Traffic Microsimulation Study to Evaluate Freeway Exit Ramps Capacity

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Abstract

Growing traffic in urban and suburban areas has resulted in a demand for freeway exit ramps with higher capacity in order to avoid congestion. The main objective of the paper was to elaborate recommendations about the best exit ramp layout according to different parameters by evaluating capacity. Seven different diverge layouts were analyzed using traffic microsimulation. The average delay of the vehicles among their exit path was calculated on each diverge layout; and the capacity was obtained as the diverging flow from which the average delay grew exponentially. The capacity of each diverge layout varied from 1600 to 2000 vehicles per hour in one-lane exit ramp. The values for two-lane exit ramp were included on the interval [2000, 4400] vehicles per hour.

Keywords: Motorway diverge; exit ramp; capacity traffic; microsimulation.

1. Introduction

Motorway merging and diverging usually results on bottlenecks in freeway operations. An efficiently designed diverge may allow traffic to leave main carriageway as quickly as possible, without disruptions on traffic remaining on mainline. The Spanish Standard (Ministerio de Fomento, 1999) established deceleration lane as a functional element designated to facilitate exiting mainlines. Two different diverge layout were proposed: taper; and parallel, which are shown in Figure 1. Both layouts are one-lane exit ramp.

In order to calculate deceleration lane length, a dynamic model was adopted. The model considered both operational speeds in upstream segment and exit ramp; and average grade. However, many other factors, which may result important on the design of this type of junction, were not considered, such as traffic flow and safety.

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Moreover, these diverge layout may be inefficient on motorways on urban and suburban areas, where traffic flow is higher and near approaching capacity.

Figure 1. Motorway exit ramp layout: (a) Taper; (b) Parallel.

Other countries considered on their design guidelines not only exit ramp with one lane, but also two-lane exit ramps (AASHTO, 2004, Department of Transport, 2006). The need for understanding capacity is critical, as reflected in the U.S. Highway Capacity Manual (TRB 2000). Specifically, the HCM procedures provide estimates of levels of services but not of capacity. The latest UK Standard (Department of Transport, 2006) provided engineers a diverging flow-region diagram to help on the selection of the most appropriated layout depending on the mainline and diverging flows. Five layouts were considered: taper; parallel; taper lane drop; parallel lane drop; and parallel double lane drop. The regions were formed based on the maximum design working flows on both diverging and mainline. Both taper diverge and lane drop at taper diverge had a capacity of 1400 veh/h, while parallel diverge had 1800 veh/h capacity. Two-lane exit ramps presented capacity of 3600 veh/h at lane drop and lane drop at parallel diverge. Nevertheless, the research which these figures were based on is unclear and the design flow rate was lower than maximum working design flow (Wall and Hounsell, 2004). A microscopic model was used to verify the realistic representation of the diagram (Wall and Hounsell, 2005). It was concluded that taper and taper lane drop diverge layout had a limited range of diverging flows where operation was efficient. Parallel layout offered higher throughput results. However, no capacity values were given as result of the study.

A few research were conducted on freeway exit ramps areas focused on exit ramp performance analysis of safety and operations (Michalopoulos et al., 1990; Al-Kaisy et al., 1999; Bared et al., 1999; Batenhorst and Gerken, 2000; Bonnenson et al., 2005; Garber and Fontaine, 1999; Khorashadi, 1998; Lord and Bonnenson, 2005; Rakha and Zhang, 2006; Xinkai, 2007; Lu et al., 2010; Romero and Garcia, 2010; Anderson and Pedersen, 2010). It was concluded that only the off-ramp free-flow speed had a significant impact on capacity and operational performance.
on freeway parallel diverge layouts located outside the influence of other upstream or downstream ramps (Al-Kaisy et al., 1998). However, capacity of different motorways diverges and exits were not calibrated on literature. On the other hand, the lane-balance theory is used to define exit ramp types. The theory was introduced by AASHTO (2004). This design requires that the number of approach lanes on a freeway at exits should be equal to the number of lanes beyond the exit, plus the number of lanes on the exit, minus one. Designers are currently using different lane arrangements to coordinate the lane-balance needs and the consistency in basic number of lanes. Different lane arrangements may have different impacts on traffic operations and safety (Liu et al., 2010). Liu et al. (2010) analyzed safety impacts of lane arrangements on freeway segments with closely spaced entrance and exit ramps. It was found that a continuous auxiliary lane between entrance and exit ramps with a one-lane exit had the lowest average crash frequency and crash rate. Nevertheless, operational effects of different lane arrangements were not considered.

2. Objectives

The aim of the present paper was to elaborate recommendations about the best freeway exit ramp layout according to different parameters by evaluating their capacity. Traffic simulation was used to estimate capacity on diverge areas since hardly are found high capacity exit ramps in Spain, and even fewer are working with traffic flows close to capacity. A traffic simulation model created for the purpose of this research required a response similar to the one in real-world; so, two different freeway exit ramp layouts located on Valencia’s metropolitan area were used. Both areas presented high traffic flow. The applied methodology included three main components: field study; microsimulation model; and analysis of the results. Each one of the stages is being developed on the following sections.

3. Field study

A field study was carried out to obtain actual data of drivers’ performance on motorway exit ramps with two lane ramps. Two motorway diverges with two lane ramps located on the metropolitan area of Valencia (Spain) were selected. The first freeway exit ramp was located on North ring road and South ring road junction on CV-35 (Figure 2a). The number of lanes upstream and downstream the diverge area was three. The exit ramp configuration was a parallel two-lane exit ramp. The exit ramp had a full width parallel lane of 140 m length. The later 30 m of the lane had double width so two vehicles could circulate in parallel at the end of the exit ramp. The lane-balance theory was not achieved on this configuration. Consequently, the freeway exit ramp was unbalanced.

The second one was CV-35 and South ring road junction on CV-30 (Figure 2b). The exit ramp was composed of two different elements. The first element consisted of separation of the four lanes of the carriageway on two directions: two lanes to continue on the mainline (CV-30); and two lanes to exit the mainline to South ring road and CV-35. Then, the second part of the exit was a two-lane exit ramp with an optional lane design. Consequently, two lanes could be used to head to CV-35 and other two lanes were available to South ring road. This freeway exit ramp was also unbalanced.
Figure 2. Observed motorway exit ramps: (a) North ring road and South ring road junction on CV-35; (b) CV-35 and South ring road junction on CV-30.

Video records were used to analyze drivers’ behavior on exit ramps. Three cameras were located at a near building; so, the covered area included upstream and downstream the diverge nose of the first freeway exit ramp. The second was recorded from three bridges that crossed over CV-30. Data collection was conducted during peak hour. The observed traffic characteristics included: traffic volume; traffic composition; speed distribution; exit traffic volume and composition; and drivers’ path (maneuvers).

In order to identify the different maneuvers on both freeway exit ramps, some criteria were established. On the first one, five criteria were taken into account: lane of the vehicle 80 m before the start of the deceleration lane; lane while entering the deceleration lane; vehicle’s position in the deceleration lane; possible lane change near diverge gore; and final destination. A total of 32 kind of maneuvers were identified. The most representative maneuvers are summarized on Table 1. These three maneuvers represented 87% of the total whilst the rest of maneuvers had recurrence percentages lower than 1%.

| Maneuver Lane | Mainline Exit ramp | Final destination | % recurrence |
|---------------|--------------------|-------------------|-------------|
| M-A1          | Outer              | Inner             | North ring road | 40 |
| M-A2          | Outer              | Outer             | North ring road | 30 |
| M-A3          | Outer              | Outer             | South ring road | 17 |
On the second freeway exit ramp, six criteria were considered: lane of the vehicle on B1 to B5; and final destination (Figure 3). In this case, 45 maneuvers were identified. The values are represented on Table 2. Almost half of exiting vehicles located themselves into the outer lane as the exit ramp was approached. Then, they went on the same lane to exit to CV-35.

![Figure 3. Freeway exit ramp B: maneuver criteria location.](image)

| Maneuver | Lane | Final destination | % recurrence |
|----------|------|------------------|-------------|
| M-B1     | Outer | Median | Inner | CV-35 | 43 |
| M-B2     | Outer | Outer | Outer | CV-35 | 11 |
| M-B3     | Median | Inner | Inner | South ring road | 10 |

4. Microscopic modelling

The traffic simulation model VISSIM 5.1 was selected to analyze capacity at motorway exit ramps. A brief description of the traffic simulation model is presented in this section, as well as main features which are critical in modeling exit ramps operation.

4.1. Traffic simulation program

VISSIM 5.1 is a microscopic multimodal traffic simulation model. It can assign behavior to individual vehicles as they circulate from their origin to their destination. Furthermore, most of the macroscopic features can be also analyzed because of the microscopic rules calibration. Besides, different transportation modes and their interactions can be modelized. VISSIM 5.1 can be applied to multiple scenarios such as mobility studies, intelligent traffic systems (ITS), management systems and traffic control systems (Fellendorf and Vortisch, 2001; Gomes et al., 2004).

The traffic simulation program is constituted by two subprograms. Traffic flow model is built on the first subprogram, where all network features are defined. The second subprogram rules behavior of vehicles, pedestrians,
etc., depending on value of traffic flow parameters. The Wiedemann’s vehicle behavior model is implemented on VISSIM 5.1. The model defines vehicles’ response as a function of perceived relative speed between a vehicle and the previous car. Four different responses are deduced: free flow; approaching; following; and braking. Lane changing model is also implemented.

4.2. Model calibration and validation

In order to represent the observed behavior, and, consequently, obtain accurate results, a calibration of the traffic simulation model was carried out. In this process, a series of parameters and variables were adjusted. The needed data were obtained from the field study. The adjusted data were: traffic flow; composition; grade; speed distribution; and vehicles’ path distribution.

The model validation compared the results on the model with the observed data. The selected checking variable was the speed distribution since the other variables were constants during simulation process. Two speed distributions were obtained for both observed exit ramps: mainline; and exit ramp. Speed distribution was elaborated using spot speeds located at: 60 m before the deceleration lane started (mainline exit A); nose gore (exit ramp A); 150 m before the deceleration lane started (mainline exit B); and 30 m before the nose gore (exit ramp B). Speed distributions of the model were compared to the observed, as shown in Figure 4. Observed speed was slightly higher than simulated results. It can be explained as actual drivers accept shorter safety distances and lane changing gaps.

Figure 4. Comparison between speed distributions.

4.3. Motorway exit ramps description
Once the traffic model was calibrated and validated, seven different motorway exit ramp layouts were created. The created scenarios were: one-lane taper diverge (Ac); one-lane parallel diverge (Ap); two-lane parallel diverge (Bc); two-lane parallel diverge with optional lane (Bf); one-lane drop (C); one-lane drop at 150-200 m long parallel diverge (D); one-lane drop at 200-400 m long parallel diverge (E). Most freeway diverging facilities belong to one of the modellized scenarios. The analyzed layouts are summarized in Table 3 and shown in Figure 5.

To create accurately each scenario, observed layouts were modified. The introduced data were: geometry; traffic flow; composition; speed distributions; and drivers’ path distribution. Drivers’ path distribution was adapted to new geometries. Therefore, drivers’ behavior was maintained while geometry and path were modified.

Figure 5. Motorway exit ramps layout.
### Table 3 – Analyzed freeway exit ramps.

| Id | Number of lanes | Lane arrangement | Length of auxiliary lane (m) | Length of two-lane width (m) | Length of taper (m) |
|----|-----------------|------------------|-----------------------------|-----------------------------|-------------------|
| Ac | 2               | Balanced         | -                           | -                           | 100               |
| Ap | 2               | Balanced         | 150                         | -                           | -                 |
| Bc | 2               | Unbalanced       | 150                         | 30                          | -                 |
| Bf | 3               | Unbalanced       | 150                         | 150                         | -                 |
| C  | 3               | Unbalanced       | -                           | -                           | -                 |
| D  | 3               | Balanced         | 150-200                     | 150-200                     | -                 |
| E  | 3               | Balanced         | 200-400                     | 200-400                     | -                 |

#### 4.4. Simulation scenarios

After the scenarios were created, simulations were executed. Each simulation lasted 75 minutes. A warm up period of 10 minutes was used to fill the motorway with traffic and stabilize the traffic flow. The latest 5 minutes were also discarded. The corresponding data were deleted from the output file.

Many traffic demand scenarios were considered in this analysis. As the aim of the research was to determine the capacity of different freeway exit ramp layouts, exiting traffic flow was progressively increased. Traffic demand was introduced upstream the diverge area. Given the maneuver distribution from the field study and a exiting traffic flow step, the traffic flow upstream the diverge area on each simulation was calculated. The exiting traffic flow step was set on 100 vehicles per hour.

At each simulation, vehicles’ average delay was obtained. Average delay was calculated between 30 m before the start of the deceleration lane and 80 m after the nose gore (freeway exit ramp A); and between 30 m before the start of the deceleration lane and 30 m after the second nose gore (freeway exit ramp B). A total of 75 simulations were carried out. Exiting traffic flow and the number of simulations are shown on Table 4.

### Table 4. Number of simulations

| Layout | One-lane exit | Two-lane exit | TOTAL |
|--------|---------------|---------------|-------|
| Ac     | 1000          | 1500          | 3600  |
| Ap     | 1400          | 2100          | 4800  |
| C      | 1600          | 2800          | 4800  |
| Bc     | 1800          | 3300          | 5100  |
| Bf     | 2100          | 4800          | 7300  |
| D      | 1000          | 1000          | 2000  |
| E      | 1000          | 1000          | 2000  |

In order to check that VISSIM was correctly modelling the layouts, two tests were executed: checking the traffic movements associated with each layout were as expected; and checking that the driving behavior for each exit ramp was realistic. All scenarios passed both tests.

### 5. Results

The results were focused on obtaining capacity of each exit ramp. Capacity of a motorway ramp was defined as the maximum flow per unit time for the exit ramp measured in vehicles per hour. Capacity of each exit ramp was...
deduced based on average delay. Average delay was represented depending on exiting traffic flow (Figure 6). Then, capacity was determined as the exiting traffic flow from which average delay increased exponentially instead of being calculated using a predetermined threshold. The capacity of each layout is shown in Table 5. Higher capacity values could be proposed. However, conservative values were preferred. Both proposed and maximum capacity values are shown.

Table 5. Capacity of different motorway exit ramps.

| Capacity (vh/h) | Ac    | Ap    | Bc    | Bf    | C     | D     | E     |
|----------------|-------|-------|-------|-------|-------|-------|-------|
| Proposed       | 1600  | 1800  | 2000  | 2400  | 1800  | 3000  | 4400  |
| Maximum        | 1800  | 2100  | 2100  | 2600  | 2000  | 3000  | 4500  |

It can be noted that average delays which defined capacity at each scenario were on the interval [2, 14] seconds. Exit ramp Bc had the lowest average delay at capacity while C had the highest.

An analysis of typologies was performed. One-lane exit ramps and two-lane exit ramps were evaluated separately. Then, a comparison between them was established. The results are developed on the following sections.
deceleration lane. It means C presented the longest parallel exit ramp layout. An initial hypothesis could be that the longer the deceleration lane is, the higher capacity is obtained because drivers have more opportunities to leave the mainline. However, traffic demands near capacity may reduce the chances of trapped vehicles on the outer lane to maintain on the mainline. Exiting traffic may block these vehicles wishing to stay on the mainline; which results on higher delays. The effect is higher on unbalanced lane arrangements where weaving maneuvers are higher.

The results of the microsimulation showed that Ac presented the lowest capacity while Ap had slightly higher capacity than C. Consequently, not always a longer deceleration lane resulted on higher capacity due to trapped vehicles. On the other hand, lane drop allows not having the same number of lanes upstream and downstream the exit area; so the traffic flow downstream could be lower.

5.2. Two-lane exit ramps

Exit ramps Bc (parallel diverge), Bf (parallel with optional lane diverge), D (one lane drop at 150-200 m long parallel diverge) and E (one lane drop at 200-400 m long parallel diverge) were analyzed. Balanced lane arrangements (D and E) presented higher capacity than unbalanced lane arrangements (Bc and Bf). Consequently, the principles of lane balance generated higher capacity. For both balanced lane and unbalanced lane exit ramps, the longer deceleration lane was, the higher capacity was.

5.3. Lane balance

On the previous sections, capacity was found dependant on lane arrangements at equal number of exiting lanes. Moreover, number of exiting lanes on the exit may influence capacity depending on lane arrangements. Exit ramps Bc and C were both unbalanced exit ramps and different number of lanes. Both had similar results on capacity despite exit ramp Bc had two-lane exit ramp. So, capacity was conditioned by lane balance instead of number of exiting lanes.

On the contrary, capacity was not equal at balanced exit ramps Ap and D. These pair of exit ramps had the same lane arrangement and differed on number of exiting lanes. Exit ramps with two-lanes (D) had more capacity than one-lane exit (Ap). Nevertheless, capacity depended on number of exiting lanes on balanced exit ramps. It has to be noted that increasing number of lanes to augment capacity may raise number of conflictive maneuvers.

5.4. Discussion

The diverging flow-region diagram implemented on the latest UK Standard (Department of Transport, 2006) provides a preliminary indication of which diverge is most appropriate for a given downstream mainline and exiting flows. The limits between the different regions on the diagram were set at capacity of each exit ramp type. The obtained capacity on this research agrees with other microscopic models of motorway exit ramps research (Wall and Hounsell, 2005) which specifies that design capacity on the UK Standard might be too conservative; as the same authors stated on a critical review of the UK standards (Wall and Hounsell, 2004).

UK Standard limited capacity of both taper and parallel motorway exit ramps to 1400 and 1800 vehicles per hour (veh/h), respectively. The microsimulation gave values of 1600 veh/h at the taper exit ramp and 1800-2000 veh/h at lane drop or parallel exit ramp. The values are up to one third higher. The same comparison can be made with two-lane exit ramps, with differences between one fifth and one third. The results on the microsimulation model have been obtained for Spanish drivers on two different locations. The average grade and composition were slightly different than the given on the UK Standard, as well as drivers’ behavior on motorway exit ramps near capacity. These features may affect the results and distortion the comparison, as shorter gaps might be accepted. However, they represent a starting point.

6. Conclusions and recommendations
Motorway exit ramps are areas of motorways with significant vehicle maneuvers which may affect traffic operation. Nowadays, many urban and suburban areas have junctions of motorways which traffic flow is near capacity and where bottlenecks are usually located. In order to improve traffic operation, new exit ramps layouts can be designed: high capacity freeway exit ramps. However, only the UK Standards (Department of Transport, 2006) included traffic demand values to select the most appropriated motorway exit ramp layout. Nevertheless, considered capacity was not based on traffic studies and may be too conservative. A field study was carried out to analyze drivers’ behavior with traffic flow near capacity at two urban interchanges on Valencia metropolitan area. A microsimulation model was calibrated and validated to represent actual drivers’ behavior on: speed selection; and path. The most representative maneuvers were introduced into a microsimulation model.

Seven exit ramps were designed. A total of 75 simulations were carried out to obtain capacity. Capacity was calculated as the exiting traffic flow from which average delay increased exponentially. The obtained values ranged from 1600 to 2000 veh/h at one-lane exit ramp and from 2000 to 4400 veh/h at two-lane exit ramp. The values were higher than the presented on UK Standards and agreed with other studies. It was found that not always the longer the deceleration lane was, the higher capacity was. On one-lane exit ramps, long deceleration lanes could induce drivers to confusion and vehicles wishing to stay on the mainline can be blocked on the outer lane by exiting vehicles. On the other hand, it was found that balanced lane layouts had higher capacity than unbalanced lane arrangements at equal number of exiting lanes. Furthermore, unbalanced layouts had similar capacity even they differed on number of exiting lanes. Nevertheless, capacity depended on both number of exiting lanes and deceleration lane length on balanced exit ramps.

The presented values can be used to scale the diagram implemented on UK Standards in order to adopt a more realistic design flow based on actual drivers’ behavior. However, future research is needed to obtain wider conclusions on other exit ramps, especially on those near capacity. Influence of composition and average grade has to be taken into account, as well as more geometric characteristics. Safety may be also analyzed to recommend appropriate motorway exit ramps.

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