Modeling Highway Capacity: Multiple Weaving Areas

Sheida Khademi (Primary author)
University of Texas at Arlington
Department of Civil Engineering
P.O. Box 19308, Arlington, TX 76019
e-mail:Sheida.khademi@mavs.uta.edu
Tel: (940) 783-6107

Behruz Paschai, Ph.D. (Co-advisor)
C&M Associate Inc.
Dallas, Texas 75248
e-mail: behruz.paschai@gmail.com

James C Williams, Ph.D. (Faculty advisor)
University of Texas at Arlington
Department of Civil Engineering
P.O. Box 19308, Arlington, TX 76019
e-mail: jimwilliams@uta.edu
Tel: (817) 946-6741

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ABSTRACT
The Highway Capacity Manual provides concise, well-defined procedures for estimating capacity and level of service for most types of roadways and intersections. While not perfect, these procedures allow for a quick comparison of roadway geometries when making design decisions. When detailed information is necessary, the analyst can use microscopic simulation, however there is a stiff cost to doing so. However, performing an operational analysis (e.g., VISSIM) is not always an option in projects due to the higher associated costs. This is mostly the case in smaller projects, in the initial phases of larger projects where there is limited budget available for providing preliminary results, or in projects with low traffic and simple/non-complex geometry. In these cases, having an HCM-based method for evaluating all possible freeway segments becomes rather important. Also, there is pressure to limit right-of-way needed for capacity improvement projects. This constraint could result in the use of multiple weaving areas.

The current Highway Capacity Manual (HCM 2016) provides procedures for three types of freeway segments: (1) basic segments away from ramps, (2) merge and diverge segments, and (3) weaving segments, which are formed when a merge is followed closely by a diverge, increasing the amount of lane changing as traffic lines up to for its desired destination.

If the influence of a single ramp is felt beyond the next ramp to a second ramp, we have a multiple weave. The configuration is either two ramp entrances followed by a ramp exit or a single ramp entrance followed by two ramp exits. We use the former in this work. The HCM recommends segregating the weaving movements into separate merge, diverge, and simple weaving segments, which ignores the interrelated behavior of the merging and diverging traffic.

In this work, we are using microscopic simulation (VISSIM) to find relations between macroscopic variables flow, density, and speed. Capacity is evaluated by gradually raising flows for a range of geometries and flow ratios. Models are developed to express capacity in terms of lane configuration, flow ratios, truck percentage, and overall flow rate. Also, the impact of distances between the ramps and the percent trucks will be measured.

We plan to provide a procedure to allow analysts to evaluate capacity in multiple weaves without having to resort to simulation.

INTRODUCTION
Systematic, well-designed research provides the most effective approach to the solution of problems such as these facing highway administrators and engineers. Traffic congestion on freeway systems is one significant concern in urban areas throughout the U.S.A. In this era, building new freeways to reduce congestion is less feasible due to the high capital and social costs. Thus, the effective management and operation of existing freeway facilities has become a preferred approach to reduce traffic congestion.

Weaving sections are often problematic because the increase in lane changing. These are common design elements on freeway facilities between an on ramp and off ramp with an auxiliary lane. They are located between merge and diverge points, near ramps where a lane is added or dropped, and at multilane ramps. A weaving section is a freeway segment in which traffic flows cross each other without traffic control [1-3].

Traffic demands exceeding segment capacity at weaving areas cause congestion, which affects the operation of the entire freeway section. Traffic operational problems often exist at weaving areas even when traffic demands are less than capacity, and may be experienced at lower traffic flows because of the complexity of vehicle interactions, that is, increased lane changing, resulting in a degradation in level of service (LOS) and potential safety problems [4-7].

A significant amount of research has been done to estimate quality of service and capacity in weaving sections. However, little has been done to address multiple weaves. This work examines capacity and quality of service conditions for a specific example of a multiple weave. Capacity is evaluated through micro-simulation (VISSIM) by gradually raising flows for a range of geometric and fraction of weaving-traffic conditions. Our simulation model is first calibrated, using a data set for a freeway weave section in Arlington, Texas. Models are developed to express capacity in terms of lane configuration, flow ratios, traffic mix (heavy traffic percentages), and overall flow rate.

METHODOLOGY

A weaving section is a common design on major highway facilities that always has been an interest to researchers. Weaving areas are characterized by frequent lane changes, which significantly reduce the capacity of the freeway system. The HCM defined weaving capacity as "any combination of flows that causes the density to reach the LOS E/F boundary condition of 43 pc/m/ln for freeways" based on configuration, number of lanes in the weaving section, free-flow speed, length of the weave, and volume ratio.

A multiple weaving area is one where two or more weaving areas overlap. No satisfactory means of estimating capacity have been found. Current procedures make assumptions about where weaving occurs in the individual weaving segments. A multiple weaving area is found when "a series of closely spaced merge and diverge areas create overlapping weaving movements (between different merge-diverge points)." (HCM 2016)

This study is limited to cases where there are two overlapping weaving movements created by two entry ramps following by a ramp exit. It develops relations for capacity for a range of geometric, flow conditions, and traffic mix. Geometric conditions include number of lanes on the main lane entry and each ramp entrance into and ramp exit from the weaving area (n), and distances between ramps (L_s). Flow conditions include a range of flows from each of the entry and exit roadways (v) in the multiple weaving area. The traffic mix represents the fraction of heavy vehicles in the traffic stream (P_{HV}).

Simulation is the key element for this research and the VISSIM model is calibrated to ensure that the model behaves in the same way as the observed traffic. Calibrated values are used for simulation.

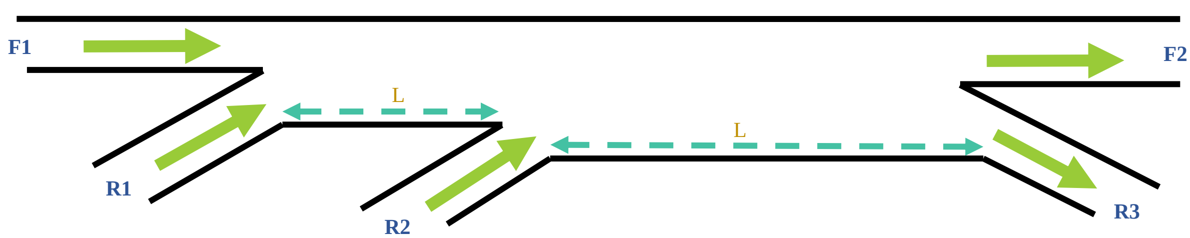

Figure 1: Multiple Weaving Area Elements

Simulation runs investigate the correlation between capacity of the weaving section and affected factors or mix of selected factors in the multiple weaving area. Regression model for estimating capacity is developed. Simulations are performed under varying variables. Where dependent variable is the weaving capacity, and potential independent variables and their ranges include:

- L_{S1}: Gore to gore distances for R1 to R2 (R1-R2), 1,000ft to1,500ft
- L_{S2}: Gore to gore distances for R2 to R3 (R2-R3), 1,500ft to 2,000ft
- VF1: Flow for freeway entrance, 1,000vph to 3,000vph
- VR1: Flow for first ramp entrance, 500vph to 1,500vph
- VR2: Flow for second ramp entrance, 500vph to 1,500vph
- HVF1: Heavy vehicle percentage for freeway entrance, 5% to 10%
- HVR1: Heavy vehicle percentage for first ramp entrance, 5% to 10%
- HVR2: Heavy vehicle percentage for second ramp entrance, 5% to 10%
- RDF1-F2: Weaving share for drivers entering F1 and exiting at F2, 70% to 90%
- RDR1-F2: Weaving share for drivers entering R1 and exiting at F2, 70% to 90%
- RDR2-F2: Weaving share for drivers entering R2 and exiting at F2, 70% to 90%
- F1: Number of lanes for freeway entrance, 2 to 4 lanes
- R1: Number of lanes for first ramp entrance, 1 or 2 lanes
- R2: Number of lanes for second ramp entrance, 1 or 2 lanes
- F2: Number of lanes for freeway exit

- R3: Number of lanes for ramp exit

Capacity is determined to be the point where the flow (VISSIM result) started to exceed the demand (vehicle input) as the variables change gradually.

A VBA code is developed to make changing variables more automatically and save a significant amount of time. More than 76,000 scenarios are simulated to compare capacity for multiple weave section under different conditions.

SIMULATIONS and RESULTS

For the following condition (Table 1), capacity is checked on links R1-R2 and R2-R3, the two main-lane links between the ramps. Here, the demands are the volumes that were specified in the VISSIM input, while the flows are the volumes that can pass the end of the subject link. Capacity is assumed to be reached when the flows drop below the demand for the links as the demand increases. Estimating capacity using density is covered in the next section.

Table 1: Number of lanes and gore to gore distance for sample condition

LS1	LS2	F1	R1	R2	R3	F2
1,000	1,500	2	1	1	2	2

1. CAPACITY ESTIMATION USING LINK FLOWS

1.1 R1-R2 Link

The demand for link R1-R2 is (VF1+VR1), and the demand for link R2-R3 is (VF1+VR1+VR2). In this section, VF1 ranges between 1,000 and 3,000 vph, and VR1 and VR2 range from 500 to 1,500 vph. Given the lane geometry specified in Table 1, the main-lane entry link and the two-ramp links stay below their capacities. In Figure 2, VF1 is only allowed to go up to 2,000 vph. The Figures were created through the pivot point analysis available in Excel.

The y-axis in Figure 2 is the sum VF1+VR1; so, for a volume of 1,500 vph, this is a VF1 of 1,000 vph and a VR1 of 500 vph. The highest volume is demand of 3000 vph, and is the condition of VF1 of 2,000 vph and VR1 of 1,000 vph.

For each volume level on the y-axis, there are 16 points, representing each run with the values for HVF1, HVR1, RDF1_F2, and RDR1_F2. The weaving shares are 70% or 90% of F1 traffic leaves the network by F2; similarly, for R1. Given that there are 2 options in each of these variables, there are 24 or 16 combinations of these variables for each value of the sum of VR1 and VF1. Using the Excel format, the values of these variables are shown in the line of boxes above the graph. The values that were used in the runs are highlighted in blue. The demands are shown in orange and the flows are shown in blue.

As shown in Figure 2, capacity was not reached for any of the combinations of VR1+VF1.

The higher demands for VF1 (3,000 vph) and VR1 (1,500 vph) are added in in Figure 3. There are still 16 points shown for each volume level, except 2,500 vph and 3,500 vph. In these two cases there are two combinations of (VF1+VR1) that yield these to flows (1,000 vph+1,500 vph and 2,000 vph+500 vph; and 2,000 vph +1,500 vph and 3,000 vph +500 vph) and there are 32 points. By and large, the orange and blue points coincide, meaning that the demands are still below capacity. However, for the combined demand of 3500 vph, the flow is slightly less than the demand for half the points, which represent the demand case of VR1 being 1,500 vph. A similar condition is observed for the combined demand of 4,000 vph, in this case VF1 is 3,000 vph. In both of these, the demand is approaching link capacity.

The interesting point is when the combined demand is 4,500 vph (VF1 is 3,000 vph and VR1 is 1,500 vph). The flows are below the demands in all 16 cases, but the weaving shares have a much greater impact than the truck percentages. The case of VF1 is 3,000 vph and VR1 is 1,500 vph is highlighted in Figure 4. The four cases with the largest difference between demand and flow are when the weaving share is 90% for both streams (90% of traffic from each entry leaves the network via F2), for both heavy vehicle values. The next two largest differences between demand and flow are the case where the weaving share for R1 traffic is 70% of traffic from R1 leaves the network via F2, while 90% of traffic entering by F1 leave by F2. The first two of each set of four represents the result for the two valued of the heavy vehicle factors.

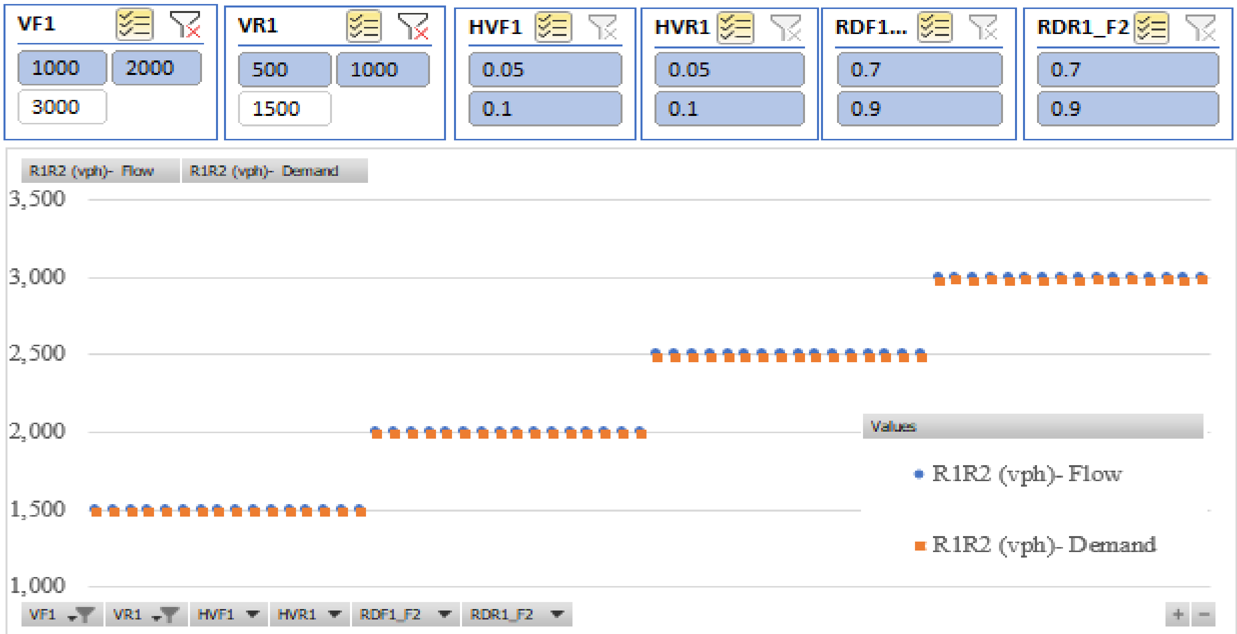

Figure 2: Demand Vs. flow for R1-R2 segment, excluding VR1=3,000 vph and VR1=1,500 vph

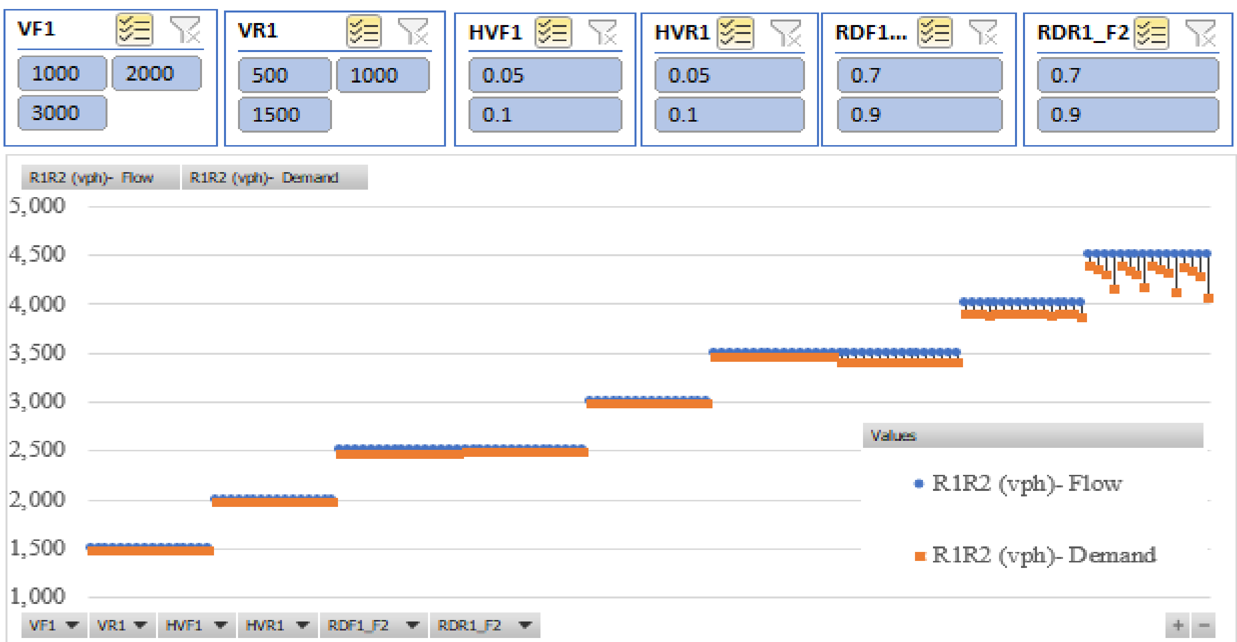

Figure 3:Demand Vs. flow for R1-R2 segment, all possible variable combinations

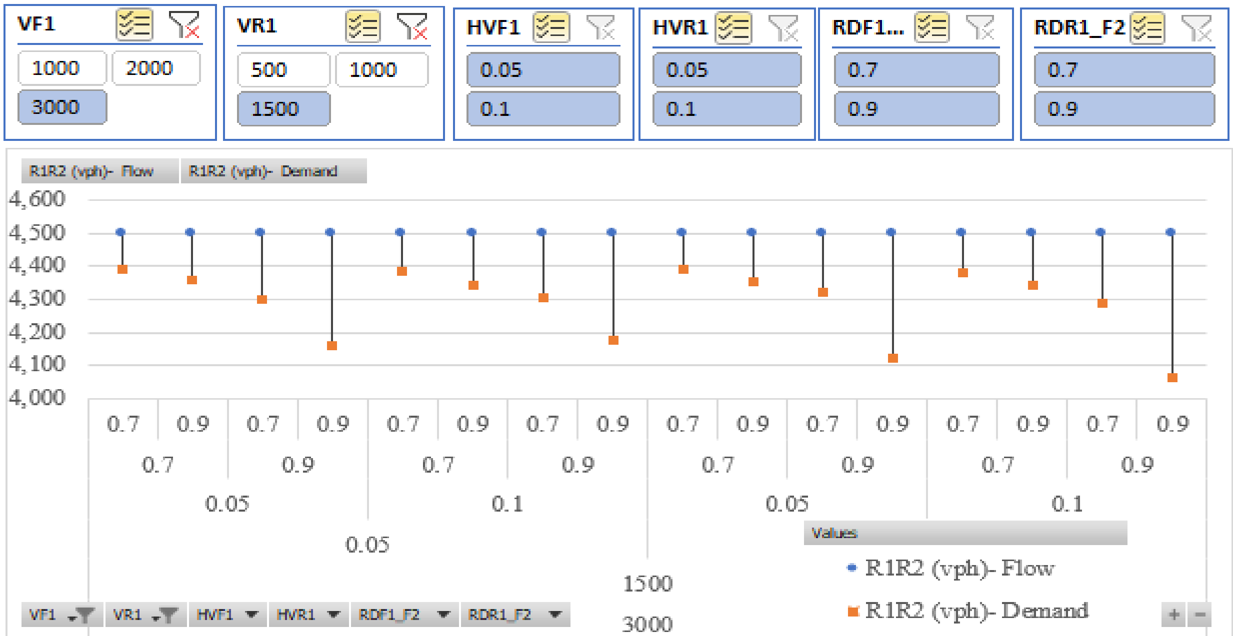

Figure 4: Demand Vs. flow for R1-R2 segment, VF1=3,000 vph and VR1=1,500 vph

1.2 R2-R3 Link

The input volumes to this link come from link R1-R2 and R2 (second ramp entrance). The range of simulation output is shown in Figure 5. The output is neatly ranked in groups of 3. The first group of 3 lines is for VR1-R2 of 1,500 vph and VR2 ranging from 500 vph to 1,000 vph to 1,500 vph. The second group is for VR1-R2 of 2,000 vph and the same range of VR2. Each short line segment has 64 points (26, as there are 6 variables with 2 possible values each).

Of course, VR1-R2 can have a value of 2,000 vph two different ways (1,000 vph/1,000 vph and 1,500 vph/500 vph), and there are two short segments at VR1-R2 of 2,000 vph and VR2 of 500 vph, each representing 64 points, for a total of 128 points. The line segments where there is a small difference between the demand and the flow (and the blue points peek out from the orange points). These points are the cases where one (or more) of the entry flows are close to capacity for that link (3,000 vph for the two-lane freeway main-lane entry (F1) and 1,500 vph for one of the two entry ramps (R1 and R2).

From Figure 5, one can see three conditions where demand exceeds capacity; VR1-R2 is 4,000 vph and VR2 is1,500 vph (Figure 7b), VR1-R2 is 4,500 vph and VR2 is 1,000 vph (Figure 7a), and VR1-R2 is 4,500 vph and VR2 is 1,500 vph (Figure 7c). In Figure 7 b, the most severe reduction in capacity is when 90% of the vehicles entering at R2 that leave the network at F2 is 90%. These maximums occur for 90% vehicles leaving by F2 from both F1 and R1.

In Figure 7a, there is a similar pattern in that the cases with the largest difference between the demands and flows are those where 90% the traffic that enters by any of the three entry points must leave the network by F2. However, the cases where R1 is only 70% and where R1 and R2 are both 70% are also similarly large.

In Figure 7c, the volume case with the highest flows, the cases where 90% percent of all traffic must leave the network by F2, regardless of their network entry location, are still the situation that experience the largest reduction in capacity. However, many of the other combinations (including fraction of heavy vehicles) also produce sizeable reductions in capacity.

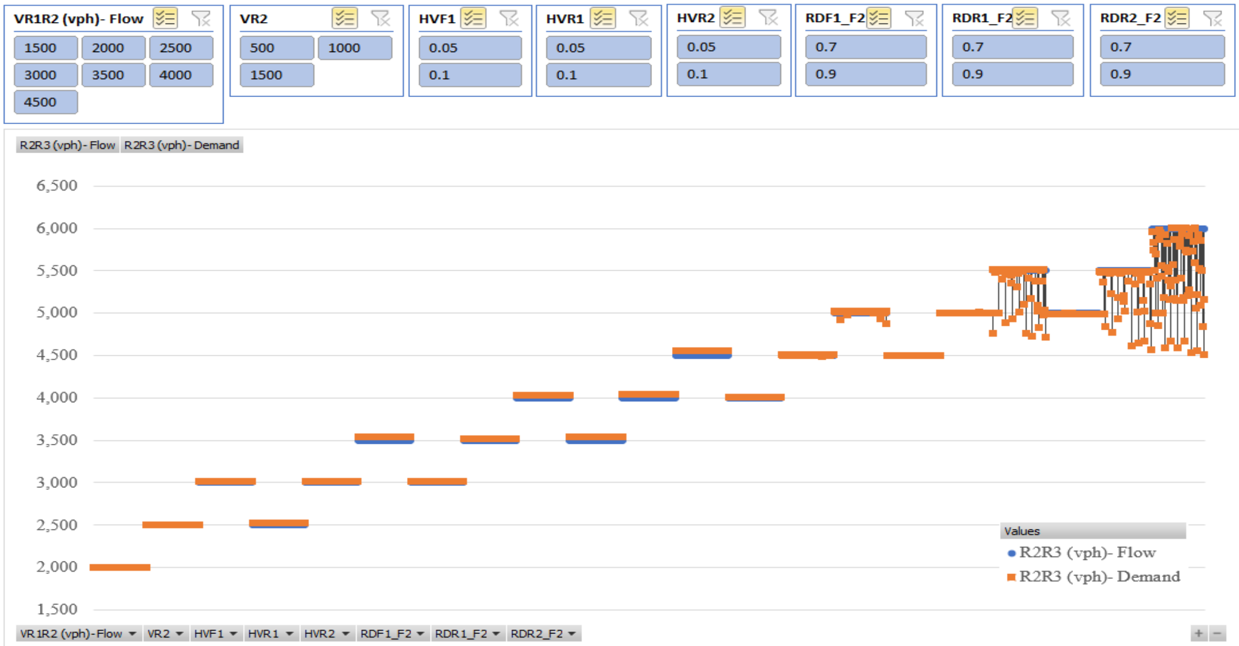

Figure 5: Demand Vs. flow for R2-R3 segment, all possible variable combinations

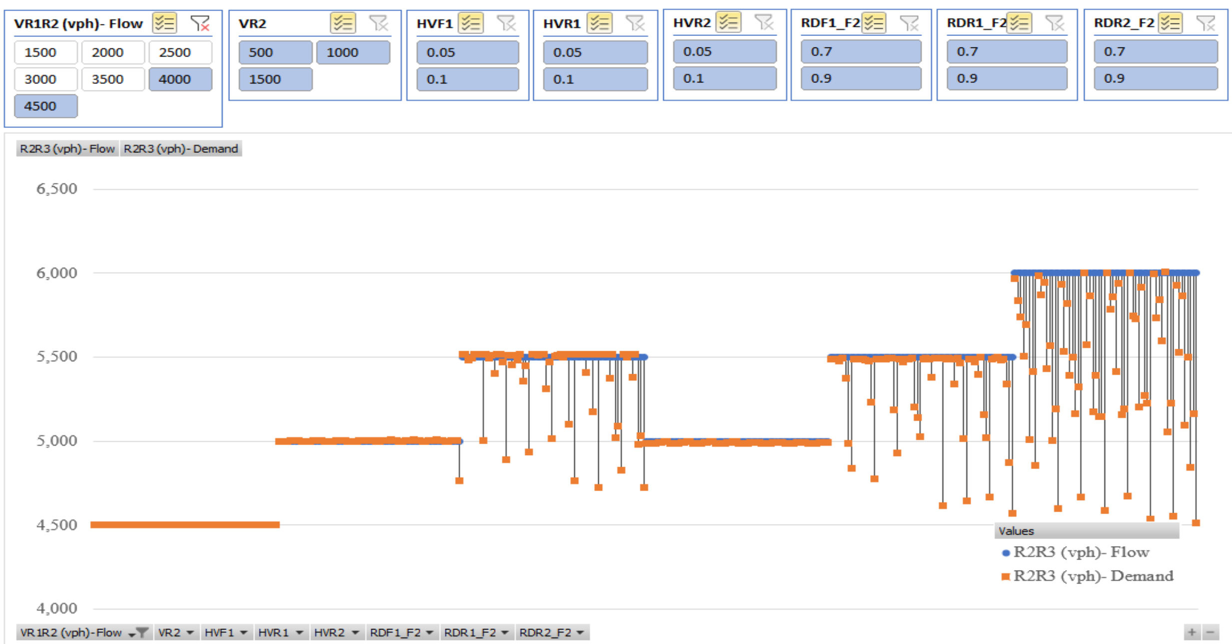

Figure 6: Demand Vs. flow for R2-R3 segment, VR1R2= 4,000/4,500 vph

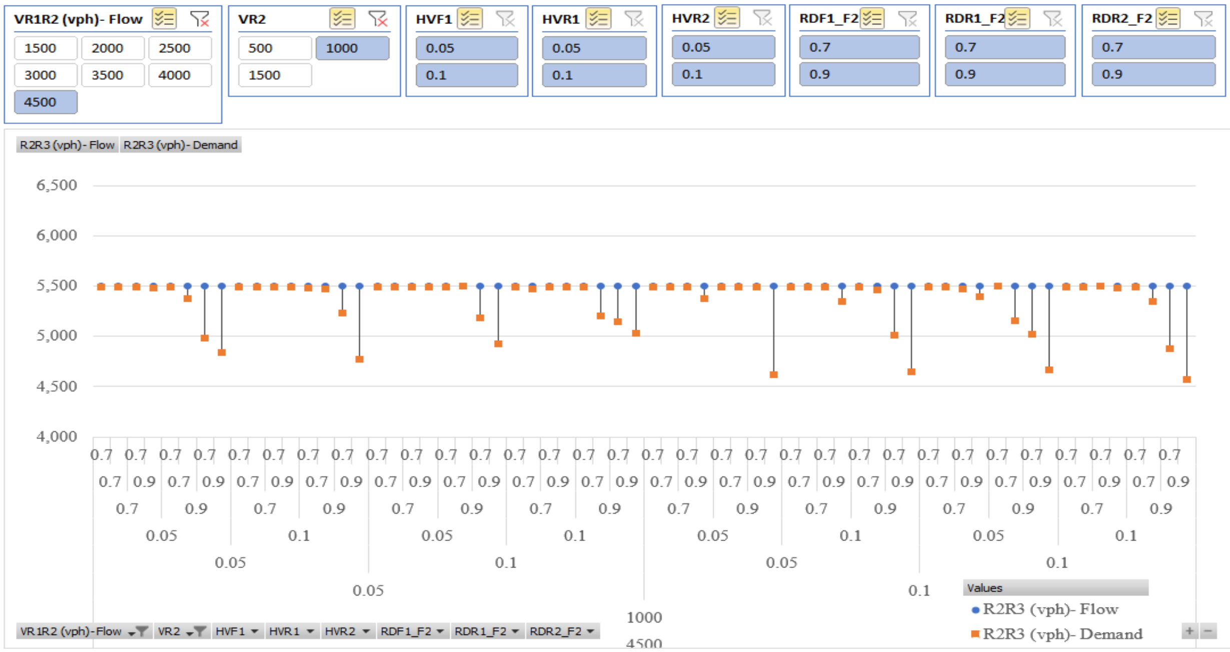

Figure 7-a: Demand Vs. flow for R2-R3 segment, VR1R2= 4,500 vph and VR2= 1,000 vph

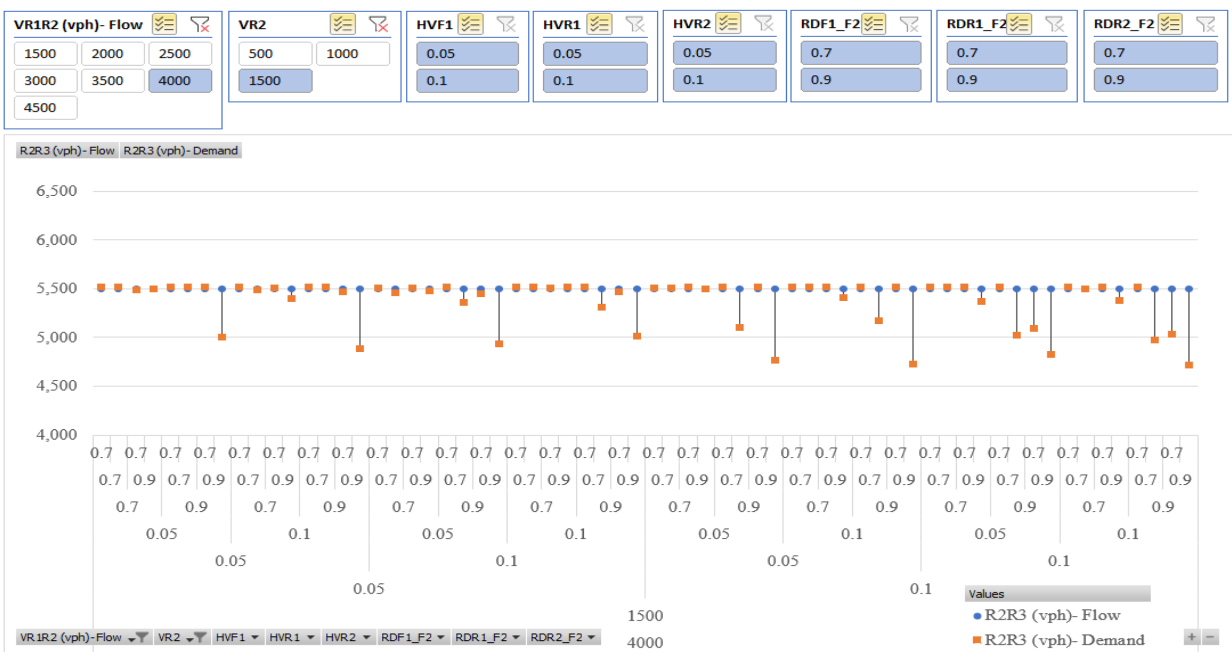

Figure7-b: Demand Vs. flow for R2-R3 segment, VR1R2= 4,000 vph and VR2=1,500 vph

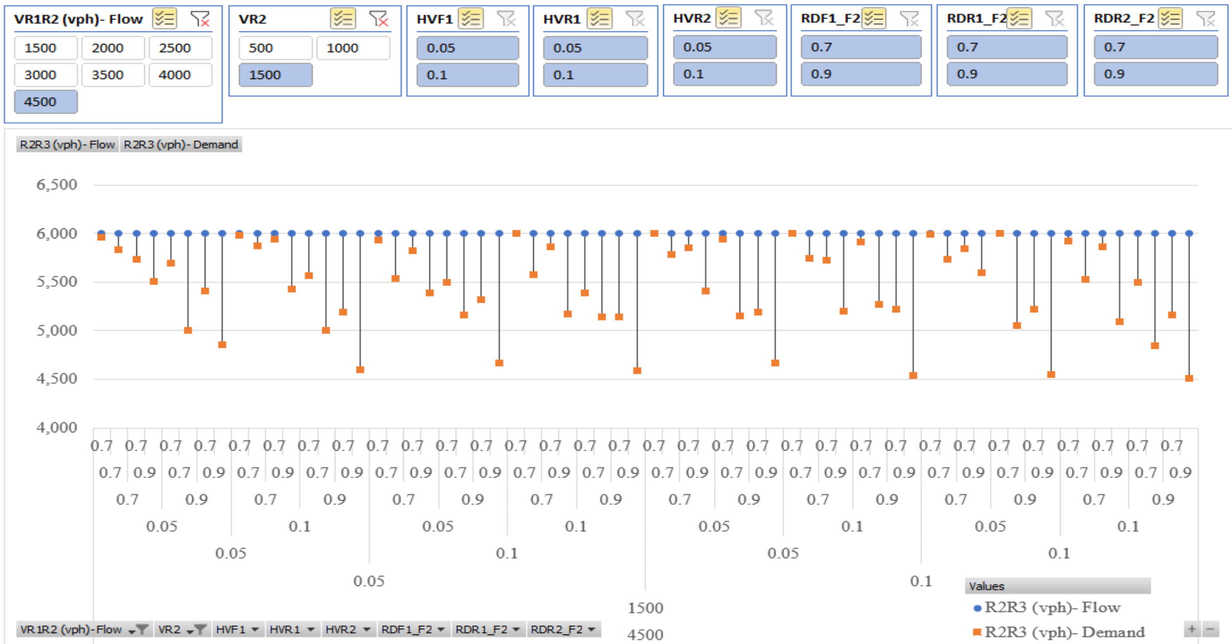

Figure 7-c: Demand Vs. flow for R2-R3 segment, VR1R2= 4,500 vph and VR2=1,500 vph

2. CAPACITY by DENSITY

Density is used to define capacity in the HCM 2016. In this section we compare the density from the VISSIM runs to the density that defines capacity. The density at capacity is 43 pc/lane/mile. VISSIM calculates density by averaging the number of vehicles on a link during the simulation time. VISSIM reports this information as the average number of vehicles on the link, we then calculate the density by dividing the number reported by VISSIM by the length of the link and dividing by the number of lanes on the link, resulting in the density in veh/lane/mile, this is further corrected for the percentage trucks by multiplying the density (in veh/lane/mile) by the f_{HV} factor, adjusted for the percentage of trucks in the traffic stream.

Density values for links R1-R2 and R2-R3 are shown in Figure 8, the density at capacity (43 pc/hr/lane) is the grey line across the Figure. Densities for link R1-R2 are shown as blue dots, and orange dots are used for link R2-R3. The only conditions which result in capacity are towards the right in the Figure. The volume combinations omitting 1,000 vph for VF1, and 500 vph for VR1 and VR2 are shown in Figure 9.

The bulk of the capacity runs are those with 2,000 or 3,000 vph from VF1, and 1,000 and 1,500 vph from the two ramp entrances. Virtually all of the capacity runs occurred when 90% of the vehicles entering from the freeway main-lanes or from one of the ramps. Similarly, capacity conditions occur when the 10% of the entering flows are heavy vehicles. Both conditions are expected, since the truck percentages increase the flows (converting veh/hour to pc/hour) and the higher percentage of traffic leaving the network on F2 induces more weaving from the ramp entrance traffic, since that traffic must weave to the left.

Density is used to define levels of service in the weaving chapter of the Highway Capacity Manual (HCM). The objective of this section is to present the density associated with the simulation runs summarized above and to compare these values with the values in the HCM.

Illustrating in Figures 8 and 9, density neither for R1R2 nor for R2R3 segments exceed the 43 pc/h/lane (HCM density cap) if:

a) F1 flow is less than 3,000 vph or 1,500 vph/lane.
b) R1 and R2 flows are less than 1,500 vph.
c) Weaving share for one of the routes heading to F2 is less than 0.9.

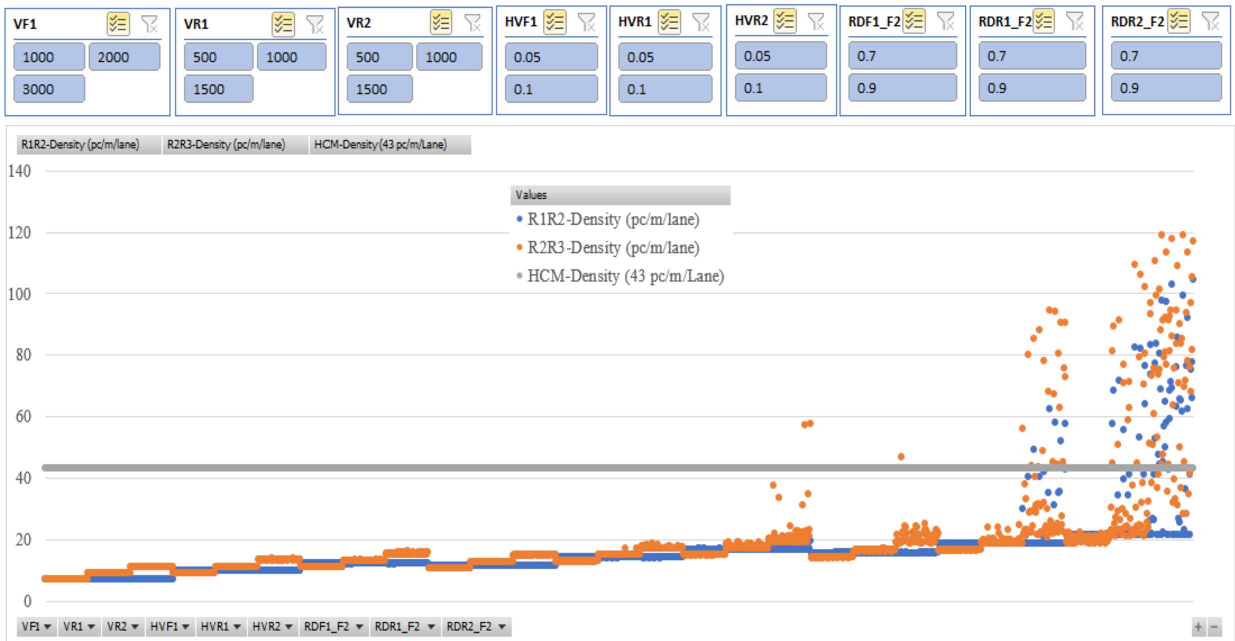

Figure 8: Density presentation for R1-R2 segment

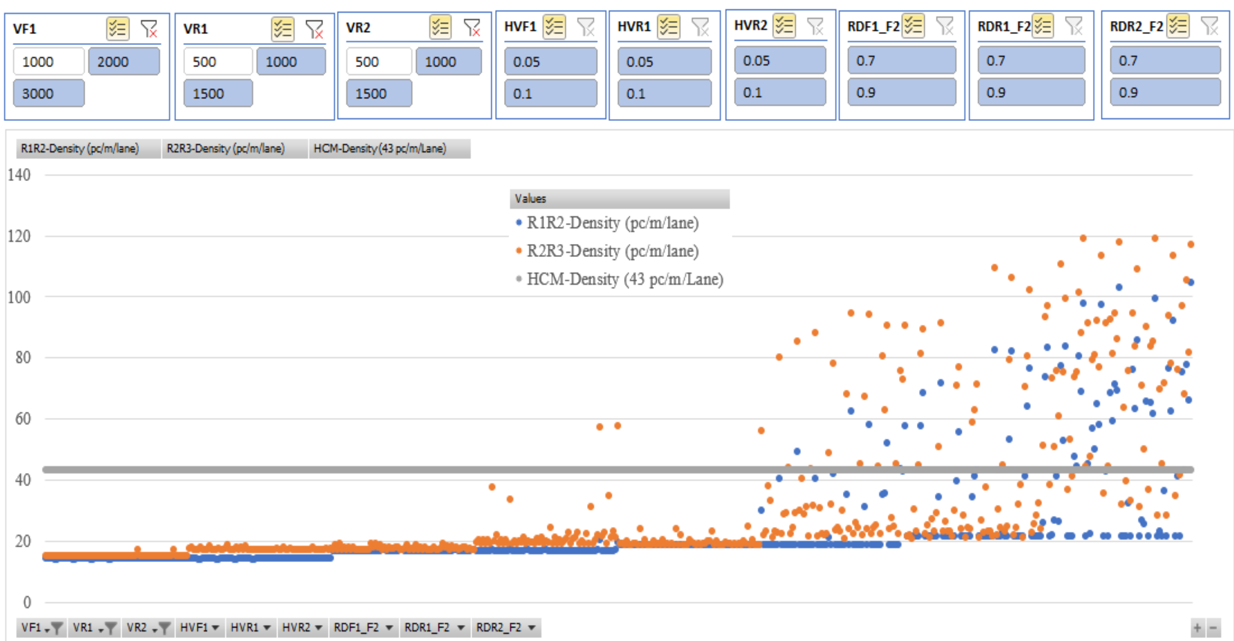

Figure 9: Density presentation for R1-R2 segment

3. REGRESSION ANALYSIS

A stepwise regression model is developed using the data presented in section 2. Density is the dependent variable in the developed model and the independent variables are flow for each entrance leg, Weaving share for each route, and heavy vehicle percentages for each entry legs.

Stepwise regression first selects the independent variable that has the highest correlation with the dependent variable, then checks the significance of the model. This process is followed for each independent variable. At each step, an additional variable is considered, if it fails to improve the model by a preset level, the variable is not added to the model. Also, at each step, variables in the model are checked to see if they still provide a significant improvement to the model. A once important variable may be dropped if other variables are correlated with the dropped variable but, in combination, improve the model to a greater extent. Once each independent variable is tested, the procedure stops. The confidence interval for the regression analysis was 95%.

3.1 R1-R2 Analysis

Applying stepwise regression, using simulated results, VF1 has the most significant effect on density. Higher density will result congestion.

$$\textit{Capacity (based on density)} = (0.525\times VF1) + (0.367\times VR1) + (0.142\times VR2) + (0.116\times RDF1\_F2) + (0.077\times RDR1\_F2) + (0.075\times RDR2\_F2)$$

3.2 R2-R3 Analysis

For the R2-R3 segment, VF1, VR2, VR1, RDR2_F2, RDF1_F2, RDR1_F2 have the most significant impact on capacity, respectively.

$$\textit{Capacity (based on density)} = (0.460\times VF1) + (0.321\times VR2) + (0.320\times VR1) + (0.103\times RDR2\_F2) + (0.099\times RDF1\_F2) + (0.069\times RDR1\_F2)$$

CONCLUSIONS

This paper is developed to predict capacity for feasible ranges of flow, fractions of heavy vehicles, and weaving share combinations within the multiple weaving area.

- ✓ For the geometry of freeway entrance has two lanes, ramp entrances have one lane each, ramp exit has two lanes, and first gore to gore is 1,000ft, while second one is 1,500ft, results show that to prevent congestion:
  - Freeway entrance (F1) flow should always be less than 3,000 vph, even when the entering ramp flows are small.
  - R1 and R2 ramps capacity should each be less than 1,500 vph if F1demand exceeds 2,000 vph.
  - Entrance legs should have the heavy vehicle percentage of less than 10%.
  - If the weaving share for any one of the three routes heading to F2 is 90% there is congestion on the R2-R3 link.
- ✓ Also, more simulations performed for different geometric conditions and results analyzed the same way. Outcomes show that for each segment the most effective factors are: (Table 2)
  - For R1R2 segment: (1) VF1 > (2) VR1 > (3) RDR1-F2 & RDF1_F2 > (4) VR2 > (5) RDR2_F2
  - For R2R3 segment: (1) VF1 > (2) VR2 > (3) RDF1-F2 > (4) VR1 > (5) RDR1_F2 > (6) RDR2_F2

Table 2: Most effective factors

LS1	LS2	F1	R1	R2	R3	F2	Most effective factors, R1R2 segment	Most effective factors, R2R3 segment
1,000	1,500	2	1	1	1	2	VF1	VR2 & VF1
1,000	1,500	2	2	1	2	2	VF1 & RDR1_F2	VF1 & VR2 & RDR1_F2
1,000	1,500	2	1	2	2	2	VF1	VF1 & VR2 & RDF1_F2 & RDR1_F2
1,000	2,000	2	1	1	2	2	VF1	VF1 & VR2
1,000	2,000	2	1	1	1	2	VF1	VR2 & VF1
1,000	2,000	2	2	1	2	2	VF1	VF1 & VR2
1,000	2,000	3	1	1	1	3	VF1 & VR2 & VR1 & RDF1_F2 & RDR1_F2	VF1 & VR2
1,000	2,000	2	1	2	2	2	VF1	VF1 & VR2 & RDF1_F2
1,500	1,500	2	1	1	2	2	VF1	VF1 & VR2 & RDR1_F2
1,500	1,500	2	1	1	1	2	VF1	VF1 & VR2
1,500	1,500	2	2	1	2	2	VF1	VF1 & RDF1_F2 & RDR2_F2
1,500	1,500	3	1	1	1	3	VF1 & RDF1_F2 & RDR2_F2	VF1 & VR2 & VR1
1,500	1,500	2	1	2	2	2	VF1	VF1 & RDF1_F2 & VR2 & RDR1_F2
1,500	2,000	2	1	1	2	2	VF1 & RDF1_F2 & VR1 & RDR1_F2	VF1 & RDF1_F2 & VR2 & RDR1_F2
1,500	2,000	2	1	1	1	2	VF1	VR2 & VF1
1,500	2,000	2	2	1	2	2	VF1 & VR1 & VR2 & RDR1_F2	VF1 & VR2 & RDR1_F2
1,500	2,000	3	1	1	1	3	VF1 & VR1 & VR2 & RDF1_F2 & RDR1_F2	VF1 & VR2 & VR1
1,500	2,000	2	1	2	2	2	VF1	VF1 & VR2 & RDF1_F2 & RDR1_F2

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