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INVESTIGATION OF THE RELATIONSHIP BETWEEN UPSTREAM AND ON-RAMP FLOWS AT DOWNSTREAM CAPACITY LEVEL ON ISTANBUL FREEWAY MERGES

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Abstract

Traffic congestion usually occurs at freeway merges due to the inequality of lane numbers at upstream and downstream. The freeway entry, defined as on-ramp, is the main cause of this irregularity and in order to clarify its effect, three freeway merges are investigated in this study with macroscopic flow parameters where a variety of geometric properties are present. In each merge, when the capacity flow is achieved at downstream, the on-ramp and upstream flows are determined and the relationship between upstream flow rate and 'on-ramp ratio', which is calculated by dividing the on ramp flow rate to the sum of on-ramp and upstream flow rates, is investigated. An inverse relationship is determined between total upstream flows (upstream flow plus on-ramp flow) with respect to on-ramp ratio. As a result, the merge with one lane drop and three-lanes at downstream seems to be least influenced type while the merge with two lanes drop and four lanes at downstream is the highest. For the former, 1% increase in on-ramp ratio causes a reduction of 20 pcu/h/lane on sum of total upstream flows while for the latter 26 pcu/h/lane. It is seen that the term on ramp ratio, can be quite useful variable for establishing capacities of freeway merges with the help of upstream and on-ramp traffic demands.

Keywords: Freeway merge, on-ramp flow, upstream flow, downstream capacity

İSTANBUL OTOYOL KATILIMLARINDA AKIM AŞAĞI KAPASİTE SEVİYESİNDE AKIM YUKARI VE KATILIM AKIMLARI ARASINDAKİ İLİŞKİNİN İNCELENMESİ

Özet

Otoyollarda yaşanan trafik sıkışıklıkları genellikle katılım bölgelerinde akım yukarı ve akım aşağı yöndeki şerit sayılarının eşitsizliğinden kaynaklanmaktadır. Bu çalışmada, şerit sayıları açısından değişiklik gösteren üç farklı katılım bölgesinde tıkanıklığa neden olan akım değerleri makroskopik akım değişkenleri kullanılarak incelenmiştir. Her katılımda, akım aşağı yön kapasiteye ulaştığında, anayol üzerindeki akım aşağı ve akım yukarı yöndeki hacimler ile katılım hacimleri belirlenmiştir. Bu an için belirlenen katılım hacmi, katılan hacmi ve akım yukarı yöndeki hacmin toplamına bölünerek "katılım oranı" terimi hesaplanmıştır. Toplam akım yukarı hacim (akım yukarı hacim ve katılım hacmi toplamı) ile katılım oranı arasında ters orantılı bir etkileşim bulunmuştur. Sonuç olarak, bu etkileşimin akım aşağı yönde üç şeridi bulunan ve bir şerit azalmasının görüldüğü otoyol katılım bölgesi birleşiminde en az olduğu, akım aşağı yönde dört şeridi bulunan ve iki şerit azalan otoyol katılım bölgesinde ise en fazla olduğu belirlenmiştir. Katılım oranında %1'lik artış, sözü edilen ilk katılım bölgesinde toplam akım yukarı hacmini 20 bo/sa/şrt azaltırken, ikinci katılım bölgesinde 26 bo/sa/şrt azalmaya neden olmaktadır. Katılım oranı teriminin, otoyol katılım bölgelerinde kapasitelerinin belirlenmesinde ve kapasite akımını oluşturan katılım hacmi ile akım yukarı hacminin ilişkilendirilmesinde yararlı bir araç olabileceği görülmektedir.

Anahtar Kelimeler: Otoyol katılımı, katılım akımı, akım yukarı hacim, akım aşağı kapasite

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1. Introduction

Freeway entrance and exits locations are the main regions of congestion due to the presence of relatively short distances for weaving or merging movements, and inequality of lane numbers. Associated with the bottleneck capacity at these sections, unsurprisingly congestion occurs. When the upstream or/and on-ramp demand reach to a critical value, speeds reduce on both flows that causes frequently queue formation.

The on-ramp flow (Q_{on}) has a crucial effect on both upstream (Q_{up}) and downstream flows. Accordingly, the scope of this paper is to analyze the relationship between Q_{up} and Q_{on} that cause congestion at urban freeway merges (FMs) with macroscopic flow parameters. As there is no ramp-metering application at Istanbul FMs, Q_{on} has an excessive effect on congestion. The interaction of merging flows with the mainline could substantially affect the downstream flow, in other words capacity of freeway section. In order to correlate the Q_{up} and Q_{on} at a FM, the term called "on-ramp ratio" (ORR) is defined, which is equal to Q_{on} over Q_{up}+Q_{on}. The variation and relationship of Q_{on} and Q_{up} are investigated associated with ORR when the capacity flow is observed at downstream.

The paper starts with the overview about the existing literature related to FMs, including different approaches of modeling. Afterwards, the study area and data collection procedure are explained. The data analysis technique is stated in detail and model development for each merge is clarified by geometric differences. Finally, change of Q_{up}+Q_{on} has been modelled with respect to ORR by aggregating three FM data.

2. Literature Review

In the literature, researchers aimed to correlate the upstream and on-ramp flows on a merge section by using several features of a freeway geometry or traffic flow characteristics in order to create a freeway merge model at macroscopic level. The interaction between upstream and on-ramp flows inevitably could end up with the congestion, and cause to decrease downstream capacity. From this perspective, the ratio between upstream and on-ramp flows is used in several studies; however, it is named and defined differently [1], such as the demand ratio (proportion of both link demands) [2], the capacity ratio (ratio between both upstream link capacities) [3, 4], the ramp-to-freeway demand ratio (ratio of ramp demand to freeway demand) [5], and the lane ratio (ratio between both link number of lanes) [6].

Several studies on FM bottlenecks are performed from the macroscopic perspective in the literature. Analyses rely on the relationship between upstream flows and the decrease on discharge flow that is observed at downstream. One of the simplest model proposed for merging behavior is the Cell Transmission Model (CTM), which offers a macroscopic simulation based on traffic flow model to propagate the traffic along the homogenously divided road sections [7]. Other studies are conducted for the ramp-metering control strategies [8] and the analytical prediction of capacity drop concerning on-ramp demand [9]. Offered methodology with this study allows to observe traffic flow more efficiently and easy to use for specially traffic management applications.

Researchers investigated the effect of number of lanes as to capacity drops on merge sections from a macroscopic perspective, and indicated that the capacity drop is negatively related to the number of lanes on urban highways. For a five-lane highway, the capacity drop was determined as 8.85%, while it was 16.33% for two-lane. In addition, decrease in the capacity drop was observed with the increase in off-ramp flow [10]. Level of capacity drop is related between the ratio of upstream and on-ramp flows; however, the ramp-metering strategies did not affect capacity drop level on FMs [11].

The investigation of the queue formation at an active merge bottleneck proved that the ramp-metering favorably affected the capacity drop mechanism. It was concluded that the capacity drop encountered just before occupancies increased to 27%, and the capacity of a merge was not constant, because it can be effected by queues that were formed at upstream of a merge [12]. Analyzing the capacity drop is out of scope of existing study, however to find critical ORR which creates capacity flow at bottleneck is crucial in order to develop well working management strategies. From this perspective, it would be possible to estimate pre-breakdown traffic flows with the findings of this study even in real time. This will bring more flexibility for especially real time traffic management applications.

The kinematic wave models were similarly used for FM bottlenecks in order to identify the congestion, traffic management strategies and route guidance for drivers [3, 13]. It was indicated that the decrease in traffic volume observed at the same time with the speed drop and occupancy increase [13]. It was similarly found that higher flows prior to the queue formation were sustained for relatively short periods. It is mentioned that during a congestion period, merges have more spread along acceleration lanes and vehicles were able to merge at the end of an acceleration lane by accepting the smallest gaps between 0.75 and 1.00 sec in congested conditions [14]. Merge bottleneck capacities have been analyzed by using the ratio of ramp flow to freeway flow and it is indicated that even freeway demand remains constant, the increase of ramp flow causes a reduction in merge capacity [5]. However, as the analyses are realized only for one lane dropped freeway merge bottlenecks, the possible effects of geometric differences cannot be investigated.

Another aspect of analyzing FMs is to estimate the probability of breakdown. It is concluded that speed drop is a superior indicator for estimation of breakdown compared to occupancy or volume-occupancy relationship on FMs [15]. Asgharzadeh and Kondyli [16] analyzed breakdown probability flow rates with considering number of lanes, ramp flow rate, presence of lane drops and ramp-metering. They concluded that number of lanes exposed inverse relationship with the average pre-breakdown flow rate per lane. Higher on-ramp demands resulted in higher breakdown probability and lower capacities which is consistent with the findings of existing study. Since the breakdown probability is crucial on FMs, this topic is out of scope for the perspective of this study. However, findings will be lead to improve probability studies and increase performance of traffic management strategies.

Amongst the studies encountered in the literature, this study proposes a new method to correlate the Q_{up} and Q_{on} when the downstream flow reaches to its capacity. Additionally, effects of on-ramp flows are analyzed in relation with the geometric properties of each FM, since the number of lanes at downstream or upstream shows variation in each site.

3. Study Area

Istanbul is a mega city with more than 15 million habitants that extends nearly 150 km east-west direction with a substantial highway network. Trans European Motorway (TEM) is the main part of Istanbul's urban freeway on which Fatih Sultan Mehmet Bridge provides Bosporus crossing with four lanes in each direction. The highway network of Istanbul with the studied FMs are given in Fig. 1. The FMs used in this study are selected along the TEM by taking into account the heavy traffic congestion and presence of upstream, on-ramp and downstream traffic data, that are being gathered by remote traffic microwave sensors (RTMS).

Figure 1. Freeway merge locations and highway network of Istanbul.

On each investigated FM, TEM has 120 km/h speed limit, 3.75 m lane and 1.5 m shoulder width. One of the three FMs is located at European Side while other two are at Asian Side of Istanbul. All studied FMs are located near residential and commercial districts with substantial traffic demand, and suffer congestion problems every weekday. Geometric details of each FM are given in Fig. 2 including lane numbers at both upstream and downstream.

On FM1 as in Fig. 2(a) an unusual geometric detail is distinguished such as the lack of an acceleration lane (tapered shape on-ramp) for on-ramp flow and existence of two bottlenecks. The upstream flow drops from three lanes to two lanes along a short distance just before the on-ramp. Additionally, on the on-ramp, the number of lanes drops to one from two along merging area. The analysis of the speed data shows that the speed drop initially occurs at the downstream RTMS (#410) compared with upstream RTMS (#409). This speed drop order shows that the upstream demand is not high enough to generate a bottleneck effect even though the number of lanes drops from three to two; consequently, the upstream flow considered as two lanes, because merging flow is compromise of two lanes [16]. As the total number of merging lanes at upstream and on-ramp flows are four and at the downstream three, this lane combination leads to define the FM1 as one lane drop merge.

On FM2, given in Fig. 2(b), 350 m parallel acceleration lane makes possible to join two on-ramp lanes with four upstream lanes. The upstream and on-ramp consist of six lanes as well as the downstream has four lanes, hence, this merge generates a two-lane drop.

On FM3, given in Fig. 2(c), 330 m tapered acceleration lane exists. Two-lane on-ramp joins with three-lane upstream, and continues as four-lanes at downstream, which causes a one-lane drop case.

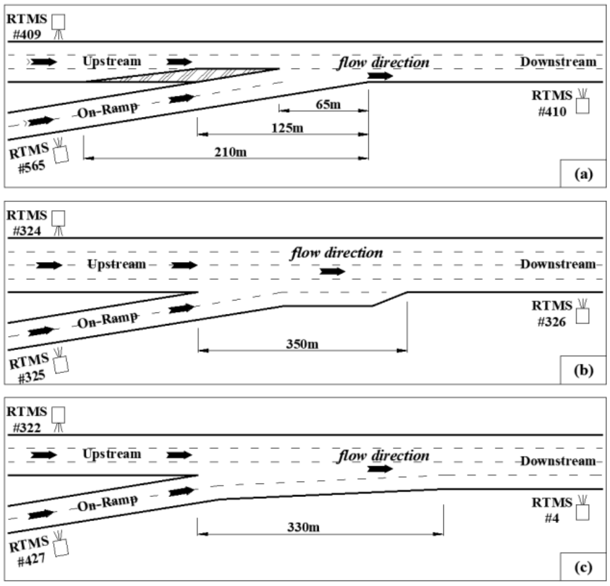

Figure 2. Geometric details of (a) FM1, (b) FM2 and (c) FM3

As described, all three FMs have geometrical difference. Although FM1 and FM3 are one-lane drop merge, the number of lanes at downstream shows a variation. This difference allows us to analyze its effect on merging movements which is not covered in the literature.

4. Data and Methodology

The traffic data of this study consists of 2-min volume, speed, and heavy vehicle ratio per lane automatically collected by RTMSs. In this study, the data used for the analyses of three FMs are gathered by nine RTMS located on upstream, on-ramp and downstream of each FM for the years 2011, 2012 and 2013. In addition, the speed data of three RTMS, which are located at further downstream direction of each FM, are used to determine the presence of queue spillback phenomena. All RTMS data are obtained by Istanbul Metropolitan Municipality, Traffic Control Center.

On Istanbul urban freeways, the passage of heavy vehicles, except busses, is restricted during peak hours (06:30-10:30 and 16:00-22:00) in order to reduce the traffic demand. The average of heavy vehicle (minibus, RV, bus) ratio is calculated as 5.80% for peak hours on the investigated FMs. In the analyses, heavy vehicles are converted to passenger car unit (PCU) with 1.23, 1.76, and 1.22 coefficients by taking into account the longitudinal gradient for FM1 (1.36%), FM2 (2.71%) and FM3 (1.34%), respectively, with the guidance of Highway Capacity Manual [17] approach.

The data analysis is realized with only weekday data, because of the lack of congestion during weekends. Moreover, in order to exclude possible effects of adverse weather conditions, weather data (rain, snow and fog) are obtained from State Meteorology Institute and only sunny days (the days when the pavement is dry and visibility is more than 10 km) are considered.

The congestions caused by traffic accidents are not included in the data set. The differentiation between regular congestion and traffic accident congestion is made by investigating the nature and time of speed drop on the speed time series. Besides, traffic accident database, provided by Traffic Control Center of Istanbul, is similarly considered. During a traffic accident, speed drops suddenly to a quite low (0-5 km/h) values. Additionally, a traffic accident congestion occurs usually during off-peak periods. Finally, the congestions caused by queue spillback from downstream merges are eliminated from the data set. These congestions are determined by investigating initial speed drop times of further downstream RTMS (#146, 327, 323) and compared them with merge downstream RTMS (#410, 326, 4). If the speed dropped at further downstream RTMS before the downstream merge RTMS, this case is defined as the indicator of queue spillback.

The capacity flow at downstream, formed by the upstream and on-ramp flows are distinguished by speed time series and re-scaled cumulative flow curves as previously mentioned in quite a few studies [18-21]. Core point of the analysis is to determine formation of capacity flow at downstream by on-ramp and upstream flows of a merge. In the speed time series graph, speed drops are evaluated as the potential indicator of capacity conditions. However, the speed drops that last less than 15 minutes are not considered as a speed drop as suggested by other studies [22]. In the speed time series, once a speed drop is distinguished (for speed drops that last longer than 15 minutes), then exact time of capacity flow is identified with the help of re-scaled cumulative flow rate diagram drawn for downstream of the merge. During the speed decrease, the traffic state changes from free flow to congested flow. By this approach, slope changing point on the re-scaled cumulative flow curve during the speed drop period, the moment when the slope of the curve changes, is determined as the moment that the capacity is observed. The identification of a capacity flow is given in Fig. 3 as an explanation. The critical point is to determine that capacity at downstream constitute by upstream and on-ramp flows. Considering the procedure, after this moment traffic state will no longer be at free flow conditions. This moment always indicates the capacity speed (which is 70-80 km/h for analyzed sections) similarly.

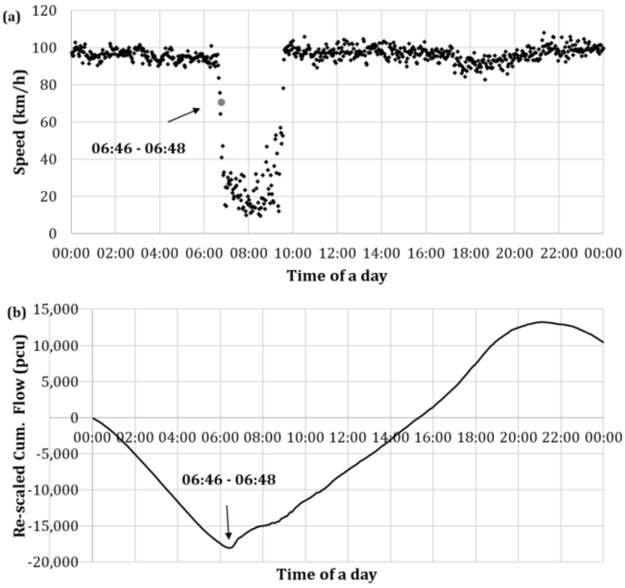

Figure 3. Downstream (a) speed variations and (b) re-scaled cumulative flow diagram for FM3 on February 20, 2012.

Fig. 3(a) shows a specific time series of speed variation character for FM3 on February 20, 2012 Monday. Single speed drop is observed during the morning peak hour and the congestion lasted nearly three hours. As each point represents 2-min observation, it can be concluded that the speed drop period for this day was around 12 minutes (06:42-06:54, six data points between congested and uncongested flow conditions). The maximum flow rate (capacity) during speed drop period is clarified with re-scaled cumulative flow curve. Certainly, it is determined that the maximum flow rate (2,310 pcu/h/lane) is observed when the speed is 70.5 km/h at time interval 06:46-06:48. This means that the capacity of this merge section is observed when speed is 70.5 km/h as 2,310 pcu/h/lane at downstream of a merge by using the data of RTMS #4. In Fig 3(b), the negative gradient in the re-scaled cumulative flow curve indicates that the number of vehicles passing from this section is less than selected reference volume. As a result, slope changing point clarifies crucial information about the traffic flow. At this point (06:46-06:48 in Fig. 3 (b)), number of passing vehicles increased and reached at a certain value, which is greater than before. The investigation of speed time series shows that the frequency and pattern of speed drop and capacity vary day by day. In some days, the speed drop is realized once a day (generally during morning peak), in other days more than once.

Finally, by this data identification procedure, 303, 424 and 322 capacity observations have been determined for downstream of FM1 (RTMS #410), FM2 (RTMS #326), and FM3 (RTMS #4), respectively. In all these capacity flows, it is found that the optimum speed (capacity speed) changes from 70 to 80 km/h.

The capacity determination from 2-min observations may lead to overestimate of capacity; however, it has sufficient and powerful explanatory influence for the analysis. Besides, the value of reference volume has no effect on offered procedure. It is basically magnifying the change of traffic demand. Then it could be determined according to best representative to show maximum flow during speed decrease.

5. Data Analysis and Findings

As the aim of this study is to investigate the relationship between Q_{on} and Q_{up} when downstream reaches to its capacity, initially, the ORR is defined as the proportion of Q_{on} over $Q_{up}+Q_{on}$ as given in Equation (1).

$$ORR = \frac{Q_{on}}{Q_{up} + Q_{on}} \quad (1)$$

Actually, ORR indicates the percentage of on-ramp traffic flow within the total (on-ramp and upstream) flow. The change of ORR is analyzed with respect to $Q_{up}+Q_{on}$ on each FM, possible change of increase and decrease of ORR have been investigated. By this way it could be possible to investigate the effect of on-ramp flow to downstream capacity on a FM. The increase of ORR means either an increase at on-ramp flow or a reduction at upstream flow and both cases ends up with the reduction of downstream capacity.

In order to take into consideration, the travel time from upstream and on-ramp to downstream, one-time interval (2-min) lag is considered (as the data are gathered with 2-min period, shorter time lag cannot be used). When the capacity at downstream is archived (06:46-06:48 in Fig. 3), the flows passed 2-min before (06:44-06:46) at upstream and on-ramp are used to calculate ORR. Consequently, when the capacity for downstream is determined at the time interval 'i', the upstream and on-ramp data are picked up at the time interval 'i-1'. In other words, it is possible to express that flows passing at time 'i-1' at upstream and on-ramp generate a capacity flow at downstream at time 'i'.

5.1. FM1: One-Lane Drop Merge

FM1 is formed by two lanes at upstream, two lanes at on-ramp and the three lanes at downstream as given in Fig. 2(a). In order to determine the effect of the on-ramp flow to downstream capacity level, the relationship of $Q_{up}+Q_{on}$ (per lane) with respect to ORR is analyzed as given in Fig. 4. As a reminder, all the data points are determined when the downstream flow reaches to its capacity. In other words, all data points that are seen in Fig. 4. led to downstream capacity of the merge. The inverse proportion between ORR and $Q_{up}+Q_{on}$ that have been revealed from Fig. 4, implies that if the traffic demand increases at the on-ramp of FM, $Q_{up}+Q_{on}$ (total flow) tends to decrease at capacity level of downstream. This means, the decrease of upstream flow is higher than the increase of on-ramp flow when the ORR increases. If the upstream flow decreased as much as the increase of on-ramp flow, the developed regression model would be a horizontal line (with zero slope and quite low coefficient of correlation). Even though on FM1 the total flow ($Q_{up}+Q_{on}$) involves four lanes (two lanes on-ramp and two lanes upstream), data in Fig. 4 are given per lane to increase the comprehensibility.

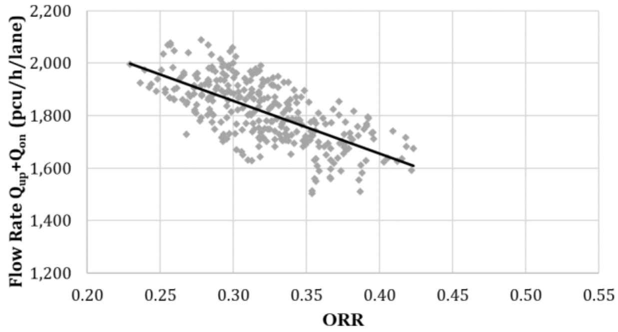

Figure 4. $Q_{up}+Q_{on}$ versus ORR on FM1.

Even though the relationship between two variables is quite spread, the change of ORR and $Q_{up}+Q_{on}$ are found inversely proportional. Total flow ($Q_{up}+Q_{on}$) is decreasing with the increase in ORR. It is obvious that the increase in ORR causes a reduction of the total ($Q_{up}+Q_{on}$) flow. The simple linear regression equation of data points in Fig. 4 appears as in Equation (2).

$$Q_{up} + Q_{on} = 2{,}457.1 - 2{,}003.5 \times ORR \quad (2)$$

The coefficients of determinations (R^2) are calculated as 0.441, 0.448, 0.445, 0.447, and 0.447 for exponential, linear, logarithmic, polynomial (second order) and power form of simple regressions, respectively between $Q_{up}+Q_{on}$ and ORR. The R^2s, which are very close to each other for any form of simple regression model, show the strength of this relationship is moderate (The R^2 is between 0.25 and 0.56). As seen in Table 1, the p-values of regression coefficients are found statistically significant since they are below 0.05.

Table 1. Linear regression statistics for FM1.

	Coefficients	Standard Error	t Stat	P-value
Intercept	2,457.1	41.5	59.2	6.52E-168
ORR	-2,003.5	128.2	-15.6	1.05E-40

The reasons of the quite scattered relationship in Fig. 4 is the illegal usage of shoulder and lack of lane discipline, which are excessively common on merges especially at capacity level at Istanbul. Since RTMSs are dedicated to lane by lane measurements, the lack of lane discipline causes a vehicle counting error. Similarly, as a result of undesired behavior of drivers, RTMSs are unable to measure the flow on shoulder and miscount the vehicles. Besides, the interaction between drivers increases as a result of illegal lane usage.

The range of ORR varies between 0.23 and 0.42 on FM1 at downstream capacity level. This implies that when 23% to 42% of total flow ($Q_{up}+Q_{on}$) compromises of on-ramp flow then the capacity flow is observed at downstream on FM1. The crucial point is that the downstream capacity is only experienced when the ORR is between 0.23 and 0.42. The capacity has been observed at downstream of a merge, when the measured on-ramp flow rates are between 909 pcu/h/lane and 1,434 pcu/h/lane, while for the upstream flow rates change between 1,228 pcu/h/lane and 2,058 pcu/h/lane.

According to Equation (2), as the ORR increases, growth of the on-ramp flow is smaller than the decrease of upstream flow. Consequently, the increase of on-ramp ratio reduces downstream capacity, which can be easily calculated by the summation of on-ramp and upstream flows. This could be explained by the growing interaction effects between upstream and on-ramp flows, which cause to reduction of merge capacity as expected.

5.2. FM2: Two-Lane Drop Merge

The difference between FM2 and FM1 is the number of lanes at both downstream and upstream. On FM2, the upstream and downstream flows have four lanes, and the on-ramp flow has two lanes as given in Fig. 2(b). Therefore, six lanes in total cause two-lane drop merge along 350 m acceleration lane. The relationship between ORR and $Q_{up}+Q_{on}$, given in Fig. 5, is determined inversely proportional and quite scattered, similar to FM1.

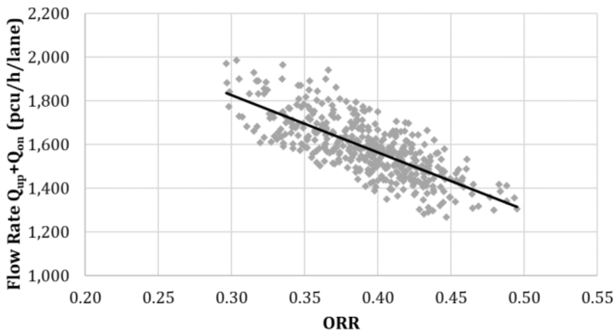

Figure. 5. $Q_{up}+Q_{on}$ versus ORR on FM2.

On the other hand, R^2s are determined higher compared to FM1 such as 0.560, 0.561, 0.560, 0.561, and 0.560 for exponential, linear, logarithmic, polynomial (second order) and power form of simple regressions, respectively between $Q_{up}+Q_{on}$ and ORR. These coefficients indicate a strong relationship between the on-ramp ratio and the sum of upstream and on-ramp flows (The R^2 is equal or greater than 0.56). The estimated simple linear regression model of FM2 is given in Equation (3).

$$Q_{up} + Q_{on} = 2{,}607.3 - 2{,}612.4 \times ORR \qquad (3)$$

The range of ORR is affected by the demand or merge geometry compared to FM1, while it is calculated between 0.30 and 0.50 for FM2. The meaning of 0.50 ORR is that the on-ramp and the upstream per lane flows are equal to each other. According to Equation (3), when ORR equals to 0.50, the on-ramp flow rate is calculated as 1,302 pcu/h/2-lanes, while the upstream flow rate is estimated as 2,604 pcu/h/4-lanes, and for both flows, per lane flow rate is equal to 651 pcu/h/lane. Table 2 shows p-values of regression statistics given in Equation (3) which are found statistically significant since they are below 0.05 similar to FM1.

Table 2. Linear regression statistics for FM2.

	Coefficients	Standard Error	t Stat	P-value
Intercept	2,607.3	44.3	58.9	1.14E-205
ORR	-2,612.4	112.4	-23.2	1.63E-77

At downstream capacity, the on-ramp flow rates are observed between 1,542 pcu/h/lane and 2,166 pcu/h/lane, and the upstream flow rates change between 989 pcu/h/lane and 2,081 pcu/h/lane. Inverse nature of total flow ($Q_{up}+Q_{on}$) and ORR are clarified with FM2 merge geometry, and found slightly different (seems more affected with increase in ORR) when compared to FM1 relationship as given in Equation (2).

5.3. FM3: One-Lane Drop Merge

On FM3, there are four lanes at downstream similar to FM2; however, three lanes exist at upstream as given in Fig. 2(c). Since on-ramp flow has two lanes, the sum of upstream and on-ramp flows formed by five lanes merge to four lanes at downstream by creating one-lane drop merge. The inverse relationship among total flow ($Q_{up}+Q_{on}$) and ORR is similarly determined for FM3 as given in Fig. 6.

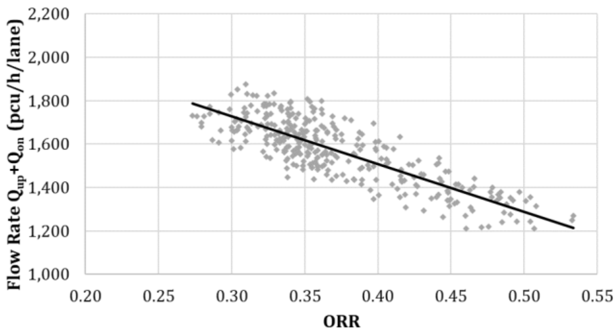

Figure 6. $Q_{up}+Q_{on}$ versus ORR on FM3.

At FM3, R^2s values are calculated as 0.671, 0.675, 0.665, 0.675, and 0.672 for exponential, linear, logarithmic, polynomial (second order), and power form of simple regressions, respectively between $Q_{up}+Q_{on}$ and ORR. Among three merges, the highest R^2 is found for FM3 as 0.675 and the regression model appears as in Equation (4).

$$Q_{up} + Q_{on} = 2{,}387.7 - 2{,}201.6 \times ORR \qquad (4)$$

It is seen from the data in Fig. 6 that ORRs change from 0.27 to 0.53 on FM3. When ORR is greater than 0.50, it implies that per lane on-ramp flow is greater than the per lane upstream flow. Observed minimum upstream flow rate shows up as 974 pcu/h/lane for the highest ORR, while the maximum as 2,160 pcu/h/lane for the lowest ORR. Meanwhile the on-ramp flow rates change from 1,161 pcu/h/lane to 1,713 pcu/h/lane. In Table 3, p-values of regression statistics are given for Equation (4) which are found statistically significant since they are below 0.05 similar to FM1 and FM2.

Table 3. Linear regression statistics for FM3.

	Coefficients	Standard Error	t Stat	P-value
Intercept	2,387.7	32.0	74.5	3.00E-204
ORR	-2,201.6	85.5	-25.8	5,11E-80

6. Effect of Merge Geometry

Consideration of Equations (2), (3) and (4) provides possible effects of merge geometries. Even though ORR changes in different ranges for each merge, general inferences can be done with slope of each equation. Fluctuations in $Q_{up}+Q_{on}$ with respect to ORR are given in Fig. 7 as a result of Equations (2), (3) and (4).

Fig. 7 actually explains numerous results about each merge. In this context, FM1 seems to be least affected FM with respect to increase in ORR since Equation (2) has the lowest slope (-2,003.5) amongst others. In other words, 0.01 increase in ORR causes to 20 pcu/h/lane reduction in total upstream ($Q_{up}+Q_{on}$) flow rate. Although FM1 has two undesirable bottlenecks, it is the least affected merge with increase in ORR. It seems to one lane drop merge area reduces interaction effect among vehicles.

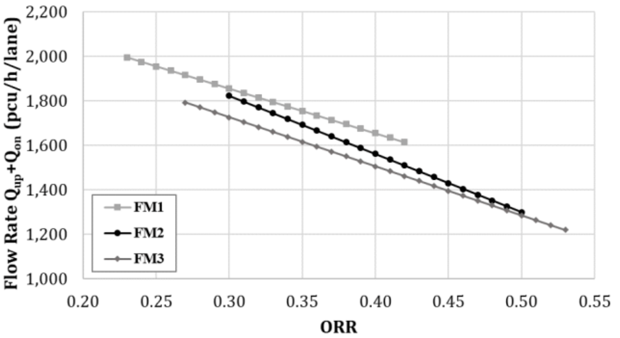

Figure 7. Change of $Q_{up}+Q_{on}$ with respect to ORR.

With the same approach, the moderately affected merge with increase in ORR is clarified as FM3 from Fig. 7, since it has the second lowest slope (-2,201.6) as given in Equation (4). FM3 is one lane dropped such as FM1, however it has three lanes in upstream and four lanes at downstream unlike FM1. According to this geometric variation, reduction of $Q_{up}+Q_{on}$ determined as 22 pcu/h/lane with respect to 0.01 increase in ORR from Equation (4). It can be concluded that increase in the number of lanes at both upstream and downstream (by preserving one lane drop) make FM more sensitive in terms of on-ramp flow compared to FM1. Even though FM3 has acceleration lane unlike FM1, it is clearly seen that most obvious effect emerged as lane number.

Critical merge geometry that effects more significantly to merging vehicles appears as FM2, which has two lane dropped and four lanes at both upstream and downstream. Highest slope (-2,612.4) appears at FM2 from Equation (3) amongst others, which makes this merge more sensitive for merging flows. Consideration of Equation (3) shows 0.01 increase in ORR causes to 26 pcu/h/lane reduction on $Q_{up}+Q_{on}$, which is greater than both FM1 and FM3. Unlike FM1 and FM3, FM2 creates two lane drop at merging area and it is clearly seen that this geometric condition has greatest impact on merging vehicles compared to others. Although 350 m and highest parallel acceleration lane existence, greatest reduction is determined at FM2.

6.1. Aggregation of FMs Data

In order to determine the impact of on-ramp flows when downstream capacity, with considering their geometric differences; data from three FMs have been gathered. Various ranges of ORRs have been analyzed with on-ramp, upstream and downstream lane numbers in order to develop more universal model. In the aggregated data set, ORR changes from 0.23 to 0.53, number of lanes at upstream changes from four to six, downstream lane number changes from three to four while at on-ramp lane number is always two. In this way, similar (nevertheless wider) patterns are clarified compared to those examined individually. Besides, the impact of road geometry on total flow rate ($Q_{up}+Q_{on}$) has been considered. The scatter diagram of total flow rate and ORR is given in Fig. 8 for aggregated data.

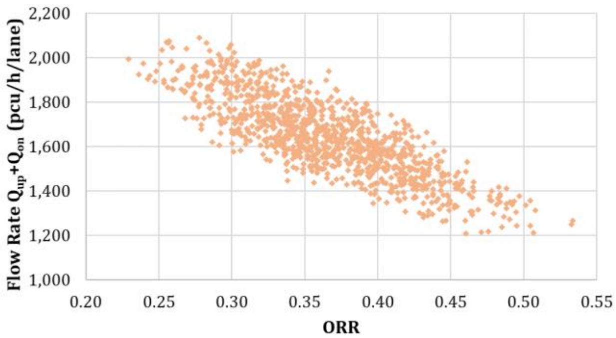

Figure 8. $Q_{up}+Q_{on}$ versus ORR for aggregated data.

Multiple regression models have been developed with the ORR, the number of lanes at on-ramp over number of lanes at upstream plus on-ramp ($L_{on}/L_{up}+L_{on}$), and the number of lanes at downstream (L_{down}) as independent variables while the "ln" of total flow rate ($Q_{up}+Q_{on}$) is considered as dependent variables. The highest R^2 has been calculated for the Equation (5).

$$Q_{up} + Q_{on} = e^{8.073-1.906\times ORR^2-0.745\times\left(\frac{L_{on}}{L_{up}+L_{on}}\right)^2-0.021\times L_{down}^2} \quad (5)$$

In Equation (5), R^2 has been calculated as 0.739 which points out a strong relationship among variables. In Table 4, p-values of regression statistics are given for Equation (5) between variables which are found statistically significant since they are below 0.05.

As the ORR changes between 0.23 and 0.53, estimates within this interval are reliable; however, the estimates based to the outside of it, have to be evaluated with precaution. Similarly, this model has been developed only for the lane configurations which are explained in Fig. 2. Hence, the estimation of Equation (5) has to evaluated with precaution for the merges with various lane configurations.

Table 4. Multiple regression statistics for aggregated data.

	Coefficients	Standard Error	t Stat	P-value
Intercept	8.073	0.035	232.361	0
ORR^2	-1.906	0.049	-38.778	1.54E-204
$(L_{on}/L_{up}+L_{on})^2$	-0.745	0.083	-8.949	1.60E-18
$(L_{down})^2$	-0.021	0.001	-13.977	8.01E-41

By using the Equation (5), $Q_{up}+Q_{on}$ can be calculated for various geometric features. By providing number of lanes at upstream, on-ramp and downstream, total volume of on-ramp and upstream can be calculated which create the capacity flow at downstream. From this point of view, the model result based on Equation (5) with respect to ORR are given in Fig. 9. It should not be forgotten that the Equation (5) yields total flow rate ($Q_{up}+Q_{on}$) with respect to ORR. In order to calculate Q_{on}, the estimate of Equation (5) has to be multiplied with ORR. As ORR changes from 0.20 to 0.60 in Fig. 9, it is clearly seen that the increase of on-ramp flow is less than the decrease of upstream flow, which means an increase of on-ramp demand causes a decrease of $Q_{up}+Q_{on}$. Fig. 9. is obtained by using three freeway merge geometries in order the show its application and to show effect of geometric differences of FMs used in this study.

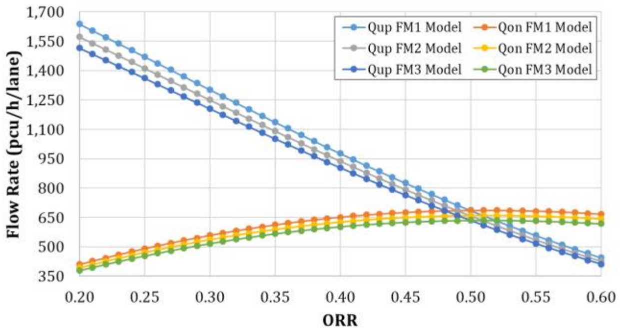

Figure 9. Change of Q_{up} and Q_{on} versus ORR for FM1, FM2 and FM3 geometric features.

According to Fig. 9, when ORR is equal to 0.2, Q_{up} is estimated as 1,638, 1572 and 1516 pcu/h/lane for FM1, FM2 and FM3 respectively. Correspondingly, it drops to 445, 427 and 412 pcu/h/lane when ORR increases to 0.6 for FM1, FM2 and FM3. For three FMs, by using Equation (5) the upstream and on-ramp flows have been calculated for some ORRs as given in Table 5.

Q_{on} is calculated as 409 pcu/h/lane for the lowest and 667 pcu/h/lane for the highest ORR in FM1 model. In other words, upstream flow decreases 73% while on-ramp flow rate increases only 63%. This clarifies that on-ramp flow influences potential of upstream flow, since the increase of on-ramp flow is greater than the reduction of upstream flow. In other words, if the on-ramp flow increases one unit, $Q_{up}+Q_{on}$ decreases more than one unit. Similar reductions have been calculated for FM2 and FM3 lane configurations too.

Table 5. Upstream and on-ramp flows with respect to ORR in each FM.

ORR	Upstream Flow Rate (pcu/h/lane)		
	FM1	FM2	FM3
0.2	1638	1572	1516
0.3	1303	1250	1206
0.4	977	938	904
0.5	686	658	635
0.6	445	427	412
ORR	**On-Ramp Flow Rate (pcu/h/lane)**		
	FM1	**FM2**	**FM3**
0.2	409	393	379
0.3	558	536	517
0.4	652	625	603
0.5	686	658	635
0.6	667	641	618

According to Table 5, when ORR is 0.5, maximum flow (per lane) is observed at FM1 while the lowest at FM3. Similarly, the highest upstream and on-ramp flows observed at FM1 while the lowest at FM3.

In terms of the change of upstream and on-ramp volumes, FM1 seems to be least affected merge geometry type in the aggregated data model. From this perspective, FM2 is moderately and FM3 is highly affected merges.

Findings indicate that when the percentage of on-ramp flow become lower, the capacity of a freeway merge increases.

7. Conclusion

This study aims to determine the interaction between upstream (Q_{up}) and on-ramp (Q_{on}) flows at capacity level on FMs without ramp-metering. Three urban FMs are selected as study scope and three-year data have been investigated for the analysis.

The term on-ramp ratio (ORR) is defined as the ratio between on-ramp flow rate (Q_{on}) and upstream flow rate plus on-ramp flow rate ($Q_{up}+Q_{on}$), express as total flow in the study. The scatter plots of $Q_{up}+Q_{on}$ versus ORR on each FM indicate the existence of inversely proportional relationship among them. This study shows clearly how the share of on-ramp flow within the total flow affects downstream capacity.

FM2, which is a two-lane drop merge with four lanes at both upstream and downstream, has the greatest impact on merging vehicles, in order words, the total flows ($Q_{up}+Q_{on}$) are highly sensitive to increase of ORR. In the aggregated data model, in terms of $Q_{up}+Q_{on}$, FM2 is found to be moderately affected merge.

On the basis of merging vehicle interaction, FM1 has the least effected merge geometry with one-lane drop and two lanes at upstream, while three lanes at downstream. When ORR increases 1% on FM1, 20 pcu/h/lane reduction is determined at total flows (Q_{up}+Q_{on}), while this value is 26 pcu/h/lane for FM2 and 22 pcu/h/lane for FM3. These changes clearly show the influence of geometric differences on merging flows. Similarly, FM1 is found to be the least affected merge in aggregated data model.

According to individual model, FM3 is found to moderately sensitive to ORR. However, aggregated data model reveals it has the critical geometric type in terms of Q_{up}+Q_{on} change.

The aggregation of three FMs data allowed to develop more universal model that shows a strong relationship among the ORR and number of lanes at upstream, on-ramp and downstream of a merge. It is concluded that the lack of ramp-metering application causes to a capacity decrease when Q_{on} increases. It is found that, when on-ramp flow increases by 63%, upstream flow reduces by 73% per lane, which shows the capacity loss as a result of uncontrolled merges.

As initially indicated, the impact of on-ramp flows on downstream capacity is obvious. Interactions between upstream and on-ramp flows result in a decrease of downstream capacity. As a traffic management strategy, many ramp metering procedures could be applied in order to increase efficiency of a FM. However, FM flows are being influenced by several geometric factors such as the number and width of lanes, the length and existence of acceleration lanes, the lateral clearance, number of lane differences between upstream and downstream flows and so on. This study shows on traffic management solutions, it is not enough to decrease the demand, but also geometric features need to be improved on FMs. For each FM, there may have been distinct relationships between on-ramp, upstream and downstream flows. For this reason, in particular, the interaction of merging flows should be revealed before providing a ramp metering solution on FMs, by taking into account their geometric characteristics.

From this perspective, further studies can be focused to improve the findings of this study by providing more geometric features (such as gradient, lane with, lateral clearance, so on); and to determine the capacity drops on FMs with respect to geometric properties. In particular, mathematical formulations related to the impact of the number of lanes can help to understand the advantage of adding extra lanes to downstream.

This study demonstrates the significance of merge geometry and demand of upstream and on-ramp flows on capacity of a freeway which is one of essential field in traffic management aspect. Considering the results of existing study, the traffic management strategies (such as ramp metering or capacity/demand management) could be more optimum, realistic and overarching.

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