

## **Chapter 2: Literature Review**

### **2.1 Introduction**

In this chapter, the literature behind weaving analysis is discussed. Since the scope of this research is to provide a comparative analysis between HCM and CORSIM for weaving highway sections, various factors such as speed, capacity of the freeway etc. affecting weaving operation is also outlined. Past and current research on these factors are also discussed. The various analytical models, which led to the development of the current version of the simulation model, are also discussed. This chapter also talks about the advantages and disadvantages of using a computer model versus an analytical model. Finally this chapter concludes with a discussion on different computer models available in the market and their advantages and disadvantages.

### **2.2 Past Research Related to Freeway Weaving/Capacity Analysis**

The methodology adopted in the comparative analysis is to model a particular weaving scenario using both HCM and CORSIM. To adjust the simulation model, various factors such as capacity of the weaving section, speed, driver characteristics etc needs to be studied. As the scope of my research is to identify various parameters which affect the result of simulation and methods to improve them, the next few paragraphs talk about some earlier research done on some of the various parameters which might affect the calibration of the model and their resulting conclusions.

A study on capacity and level of service at ramp freeway junctions by Roger P. Roess and Jose M. Ulerio [31] found that the results of FRESIM is different from the results of 85 HCM in predicting operational conditions in ramp junctions. Moreover the study pointed out that if some parameters such as volume distribution, speed variance can be improved, its use could augment field data and allow more consistent and thorough calibration of regression/simulation models

The importance of the driver population to the freeway traffic operation analysis should not be neglected. In analyzing freeway capacity, one of the most important factors is speed because service flow rate can be obtained from the value of density multiplied by the value of average speed [24]. Most traditional weaving analysis methods use roadway geometry and traffic volumes as inputs and provide an estimate of speed as an output. The use of speed for assessing the capacity and level of service for weaving has proved to be a poor choice. One reason is that speed is not very sensitive to flow at saturation level. Recent studies conducted by Halati et al [19] has shown that the concept of a stable relationship between speed and flow is fundamentally flawed. As flow nears capacity, it begins a series of fast and unstable jumps from the smooth flow to an unstable one. With this approach, traffic only flows at capacity speed while transitioning from fast sub capacity flow to a slow congested flow. In effect, capacity speed is ephemeral and can be quantified in averages.

Since speed has been identified as one of the important factors that might affect the calibration of the model, the variance of speed in the output results needs to be studied. The next few paragraphs talk about the impact of speed limit on a freeway.

A study conducted by Jack D. Jernigan and Cheryl W. Lynn [26] on impact of speed limit on freeway showed that the speed limit has influence on average speed, percentile speed and speed variation. According to their study for Virginia's rural interstate highway, they indicated that the average speed of Virginia's rural interstate was 56.3 mph when the speed limit was 55 mph and the percentile speed was 62mph. One

year after the speed limit was increased to 65mph the average speed was 63.5mph and the percentile speed was 70mph. In another study, Harkey, David L., Robertson, Douglas, and Davis, Scott E.[20], found that an increase of 4mph occurred in percentile speed of the passenger vehicles along the rural interstate highways in Illinois after the change of the 65mph speed limit from 55 mph speed limit.

Nicholas J. Garber and Ravi Gadigaru [15] conducted a study on factors affecting speed variance. They found that the difference between the design speed and the posted speed limit had a statistically significant effect on speed variance. Furthermore they found that drivers tend to drive at increasing speeds as the roadway geometrics improved, regardless of the posted speed limits.

A simulation (FRESIM) study conducted by Zoltan A. Nemeth and Ajay K. Rathi [34] on potential impact of speed reduction at the freeway lane closures indicated that compliance with reduced speed limits will have no significant impact on the declarations but will reduce variance in speed distributions.

Another study was conducted by Adolph D. May., [30] to determine the congestion causes in weaving areas. One of the important observations that came out from this research was that vehicles tend to reduce speed in weaving areas depending upon the merging characteristics of the driver, number of lanes and volume distribution. These observations were made were based on several factors such as interrelationships between volume, occupancy and speed, the measurement of the effect of congestion on traffic flow and travel time and a comparison of traffic characteristics just before and after congestion

Essam Radwan and Sylvester A. F. Kalevela [10] conducted an investigation of the effect of change in vehicular characteristics on the highway capacity. The results from analyzing traffic flow models and time headway's showed that despite the change in vehicular characteristics there has not been a discernible corresponding change in highway parameters. This research clearly shows that by altering various vehicular parameters, there has been no influence on highway parameters.

### **2.3 Traffic Stream Models:**

The traditional HCM model follows a macroscopic analytical approach. The literature behind the development of the macroscopic analytical model used in HCM is outlined in the section below. As we all know computer simulation follows a microscopic approach, the section on microscopic model gives a brief history on various developments that led to the current model.

#### **2.3.1 Analytical Models:**

Analytical process of building a model starts from the understanding of the flow characteristics and the selection of appropriate equations, with suitable assumptions to simplify the model by forcing all the control variables at the same time which influence the traffic flow system.

Applying dimensional analysis to any two successive vehicles in traffic flow, we have the following relationship between density of flow, vehicle speed and the volume:

$$\text{Velocity (mph) (u)} = \text{flow (vph) (q)}/\text{density (veh/mil/lane) (k)}$$

##### **2.3.1.1 Macroscopic Models:**

A Linear Density relationship is given by

$$u = u_f - \left( \frac{u_f}{k_j} \right) k$$

where

$u$  = Velocity at any time

$u_f$  = Freeflow Speed

$k$  = Density at that instant

$k_j$  = Maximum density

Substituting  $u$  from the general equation of a traffic stream ,

$$\frac{q}{k} = u_f - \left( \frac{u_f}{k_j} \right) k$$

Interchanging the relationships between the variables velocity, flow and density by successive elimination of one of these variables, we find that as the flow increases, density increases and the speed decreases. At optimum density, flow becomes maximum. In other words, as the speed increases from zero, flow increases from zero, until it becomes  $q_m$  (maximum density) at  $u = u_f/2$  and  $k = k_j/2$ .

Hence

$$q_m = \frac{u_f k_j}{4}$$

Highway capacity manual and all traditional codes use this set of equations [22]. However practical field data does not follow this relationship accurately. Hence a number of theoretical models have cropped up over the past six decades . Earlier models assumed a single regime that would include a gamut of flow conditions

### **Greenshields Model**

According to Greenshields [31] , speed is a linear function of density

Thus,

$$u = u_f - \left( \frac{u_f}{k_j} \right) k$$

$$q = u_f k - \left( \frac{u_f}{k_j} \right) k^2$$

### Greensberg Model

This is a non-linear model where a hydrodynamic analogy is combined with equations of motion in mechanics . The velocity is governed by

$$u = u_0 \ln \left( \frac{k_j}{k} \right)$$

where

$u$  = speed at any time

$u_0$  = optimum speed

### Underwood's Model

This was a new single regime model proposed to account for the problem of free-flow reaching infinity value during free flow conditions in the above model. According to this theory [31],

$$u = u_f e^{-\left( \frac{k}{k_0} \right)}$$

where

$u$  = speed at any time

$k_0$  = optimum density

$k$  = Density at any time

$u_f$  = Free flow speed

### Drew's Model

Drew proposed a formulation which modified Greensfields model [31] by introducing a parameter called 'n'.

$$u = u_f \left[ 1 - \left( \frac{k}{k_j} \right)^{n + \frac{1}{2}} \right]$$

where,

$n = 1$  ~ Linear Model

$n = 2$  ~ Parabolic Model

$n = 3$  ~ Exponential Model

Since the above described models seemed to be lacking in dynamic filed data , research progressed into different models with different equations of free-flow, congested flow and transitional conditions. .

#### 2.3.1.2 Microscopic Models

“Microscopic modeling” is concerned with individual time and space headway between vehicles while “macroscopic modeling” is concerned with macroscopic flow characteristics, which are expressed as flow rates, where attention is given to temporal, spatial and modal flows” (Adolph May, 1990). Microscopic analysis may be selected for moderate sized systems where there is a need to study the behavior of individual units in the system. Macroscopic analysis may be selected for higher density, large-scale systems,

in which a study of behavior of groups of units is adequate. Knowledge of traffic situations and the ability to select the more appropriate modeling technique among the above two is required for the case. For a weaving analysis, a microscopic analysis approach is considered to be a better choice over macroscopic approach, as this model depicts the traffic flow patterns like acceleration/deceleration, merging etc. for each individual vehicle within a stream more vividly than a macroscopic model.

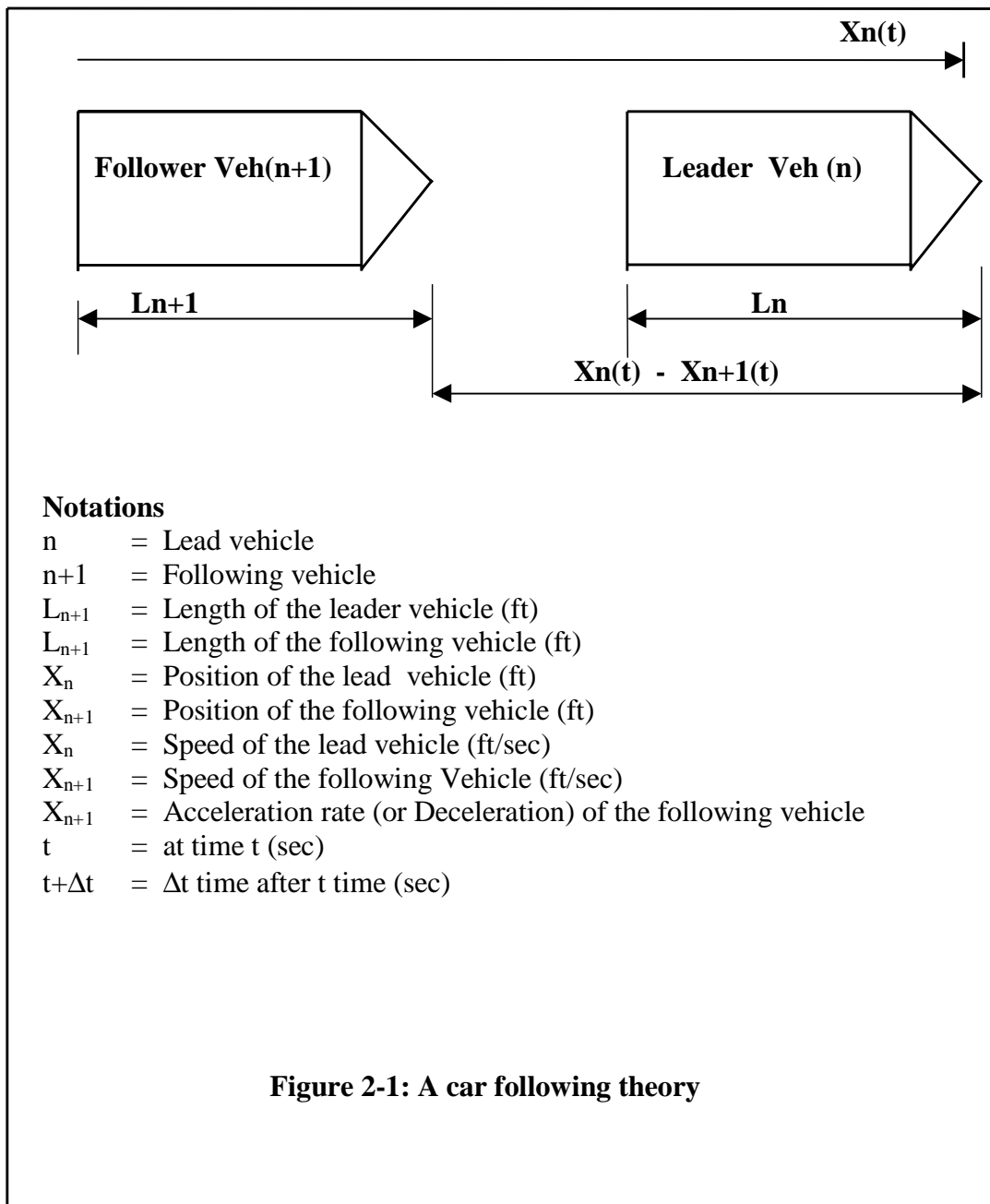
Consider two vehicles moving from left to right in the diagram. Let these be denoted by 'n' and 'n+1' respectively. Figure shows two vehicles moving at the same time and the distance between them at any time 't'. All assumptions made about the vehicle composition and behavior are valid

Researchers at General Motors have developed car following models and tested them using real world data. There were a series of car following theories proposed by professor Adolph May, 1990 in publication " traffic flow theory". The basic form of these was

$$Response = f\{sensitivity, Stimuli\}$$

where

- |             |  |
|-------------|--|
| Response    | = Acceleration or Deceleration of the vehicle which is dependent on the sensitivity of the automobile and the driver himself |
| Sensitivity | = Ability of the driver to perceive and react to the stimuli   |
| Stimuli     | = Visual and auditory inputs that influence driver's decision  |



The first General Motors model was derived using a functional value for acceleration as follows (Adolph May, 1990), with the assumption that driver sensitivity is constant for all vehicles.

$$\ddot{x}_{n+1}(t + dt) = \alpha \left[ \dot{x}_n(t) - \dot{x}_{n+1}(t) \right]$$

A second look at the model, on account of discrepancy from field values indicated that the sensitivity of the driver was higher whenever the headway was less. A relationship was drawn to account for this error. Thus

$$\alpha = \frac{\alpha_0}{d} = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)}$$

Further improvements about the sensitivity were introduced by the speed difference, i.e. relative velocity, because as the speed difference increases, the sensitivity increases. Every system has a time lag to react to changes occurring ahead of it. This is accounted for, by the term  $\Delta t$  that represents the reaction time on part of the following vehicle to accelerate and decelerate. Finally, the powers of the terms of speed and headway of the vehicle ahead were proposed and these constants were called speed component ( $m$ ) and headway component ( $l$ ). The resultant equation (The fifth General motors model) can be stated as

$$\dot{x}(t + \Delta t) = \frac{\alpha_{l,m} \left[ \dot{x}_{n+1}(t + \Delta t) \right]^m}{\left[ x_n(t) - x_{n+1}(t) \right]^l} \left[ \dot{x}_n(t) - \dot{x}_{n+1}(t) \right]$$

Ranges of values :  $m = -2$  to  $2$  and  $l = -1$  to  $4$

It can be found that upon substitution of different combinations of  $m$  and  $l$  terms, the resultant microscopic general motors formulae take the shape of various macroscopic models, proposed by various researchers, which has been discussed already. The model is widely accepted as a generalized car following model, which can be modified and applied to a particular case.

### 2.3.2 Traffic Simulation models:

For use in digital micro simulations [24], the analytical car-following models described above have two drawbacks, they have been developed for a continuous rather than discrete time parameter and no single model is appropriate to all traffic conditions. As a result traffic simulation models have been developed.

Fail safe models is a process of determining a vehicles speed and position given that its leader has a speed and position that has already been calculated, for the current time span. Such a type of model has two elements, 1) there is a car-following model which calculates the followers behavior based on some prescribed following distance and 2) the model has an overriding collision factor which prevents the following vehicle to avoid collision when the leader undergoes extreme deceleration pattern.

Four Algorithms were considered for possible use. They were

### 2.3.2.1 The Northwestern Algorithm:

This algorithm was developed at Northwestern University. The model has two key components, a car following rule that sets a minimum following distance directly proportional to the following vehicle speed and an overriding equation that prevents the minimum following distance from being violated during times of maximum deceleration by the leading vehicle

Given the speed and location of the leading vehicle at the end of the scanning period, the algorithm outputs the new speed and position of the following vehicle. Worrall and Bullen explain this algorithm in detail.[40]

### 2.3.2.2 The UTCS-1 Algorithm:

This model [16] consists of a spacing algorithm, which provides for collision avoidance when the leading vehicle decelerates suddenly to a stop. There is no specific car-following algorithm apart from the critical headway calculations. The output of the algorithm, is given by

$$a = [7(x - y - vT - L) + (2u^2 - 3v^2) / 6] / (v + 3)$$

where

$a$  = acceleration of the follower

$x$  = position of the leader

$y$  = position of the follower

$u$  = speed of the Leader

$v$  = speed of the follower

$L$  = length of the leader

$T$  = simulation scanning interval.

### 2.3.2.3 The Aerospace Algorithm

This model uses the May-Keller calibration [2] of the conventional analytical car-following model

$$a = \lambda v(u - v) / (x - y)^3$$

where  $\lambda$  is the driver sensitivity factor.

When  $(u-v)$  is positive or close to zero, the above formula is inoperative and normal acceleration patterns are followed subject to safe spacing limitations.

### 2.3.2.4 The PITT Algorithm:

As CORSIM uses the PITT algorithm developed by the university of Pittsburgh, this method will be discussed in detail. This model is founded on a combination of the Northwestern car following and the UTCS collision avoidance features. The primary car following relationship is that a following vehicle will attempt to maintain a space headway of  $L + kv + 10 + bk(u-v)^2$  feet. The sensitivity factor, “ $k$ ”, which is a function of driver type, regulates maximum lane capacity. The car following formula is



$$a = 2[x - y - L - 10 - (k + T)v - bk(u - v)^2] / (T^2 + 2kT)$$

where

$$b = \text{constant for high relative closing speed} = \begin{cases} 0.10 & \text{for } (u - v) \leq 10 \\ 0 & \text{for } (u - v) > 0 \end{cases}$$

A lag,  $c$ , is introduced into this formula after 'a' has been calculated. The lag is applied to the speed and new speed is calculated as follows

$$v_1 = v + a(T - c)$$

Overriding this car following model is a collision avoidance set of equations that prevent collisions when vehicles are undertaking maximum emergency deceleration. The formula for the emergency constraints is

$$a \leq -B/2 + [(B^2 + 4C)]^{0.5} / 2$$

$$\text{where } B = e + 2(ec + v)/(T - c)$$

$$\text{and } C = [2e/(T - c)^2] \cdot [x - y - vT - cv - (v^2 - u^2)/2e]$$

$$\text{provided } a \geq [(u^2 + e^2c^2)^{0.5} - ec - v] / (T - c) > 0$$

or

$$a < 2(x - y - vT - L) / (T - c)^2$$

$$\text{provided } 0 < v + a(T - c) < \sqrt{(u_1^2 + e^2c^2)} - ec$$

or

$$-\frac{v}{(T - c)} < a < \frac{\sqrt{u_1^2 + e^2c^2} - ec - v}{(T - c)}$$

The above equations are constraints, which determine the follower vehicles acceleration which must be maintained in order to satisfy emergency non-collision conditions

The emergency constraint is also used in lane changing mechanism where vehicles may not be in a safe position relative to each other. In such a case the above constraint set provides real acceleration but it is greater than  $e$  and thus the lane change is not initiated. Moreover the discriminant ( $B^2 - 4AC$ ) becomes negative. In this case the lane change is automatically not initiated as two vehicles on comparison are in an unsafe position to occupy the same lane.

## **2.4 Computer Simulation :**

Computer simulation plays a major role in analysis and assessment of highway system . It has a wide-ranging applicability to transportation in general. There are several different definitions attributed to simulation process. Adolph D. May defines simulation as follows (Adolph D. May, 1990): “Simulation is a numerical technique for conducting experiments on a digital computer, which may include stochastic characteristics , be microscopic or macroscopic in nature and involve mathematical models that describe the behavior of a transportation system over extended periods of real time”.

There are a number of other definitions , which also serve as reasons for the selection of simulation for the investigation of traffic operations

1. Simulation is a dynamic representation achieved by building a model and moving it through time
2. Process of conducting experiments on a model of a system as described by Mize and Cox (1980)
3. Simulation is an intimation of a real situation by some form of a model that assumes the appearance without reality - Wohl and Martin (1967) [41]

### **2.4.1 The role of a simulation model**

Freeway simulation has its primary application in the project development stage and in the refinement of ongoing traffic operational strategies. But within these areas, a major issue is whether the advantage of freeway simulation is sufficient to warrant the investment in its application. The decision to use simulation often is weighed as a direct comparison with the limitations of HCM procedures and engineer’s general understanding of its capabilities. Therefore a contrast between the approaches is necessary to put both procedures in better prospective

### **2.4.2 Contrast Between the HCM procedures and Freeway Simulation**

- The HCM procedures are widely recognized and their application reasonably well understood by the engineering community and many representatives of local government. Simulation still retains a degree of mystery and uncertainty in many agencies because it has been used much less often
- Freeway simulation is perceived to be more expensive and time-consuming method of analysis than the HCM.
- The HCM procedures examine one section at a time and are unable to evaluate interactions between sections whereas one of the most powerful aspects of simulation is the ability to determine the effect of geometric and traffic operational strategies upstream and downstream of the section
- The HCM cannot evaluate congested conditions but freeway simulation are designed to evaluate the same
- Freeway simulation models are designed to produce system related output whereas the results of HCM runs must be assembled and put into a tabular or graphic form independently
- There are situations and strategies that HCM is unable to evaluate. For example, the procedures are not designed to evaluate incident management strategies or ramp metering, stochastic driver behaviors etc.
- The HCM procedures are easy to learn and use as compared to freeway simulation models, which require additional training.

### **2.4.3 Situations for which Freeway Simulation is Appropriate:**

Use of a freeway simulation model should be considered ( in lieu of or in conjunction with the HCM) under the following conditions

- If the freeway is congested or could potentially be congested during the analysis period, a simulation model would be needed to estimate the extent of congestion remaining.
- If the operations of a section of freeway is significantly dependent on the adequacy of flow through weaving sections, multiple ramp merge/diverge are needed then a freeway simulation model would be appropriate because it would be able to consider the interactions between sections
- If several alternative design configurations are to be tested and evaluated then the simulation model would be of extreme help.
- Unusual flow patterns, particularly under saturation and unstable conditions, can be modeled which don't follow any mathematical distribution ideally.
- It is easy to build and model for complex systems and relatively inexpensive to run

### **2.4.4 Conditions where Simulation may not be Appropriate:**

Simulation has several drawbacks. It needs adequate appraisal and careful consideration before fixed adoption as a modeling strategy.

1. The use of simulation may be an overkill in certain conditions such as scheduling or resource problem where simulation may be impractical.
2. These models cannot predict changes in demand in response to a geometric or operational improvement.
3. Results of simulation are never accurate. This is especially true in the case of a stochastic simulation model . The problem may be due to model validation. If the models are not validated or calibrated, then it can't be used

## **2.5 Freeway Simulation Models in Market:**

There are a plenty of simulation models in the market . Some of them are microscopic while some of them are macroscopic [25]. These models can further be classified into static and dynamic. The following section gives a brief description of the models that can used for the comparison analysis of a weaving section of an highway. However since CORSIM is the a new simulation model developed by FHWA, it needs to be calibrated and so is selected for this study. Chapter 3 talks in detail about the CORSIM modeling methodology

### **2.5.1 FREQ:**

FREQ [5] was developed at the University of California, Berkeley in the early 1970's. It consists of a family of freeway simulation models, the latest of which are FREQ8PE and FREQ8PL. This model operates on the basis of speed/volume and demand/capacity relationships. These Models have been used to evaluate such measures as fixed-time ramp metering plans, priority mainline lanes for high occupancy lanes and priority ramp lanes for high occupancy vehicle ramp meter bypass

FREQ incorporates the weaving analysis procedures and ramp merge, diverge procedures of 1965 HCM but did not provide estimates of weaving capacities. As a result 1985 HCM procedures could not be implemented. The FREQ models can be described as quasi-static macroscopic : quasi static because changes in demand levels can only be

input at specific times , macroscopic because the movement of individual vehicles is not modeled.

### **2.5.2 FREFLO**

FREFLO is one of the components models of FHWA TRAF system. This model was developed from an earlier program MACK. It uses flow conservation principles and an equilibrium speed density relationship incorporated into a dynamic speed equation. It tracks the development and dissipation of queues based on the status at the end of the previously simulated time slice. It can accommodate more than one freeway and can simulate ramps connecting the two freeway systems. One of the shortcomings of this model is that it has more difficulty dealing with the time/space nature of traffic flow because traffic flow must be dealt within aggregate time slices.

FREFLO can be described as a dynamic macroscopic model. It is dynamic because changes in demand levels can be input for different time periods, macroscopic because the movements of individual vehicles are not modeled

### **2.5.3 INTRAS**

The INTRAS [9] model has been used to evaluate incident detection algorithms, real time ramp metering strategies, and traffic disturbances due to reconstruction alternatives[7]. The INTRAS model uses car following and lane changing laws to simulate the movement of individual vehicles[11]. Thus it can be described as dynamic microscopic model. It is dynamic because changes in demand levels can be input for different time periods, microscopic because individual vehicle movements are modeled.

### **2.5.4 FRESIM**

FRESIM [18] is a component model of TRAF simulation system designed for microscopic freeway simulation. This model is an enhancement to the INTRAS model and includes improvements to geometric and operational capabilities .

FRESIM can simulate geometric conditions, which include grades, ramps, curves, super elevation, lane additions, lane drops ,workzones and auxiliary lanes. Some of the operational features [38] include lane changing, ramp metering incidents etc.

### **2.5.5 INTEGRATION:**

The INTEGRATION [3] model was developed by Michael Van Aerade, to model the interaction of freeways and surface streets, simulation and traffic assignment, static and dynamic controls and routing in an integrated fashion. The model represents the movement of individual vehicles in a time stepping fashion, based on user specified speed-flow relationships for each link.

The model is unique in its ability to represent car following, lane changing and gap acceptance behavior in planing type of networks [29]. The integrated logic can perform HCM level type of analysis of stop sign controlled intersection and of signal coordination. On freeways, merge, diverge, weaving and bottleneck analysis is possible using dynamic O-D demands. The graphical interface permits the status of individual vehicles or links to be queried. A time series of statistics on travel time, distance, number of stops, queue sizes, fuel consumption's etc. are logged during each run to permit extensive post-processing analysis.

### **2.5.6 Highway Capacity Software:**

The Highway Capacity Software (HCS) was developed under FHWA sponsorship as an implementation tool of the procedures of the 1985 Highway Capacity Manual

(HCM). The model takes into account the effects of terrain, specific grades, trucks, width restrictions and driver population in determining highway capacity and level of service. The HCS assumes a capacity under ideal conditions of 2200 passenger cars per hour per lane (pcphpl). If values more than 2200 are entered, then manual calculations need to supplement the computer calculations in order to get accurate results

The weaving procedures compute speeds and levels of service for both weaving and non-weaving traffic. The HCS further permits the assessment of four-ramp -related situations i.e. . ramp capacity and level of service of the on ramp, ramp merging analysis, ramp diverging analysis and finally ramp capacity and level of service of the off-ramp .

#### **2.5.7 FREWEV:**

FREWEV [27] is an interactive menu driven computer program developed by CALTRANS and FHWA for designing and analyzing major freeway weaving sections. FREWEV enables the user to design a freeway section by entering input section graphically and analyze the graphical sections by using the analytical technique for the design and analysis of a major weaving sections.

This model calculates the amount of traffic by movement along a weaving section for each of the lanes that are involved in the weave. From these volumes their densities are calculated and level of service identified. This model also calculates the amount of traffic crossing the lane boundaries in the conflict area.

#### **2.6 Current Research:**

A new NCHRP research study is being conducted by Viggen Corporation [37] on Capacity and Quality of Service of Weaving areas and the following results are anticipated 1) a simple, explainable and defensive model of weaving zones 2) modifications, as necessary, to FRESIM and NETSIM to properly model weaving operations, particularly capacity 3) Comprehensive simulation of weaving scenarios 4) Incorporation of appropriate existing data 5) A detailed design method for determining saturation in weaving zones. Results of this study are expected to be included in the 2000 HCM.

Another study is being conducted by Steven I-JY Chien and Shoaib M. Choudhury [6] on freeway capacity analysis with microscopic simulation model (FRESIM). The main objective of this study is to 1) identify the factors affecting freeway capacity 2) to address the deficiencies of FRESIM which may generate bias results, 3) to recommend modifications to FRESIM, which would improve the result accuracy 4) to develop an appropriate methodology for determining freeway capacity

Many of the car-following models proposed in the literature are single regime and do not account for various scenarios of the vehicle interactions especially for congested conditions. For example some widely employed car-following models such as GM and PITT handle only one regime for the car -following logic. Hence a study is being conducted on a Multi Regime approach for Microscopic Traffic Simulation by FHWA. The main idea behind the model is to develop a model [36] that features realistic car following maneuvers with a multi regime car following logic to address complex maneuvers under congested conditions.