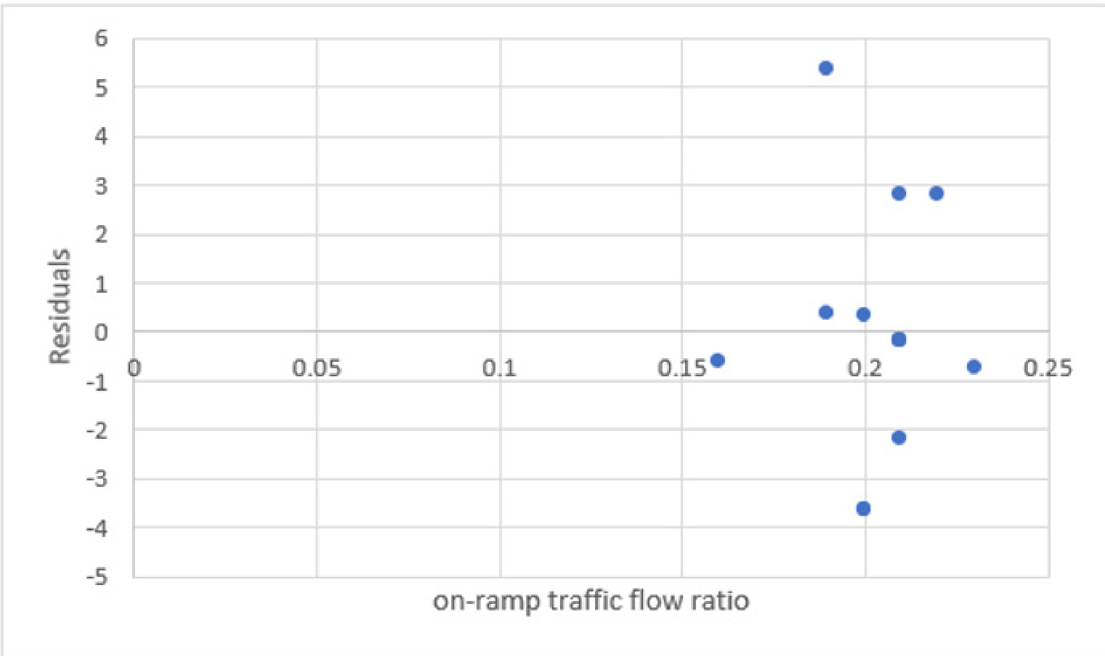

Figure 2j: Residual Scatter Plots: (j) Study Site #5 (Quadratic Polynomial Model).

The null hypothesis, which asserts that a sample is drawn from a regularly distributed population, is examined with the Shapiro-Wilk test. The Shapiro-Wilk and Kolmogorov-Smirnov p-values are shown in Table 3, both of which were greater than 0.05. As a result, the null hypothesis-which asserts that the residuals had a normal distribution might be accepted. The autocorrelation of the residuals was also investigated using the Durbin-Watson test. Autocorrelation occurs only when the Durbin-Watson number is two; otherwise, it remains fixed between 0 and 4. (Table 3) shows that for all of the instances presented, there was no autocorrelation in the residuals, with Durbin-Watson values ranging from 1.75 to 2.04.

Goodness of fit

The quality of fit is evaluated using the coefficient of determination and the F-test. The null hypothesis is rejected if the F-value for a certain significance level is higher than the crucial F-distribution value. Two scaled sums of squares (mean square due to regression and mean squared error) are compared using the F-test. The F-test findings in (Table 3) show the degree to which each regression model fit the data. The coefficient of determination is the proportion of total variance (SST) that the regression explains (SSR). We can infer that the suggested regression model explains between 91% and 97% of the variation of the observation points, based on the coefficient of determination of 0.9128-0.9677.

Conclusion

The relationship between the maximum throughput and the ramp's traffic flow was investigated using empirical data. Studies show that the maximum throughput of the merging bottleneck and the on-ramp traffic flow ratio have a convex quadratic-polynomial connection. An empirical investigation's finding of a connection was verified by residual analysis. Due to competition between on-ramp and mainline traffic, maximum throughput tended to drop to the local minimum value, which is equivalent to the critical on-ramp ratio. When the on-ramp ratio exceeded the crucial on-ramp ratio, it then went up. When the highway had a bus priority center lane, a single-lane on-ramp, and few mainline lanes, the maximum throughput to on-ramp ratio flexibility was high. The elasticity of the maximum throughput is unaffected by the length of the acceleration lane or the make-up of the vehicles. The on-ramp traffic flow's overall effect is comparable to earlier studies' findings [10, 11, 25]. A convex quadratic-polynomial relationship between the on-ramp ratio and maximum throughput is the primary contribution of the research. On-ramp traffic has different consequences depending on the highway design and the merging region's operating efficiency [10,11].

Finally, the results show that a higher maximum throughput at highway bottlenecks can be achieved by varying the on-ramp ratio. It is explained by the convex quadratic-polynomial relationship that the on-ramp ratio affects the capacity drop's magnitude. This discovery may aid in the development of more effective ramp metering systems. The local minimum on-ramp ratio can be computed and set as a ramp metering control parameter using the merging area's test operation. Further empirical analyses of the data set with other geometric configurations, however, will have to wait for another study. It's also a good idea to create a mathematical model that clarifies the relationships between the on-ramp ratio and maximum throughput.

Acknowledgement

None.

Conflict of Interest

None.

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