



# Operational Analyses of Freeway Off-Ramp Bottlenecks

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## Abstract

The paper presents the findings to date of operational analyses at freeway off-ramps with emphasis on analysis procedures on recurrent off-ramp bottleneck locations at the Attiki odos motorway (Attica Tollway) in Athens, Greece. We compared the observed traffic performance metrics at two sites with the predicted measures using the methodology of freeway diverge areas and weaving sections in the 2010 edition of Highway Capacity Manual (HCM) for a wide range of traffic conditions. The findings indicate that the HCM volume predictions at the diverge area are in close agreement with field data and the density is underestimated by 7% on the average. The HCM weaving analysis methodology underestimated the weaving section capacity especially for high weaving volumes, and overestimated the section density by 17% on the average.

*Keywords:* freeway weaving, off-ramps, freeway capacity, mathematical models

## 1 Introduction

Freeway diverging areas and weaving sections are common design elements on freeway facilities such as near ramps and freeway-to-freeway connectors. When the traffic demands exceed the capacity at these locations congestion may occur, which affects the operation of the entire freeway section. In particular when off-ramps traffic demand exceeds the capacity at the downstream ramp terminal, the resulting spillback reduces the entire freeway discharge rate, increases delays and causes potential safety problems.

The objectives of the work reported in this paper is to develop and apply analysis tools to assess the traffic operations at the Attica Tollway in Athens, Greece, identify recurrent bottlenecks and

propose operational improvements. The paper presents the findings to-date from the first phase of the research involving the application of the HCM on two off-ramp bottleneck locations.

The next section of the paper describes the study sites along the Attica Tollway. Next the findings of the HCM methodology for diverging areas are presented. The following section presents the findings from the application of the HCM weaving analysis methodology. Section 4 discusses the study findings, and outlines ongoing and future work.

## 2 Study Site

Attica Tollway consists of five interconnected tolled freeways in the Athens Greece metropolitan area, with a total centerline length of 44 miles (70 km). There are 29 interchanges, and the number of lanes varies between 2 and 5 lanes per direction. There are 38 toll stations (three stations at the main entrances with 15 lanes each, and 35 stations on the access ramps, each with three to six lanes). The Tollway is actively managed to ensure safe and smooth travel for the motoring public. There are a total of 1,400 Inductive loop detectors located every 1,500 ft (500 m) on open sections and every 180 ft (60 m) in tunnels that provide data on flows and occupancy every 20 sec to assess the operating conditions. Video surveillance cameras and freeway service patrols ensure the quick detection and removal of traffic incidents (Halkias, 2005).

The detector data are stored, processed and analyzed by the freeway performance measurement system (PeMS) (Chen, 2001). PeMS includes algorithms to compute system performance measures (veh-miles and veh-hours of travel), traveler related metrics (delay and travel time along system segments), and travel time reliability measures (Petty, 2006). We used the PeMS bottleneck algorithm supplemented by field observations to identify active off-ramp bottlenecks based on the detector data. The algorithm is based on the spatial and temporal differences in speeds at successive detector locations. Two bottleneck sites were identified: a three lane freeway section with an one lane off-ramp, and a four lane freeway weaving section with a two lane off-ramp.

The first study site is a freeway diverge segment at the Kifissias Avenue interchange. This is a three lane section with one lane off-ramp (Figure 1). The heavy exit flow from the off-ramp has to stop at a downstream signalized intersection. The insufficient capacity of the signal controlled ramp terminal causes long queues and spillback of the off-ramp traffic into the Attica Tollway mainline. This causes drop in total freeway discharge rate, long queues and very slow speeds as shown in Figure 2. These conditions occur between 8-10 AM each weekday and the queues often exceed 2 miles in length. An adaptive control algorithm has been proposed to improve the performance at the traffic signal controlling the off-ramp exit ( Spiropoulou, 2010).

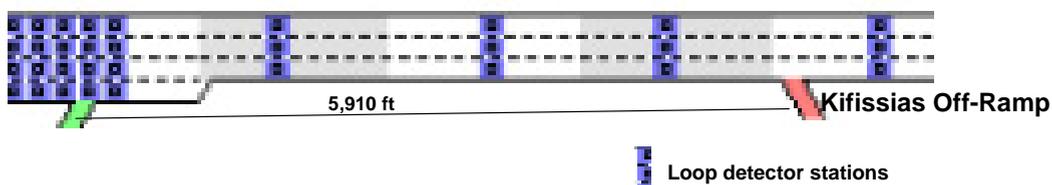


Figure 1: Study Location 1: Attica Tollway/Kifissias Avenue Off-Ramp

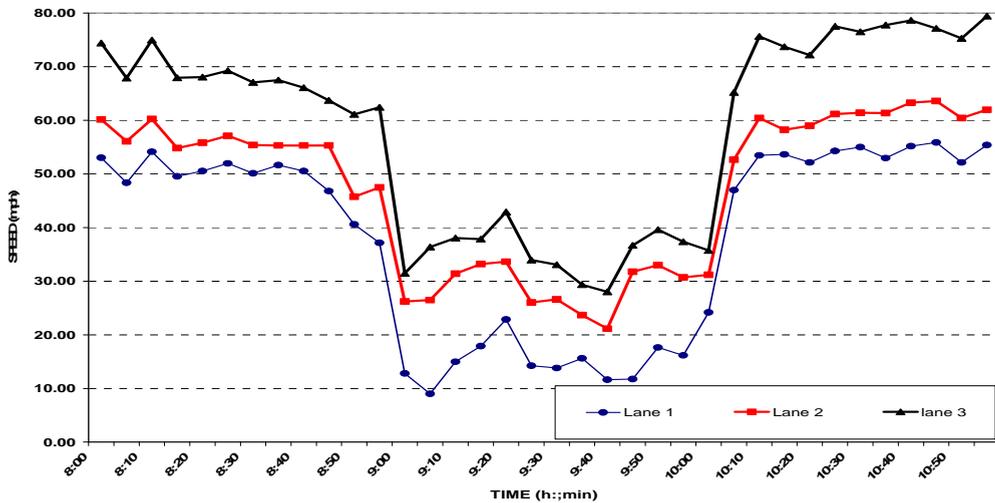


Figure 2: Vehicle Speeds at the Attica Tollway/Kifissias Avenue Diverge Area

The second study site is a weaving section at the Metamorphosis interchange, a major interchange of Attica Tollway and National Road 1. This is a four lane section with one lane on-ramp and two lane off-ramp (Figure 3). The heaviest traffic movement is the freeway-to ramp with more than 2,100 vph before the onset of congestion. The on-ramp flow is low (about 300 vph) and there is virtually no ramp-to ramp traffic. The exit flow from the off-ramp to the National road 1 is very constrained because of restricted geometrics and high opposing flows. This results in a spillback and congestion at the weaving section of Attica Tollway. Long queues are present between 7 to 9 AM on weekdays. As shown in Figure 4, vehicle speeds on the outer lanes during congestion drop below 20 mph which also presents a safety risk because traffic on adjacent lanes moves much faster.

The existing operating conditions at the interchange and several design and operational mitigations have been investigated through simulation (Prevedouros, 2009). The mitigations were primarily consisted of geometric modifications at the subject off-ramp and adjacent ramps at the interchange. The findings indicated that the proposed mitigations can alleviate most of the congestion problems, but they have not been implemented as of yet.

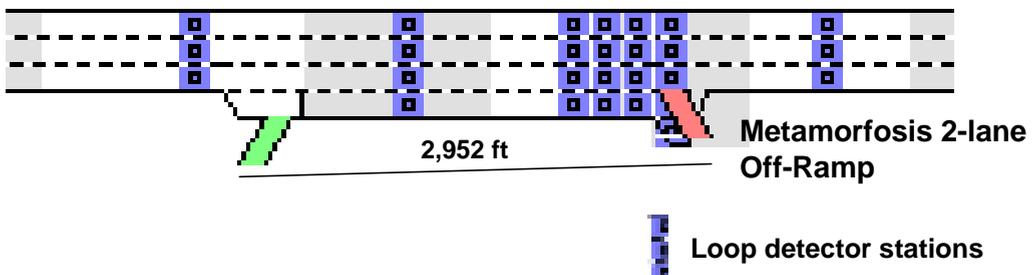


Figure 3: Study Site 2—Attica Tollway--Metamorphosis Weaving Section

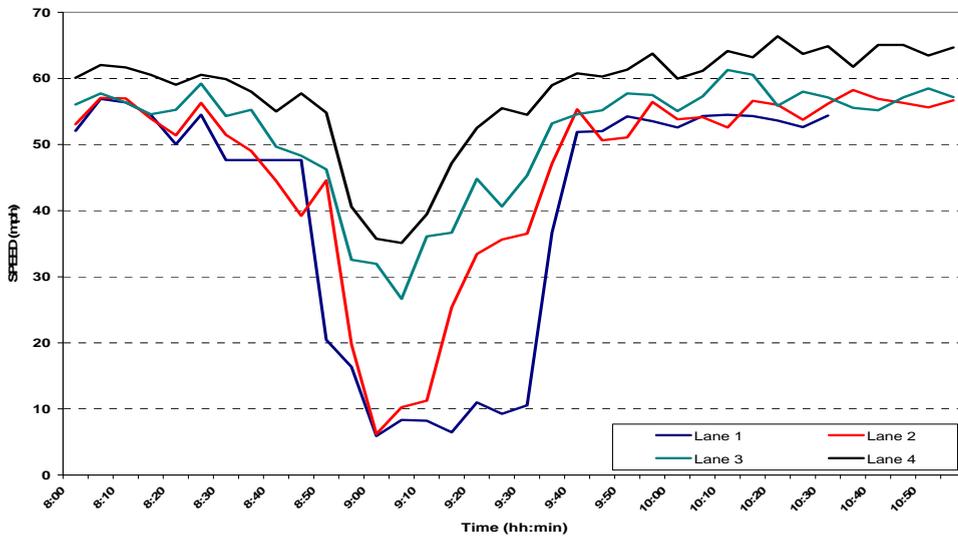


Figure 4: Vehicle Speed AM Peak--Metamorfosis Weaving Section

### 3 Application of HCM Methodology to Off-Ramp Segment

The HCM methodology for estimating the performance at freeway diverging areas consists of determining the Level of Service (LOS) within the “ramp area of influence”, as shown in Figure 5. The LOS is determined based on the density  $D_R$  which is computed from the volume in the outer lanes  $V_{I2}$  and the deceleration lane length. Table 1 shows the LOS designations.

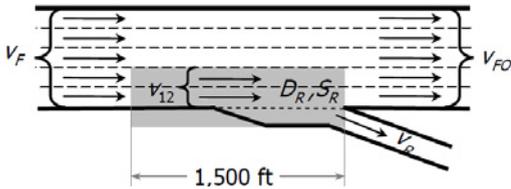


Figure 5: Freeway Diverge Area of Influence and Key Variables (Source: HCM2010)

Table 1: HCM2010 Level of Service for Merging/Diverging & Weaving Segments

LOS	Density (pc/mi/ln)
A	0-10
B	>10-20
C	>20-28
D	>28-35
E	>35
F	Demand Exceeds Capacity

The HCM methodology assumes that all the exiting traffic is located on the outer two freeway lanes lane 1 and 2, immediately upstream of the ramp. The total flow rate  $v_{12}$  in lanes 1 and 2 consists of the off-ramp traffic and a portion of the freeway through traffic. The proportion of the freeway through traffic  $P_{FD}$  remaining in lanes 1 and 2 is estimated from regression equations depending on the number of freeway through lanes, and the presence of on- and off-ramps in the vicinity of the analysis segment. In the case of the selected test section with three-lanes in each travel direction and an adjacent upstream on-ramp the following two equations can be used:

$$P_{FD} = 0.760 - 0.000025v_F - 0.000046v_R \quad (1)$$

$$P_{FD} = 0.717 - 0.000039v_F + 0.604(v_U/L_{UP}) \quad (2)$$

Where  $V_F$  is the total upstream freeway flow,  $V_R$  is the off-ramp flow,  $V_U$  is the flow rate on the adjacent upstream on-ramp, and  $L_{UP}$  is the distance between the subject ramp junction and the adjacent upstream ramp junction (ft).

In order to determine which equation is appropriate, an equilibrium distance  $L_{EQ}$  is calculated based on on-ramp volume, total volume and off-ramp volume. When the actual distance between ramps  $L_{UP}$  is greater than or equal to  $L_{EQ}$ , then Equation (1) is used, otherwise Equation (2) is used as appropriate.

Next the section density is computed:

$$D_R = 4.252 + 0.0086v_{12} - 0.009L_D \quad (3)$$

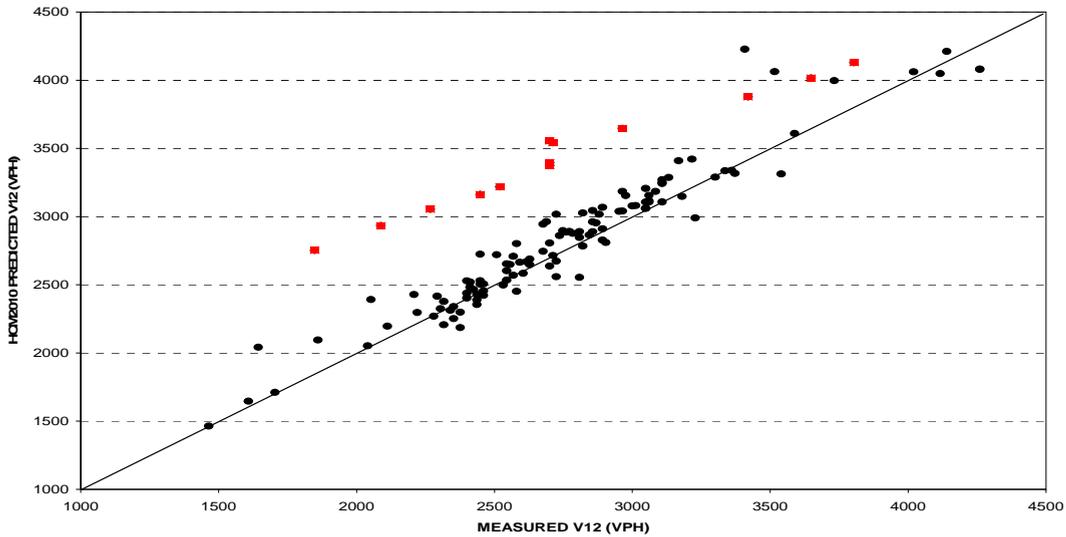
where  $L_D$  is the length of the deceleration lane (ft)

We applied the HCM methodology to the Kifissias diverge section. Figure 6 shows the measured and HCM predicted  $V_{12}$  volumes in the area of influence. The measured and computed volumes are in close agreement for a wide range of operating conditions. On the average HCM overestimated volumes by 3% compared to the field data with a root mean square error (RMSE) of 270 vehicles. The data points shown by red squares in Figure 6 represent traffic volumes under congested conditions due to the spillback from the off-ramp (figure 2) and excluded from further analyses.

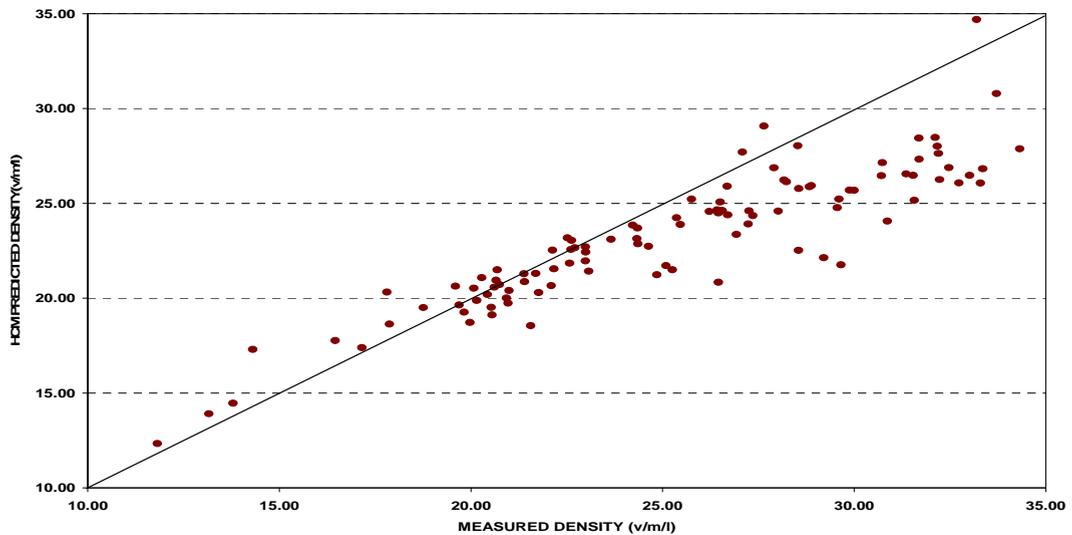
Figure 7 shows the measured and HCM predicted densities at the study section. These results indicate that the HCM methodology underestimates the section density by 7.5% on the average, with the larger differences in the higher densities. Exploratory analyses to recalibrate the density estimation formula (Equation 3) with data from the test site suggest that the density prediction could be significantly improved.

The HCM methodology also includes checks to ensure that the estimated volumes are reasonable. The average flow on the outer lane must not exceed 2,700 vph and must not be higher than 1.5 times the flow in lanes 1 and 2. These conditions are satisfied at the test site.

HCM does not provide a model is to estimate the capacity of diverging areas as function of demand, mainline demand and segment configuration design characteristics; instead HCM provides typical values for checking the capacity of mainline freeway segments, ramp roadway and the maximum flow entering the ramp influencing area as a function of the free flow speeds on the freeway and the off-ramp. The maximum observed volume was 6,756 vph observed at the onset of congestion. The maximum off-ramp volume was 1,970 vph/lane and the inside lanes volume was 2,130 vph/lane. These values compare well with the values flow rates suggested by HCM for the same free flow speed of 65 mph on the freeway mainline and 40 mph on the on-ramp.(HCM Exhibit 14-10 & 14-12).



**Figure 6: Measured and HCM Predicted Flows at the Area of Influence –Kifissias Section**



**Figure 7: Measured and HCM Predicted Densities the Freeway Diverge Area of Influence**

## 4 Application of the HCM Weaving Analysis Methodology

The HCM methodology computes two values for the capacity of the weaving section– one based upon a density of 43 pc/mi/ln, which according to the HCM2010 is the value that freeway breakdowns occur, and the other based upon the maximum weaving flow rates. The minimum of the two values estimated from Equations (4) and (5) below is the capacity of the weaving section.

The capacity of a weaving segment determined by the freeway breakdown density is given below:

$$c_{IWL} = c_{IFL} - [438.2(1+VR)^{1.6}] + [0.0765L_s] + [119.8N_{WL}] \quad (4)$$

Where  $c_{IFL}$  is the capacity of an equivalent basic freeway segment with the same free-flow speed as the weaving segment,  $N_{WL}$  is the number of lanes from which weaving maneuvers can be made with one lane change or no lane changes (proxy for segment configuration), and  $VR$  the volume ratio (total weaving volume/total volume).

The capacity of a weaving segment determined by the total weaving demand is estimated as follows:

$$c_{IW} = \frac{2,400}{VR} \text{ for } N_{WL} = 2 \text{ lanes, or } c_{IW} = \frac{3,500}{VR} \text{ for } N_{WL} = 3 \text{ lanes} \quad (5)$$

We applied the HCM methodology to the Metamorphosis weaving section. Figure 8 shows the HCM predicted capacities as a function of the  $VR$  weaving ratio, along with the field measured total traffic flows at the study site. Again in this Figure, the data points shown as red squares are from congested conditions at the site (time period 8:0 to 9:40 AM as shown in Figure 4) and excluded from further analysis. It can be seen that the measured flows are below the HCM predicted capacity based on breakdown density (equation 4) but several measured flows exceeded the HCM predicted capacity estimated based on weaving demand (equation 5).

These results indicate that the HCM methodology underestimates the capacity at weaving sections with high  $VR$  ratios, especially when the weaving volumes are higher than to 40% of the total volumes in the weave segment, particularly on weaving sections that require all weaving vehicles to execute a lane change, that is typical of ramp weaves.

The HCM methodology predicts the level of service (LOS) at the weaving section if the demand is less than the estimated capacity. The LOS is based on the weaving section density (Table 1). The density is determined from the traffic volumes and the average speed of vehicles calculated by explicitly considering the number of lane changes for both the weaving and non-weaving vehicles.

The total lane-changing rate for weaving vehicles is the sum of the minimum lane changes plus the optional lane changes for weaving vehicles that could occur in the weaving segment. The minimum lane changes depends on the number of weaving vehicles and the weaving section configuration, i.e., merging or diverging maneuvers that can be executed without a lane change. The optional lane changes are a function of the weaving section design characteristics (length, number of lanes and proximity to adjacent interchanges). The optional lane changes performed by non-weaving vehicles are made to avoid the turbulence created by the lane changing maneuvers of weaving vehicles, improve vehicle's speed/position and to facilitate movements of weaving vehicles (cooperation). These lane changes estimated depend on the demand flow rate of the non-weaving vehicles, weaving section length and proximity to adjacent interchanges.

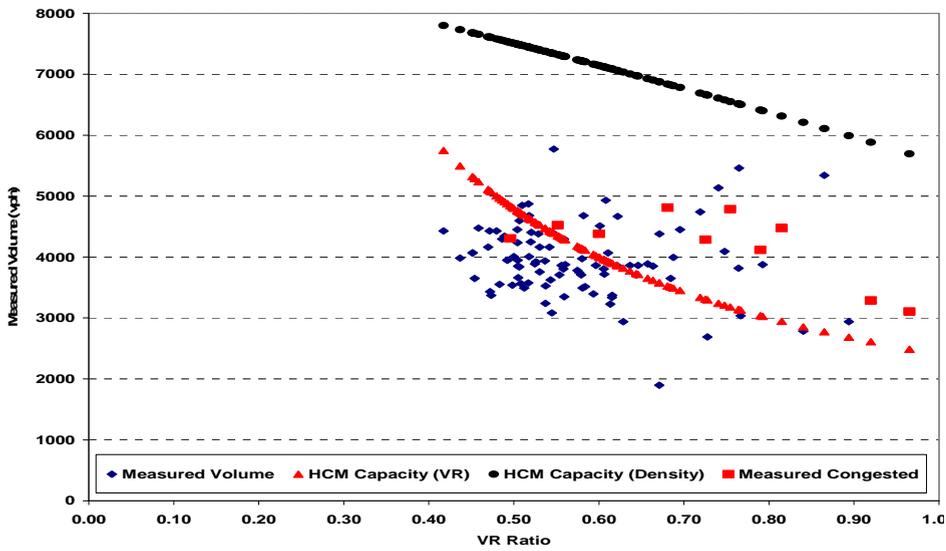


Figure 8: Measured Flows and HCM Predicted Capacities

The density of the weaving section is calculated by the flows and speeds of weaving and non-weaving vehicles. The speeds are calculated based on the number of lane changes, free-flow speed and demand volume.

The HCM methodology was applied at the test section for the time periods with traffic volumes below the HCM predicted capacity. Figure 9 shows the predicted and measured densities at the test weaving segment. On the average the HCM overestimated the density by 17%. The larger differences were observed on periods with the higher VR ratios.

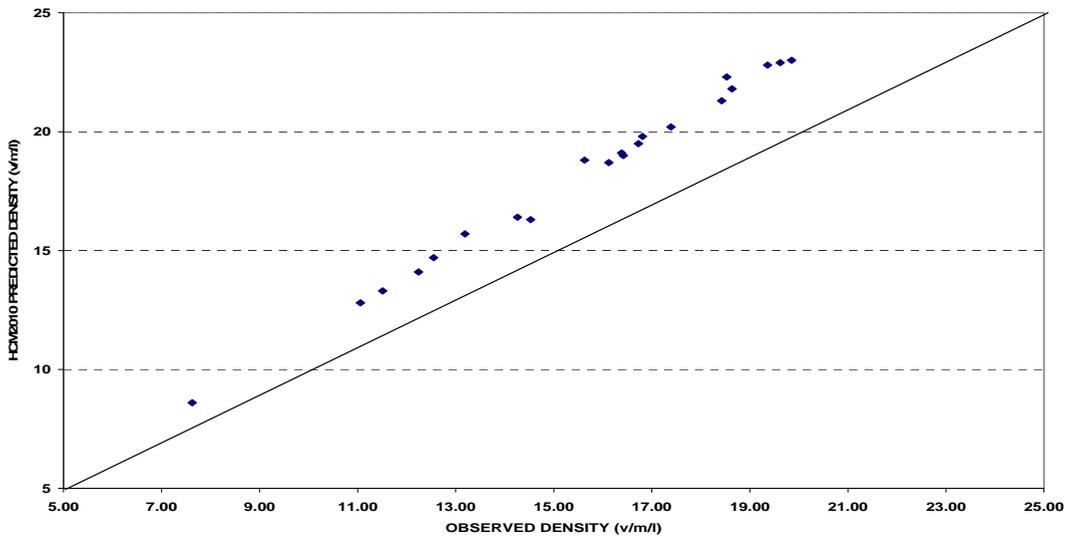
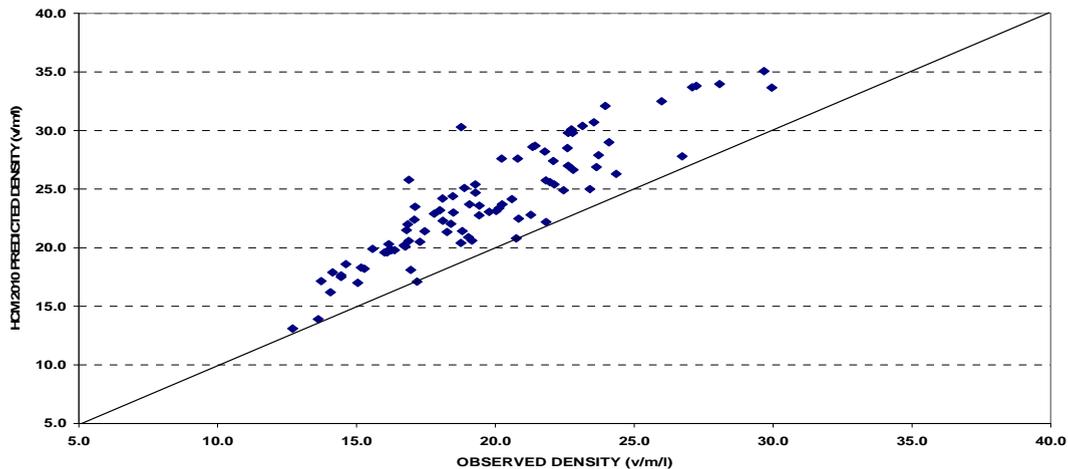


Figure 9: Measured vs. HCM2010 Predicted Densities --Metamorfosis Weaving Section

These findings are similar to the findings from a recent evaluation of HCM weaving methodology at a number of California sites with similar configuration as shown in Figure 10 (Skabardonis & Mauch, 2014). On the average, the HCM method overestimated the density by 23%, and underestimated the weaving section capacities in the case of weaving ratio VR larger than 40%. These differences can be explained due to the limited database for ramp weaves available for the development of the HCM weaving analysis methodology ((Roess & Ulerio, 2009).



**Figure 10: Measured vs. HCM2010 Predicted Densities—California Data (Skabardonis & Mauch, 2014)**

We also applied the Level D Method originally developed in California by to analyze weaving sections under heavy traffic conditions, i.e., LOS D or E (Moskowitz & Newman, 1962). The method provides the percentages of on-ramp and off-ramp traffic remaining in the auxiliary lane and the right-most through lane at 500 foot intervals through the weaving section, as well as the proportion of the freeway through traffic remaining in the outer through lane in the weaving section. These percentages are used to estimate the traffic volumes in the right most through lane and the auxiliary lane at 500 foot intervals. These values are then compared against the lane capacities in the weaving section to determine if the predicted demands would exceed the capacity. The results indicate that Level D predictions on flows (and derived densities) are closer to observed values than the HCM predictions.

## 5 Discussion

In the study we applied the HCM methodology to an off-ramp section and a weaving section of the Athens Attica Tollway. The key project findings are presented below:

- The HCM methodology predictions for lane flows in freeway diverging areas are in close agreement with field data. HCM does under predict the density values at the diverging sections by 7% on the average.
- The HCM methodology underestimated the capacity and overestimated the density at the Metamorfosis weaving section. Similar findings were found at other locations indicate that the HCM approach for the ramp weave configuration needs updating.

The work reported in this paper is part of an ongoing study to a) develop and apply analysis tools to assess the traffic operations on the Tollway and identify recurrent bottlenecks and other problems,

and b) propose and evaluate operational improvements at the Attica Tollway, as part of the proactive traffic operations and management approach of the Tollway operators. Emphasis is placed on:

- Application of HCM and deterministic techniques and simulation models to assess the Tollway performance for various performance measures, taking advantage of the comprehensive data from the extensive loop sensor network supplemented with data from emerging sources.
- Development and evaluation of operational improvements at the two study sites including capacity increases at the off-ramp's downstream intersection approach through adding lane(s) and modification of signal settings (Kifissias off ramp), changes on the freeway mainline including restriction of lane changes in the diverge area and implementation of lane assignment upstream of the off-ramp, metering of the upstream on-ramps to reduce the total demand, and speed control through variable speed limits.

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