Macroscopic Traffic Flow Modeling of Automated Highway Systems

H. Raza and P. Ioannou

Department of Electrical Engineering-Systems
University of Southern California, Los Angeles, CA 90089-2562
ioannou@bode.usc.edu

Abstract

An accurate macroscopic traffic flow model of automated highways is necessary not only for analyzing the collective dynamical behavior of automated vehicles but also for designing control laws to improve system level performance. In this paper a macroscopic model for describing the traffic flow on automated highways is developed by using the microscopic control laws that govern the motion of individual vehicles. Some assumptions were used to derive the instantaneous speed and density profiles from the kinematics of individual vehicles. We have given enough structure to the modeling task, so that the model is independent of the implementation details, hence can be applied to a wide variety of automated highway concepts. The developed model can be used to analyze the steady state behavior of AHS traffic flow for different operating conditions and is currently under study. We plan to use the results of this analysis as guidelines for designing macroscopic as well as microscopic control laws.

1 Introduction

Historically, the macroscopic behavior of highway traffic has been modeled by approximating the control actions of a human driver while driving within a group of vehicles [1]. These simple models based on human car following models [2] were progressively improved to account for the observed phenomena on highways [3, 4]. Even in the earlier development cycle of automated highways, these traditional models describing the behavior of human drivers were used to approximate the behavior of automated vehicles [4, 5].

However, as more complex control laws have been developed at microscopic level, there is an ever increasing need for a model that can describe the macroscopic behavior of these automated vehicles. Unlike human drivers, these automatic vehicle following control laws behave in a predictable manner. Hence, one way of modeling the dynamics of the system at the macroscopic level is to use the deterministic microscopic vehicle dynamics.

We will achieve the goal of this study by defining the macroscopic variables of interest in terms of the well defined relationships for the speed and relative distance for a group of vehicles under automatic control. This will enable us to study the effects of changing the individual control strategies on the macroscopic aspects of traffic flow. Given one set of operating conditions, these automatic vehicle following controllers behave in a predictable fashion, unlike human drivers who tend to produce random control actions for the same situation; Hence a representation of the system in terms of these deterministic functions can be used to develop control laws to optimize the macroscopic behavior for a set of possible operating conditions.

The modeling task has been subdivided into two parts: The first part deals with the conceptual abstraction of the system as a continuous fluid, so that the dynamics of the system can be obtained by applying the hydrodynamic theory of traffic flow. In this part, for simplicity, we have assumed one dimensional streamline flow, i.e., no lane changes and no on-ramps or off-ramps. The second part, which deals with the global connectivity of the system, assumes the responsibility of processing the real time information so that a given highway with multiple lanes and on-ramps and off-ramps can be viewed as a collection of single lane highways with no lateral traffic flow. Hence the abstraction developed in part one applies to each one individually.

In order to complete the first part of the modeling task, we start with the microscopic model which describes the relationships for motion of vehicles within each platoon. By using this microscopic model, we develope a local macroscopic model which estimates the instantaneous speed and density for a section of highway by treating each section as an arbitrary collection of platoons. Finally, within global domain, we first connect different sections to form a single lane through appropriate boundary conditions. A model for multi-lane highway system is then obtained from these single lane highways by defining lateral flow across adjacent lanes. This modeling structure is quite flexible as different automated higway concepts can be represented by the same model by changing the global connectivity conditions which are implementation dependent.

2 Microscopic Model

In this study we are modeling the macroscopic behavior of automated highways in terms of the kinematics of individual vehicles. These vehicles are assumed to be grouped together in platoons of differnet sizes[1]. The first step in the proposed modeling process is to develope the relationships for dynamics of vehicles as they are following each other according to a given inter-vehicle spacing policy. One such platoon of vehicles is shown in Figure 1. The variables used in the microscopic model which are also shown in Figure 1 are:

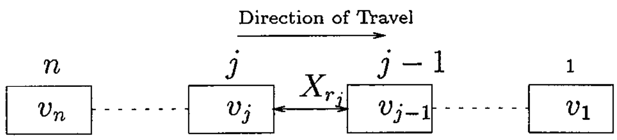

Figure 1: A platoon of vehicles.

j : vehicle number within a platoon, $j \in \mathcal{J} = \{1, \ldots, n\}$, where n is the size of platoon,

X_{r_j} : relative distance between vehicle j and $(j-1)$,

v_{r_j} : relative speed between vehicle j and $(j-1)$,

δ_j : deviation from the desired position for vehicle j,

v_j : speed of vehicle j,

V : external speed command,

h : headway command, either time headway or constant spacing,

V_{d_j} : desired speed for vehicle j,

V_l : speed of the vehicle in front of platoon leader.

The general expression for the speed and relative distance for the jth vehicle in a platoon is given as:

$$\begin{aligned} v_j(t) &= W_{1_j}(s) V_{d_j}(t), \\ X_{r_j}(t) &= W_{2_j} V_{d_j}(t), \qquad j \in \mathcal{J} \end{aligned} \tag{1}$$

where V_{d_j} is the desired speed for the jth vehicle and $W_{1_j}(s)$, $W_{2_j}(s)$ are stable proper transfer functions.

[1] A vehicle traveling alone, referred to as free agent in literature, will be considered a platoon of size $n = 1$

The exact form of these transfer functions depends on the type of controller used, but they have certain characteristics which are common, irrespective of the type of controller. These characteristics are defined by the control objectives, each of these controllers have to follow, to achieve a stable vehicle following in a platoon formation. These objectives are:

C–I $\delta_j, v_{r_j} \to 0$ exponentially or at least asymptotically. (With the assumption that there is no disturbance.)

C–II $\|\delta_j\|_\infty \le \|\delta_{j-1}\|_\infty$ and $\|v_{r_j}\|_\infty \le \|v_{r_{j-1}}\|_\infty$.

The constraint **C–II** guarantees that there is no slinky type effect in the platoon. For vehicles to follow each other in the platoon it is required that:

$$\begin{aligned} V_{d_1}(t) &= \min(V(t), V_l(t)) \\ V_{d_j}(t) &= v_{j-1}(t) \qquad j = \mathcal{J} \setminus 1 \end{aligned} \tag{2}$$

where $V(t)$ is the external speed command and is the speed commanded by the roadway when such an architecture is present and $V_l(t)$ is the speed of the vehicle in front of the platoon leader. It should be noted that under normal operating conditions $V_{d_1} = V$, however, during congestion or incidents the leader of the platoon has to track the speed of the vehicle in front which may be well below the speed commanded by the roadway due to abnormal operating conditions. In order to simplify notation, where no ambiguity is possible, we will use V to denote both the external speed command or the speed of the vehicle in front of the platoon leader.

By substituting the value of V_{d_j} from (2) to (1), we get:

$$\begin{aligned} v_j(t) &= \left[\prod_{\alpha=1}^{j} W_{1_\alpha}(s)\right] V(t); \; j \in \mathcal{J} \\ X_{r_j}(t) &= W_{2_j}(s) \left[\prod_{\alpha=1}^{j-1} W_{1_\alpha}(s)\right] V(t) \end{aligned} \tag{3}$$

Now we have the expressions for the speed and relative distance for each vehicle in a platoon. These expressions will be used to derive the model for a section of highway, which is nothing but an arbitrary collection of platoon of vehicles.

3 Local Macroscopic Model

In this section we will develop the model for a subsystem of the automated highway. The subsystem in this case is one particular section of the highway system and is shown in Figure 2. According to the

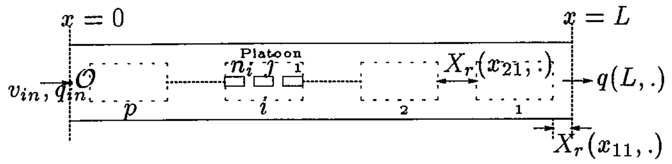

Figure 2: A section of an automated highway system.

methodoligy chosen in this paper, the modeling of the given multi-lane automated highway will be done in several steps. In the first step, we have derived the kinematics of individual vehicles within a single platoon. In the next step a section of the given highway will be considered to contain an arbitrary collection of platoons of vehicles. In this part we will consider only the longitudinal flow and will ignore the lane changes, on-ramp and off-ramp traffic. By using appropriate assumptions, the states of the system, speed and density distributions, will be represented in terms of kinematics of individual vehicles derived in the last section.

In addition to the variables defined in the microscopic model, the variables used in the local macroscopic model are:

i : platoon number within a section, $i \in \mathcal{I} = \{1, \ldots, p\}$, where p is the total number of platoon,

$\mathcal{O}$: Origin for local distance measurements, located at the section boundary at center of the lane,

j : vehicle number within a platoon, $j \in \mathcal{J} = \{1, \ldots, n_i\}$, where n_i is the size of platoon i,

x : distance measured with respect to origin $\mathcal{O}$,

$v(x,t)$, $k(x,t)$, $q(x,t)$: instantaneous speed, density and longitudinal traffic flow rate functions,

x_{ij} : position of the vehicle j in platoon i,

$v(x_{ij},t)$: speed of vehicle j in platoon i,

$V(x_{i1},t)$: speed command for platoon i, where x_{i1} denotes the position of the leader of platoon i,

l : length of the vehicle, assumed to be the same for all vehicles,

L : length of the section of highway,

$\mathbb{L}$: domain of the local macroscopic model, $\mathbb{L} = \mathcal{I} \times \mathcal{J}$.

Remarks

- According to our notation, both $v(x_{ij},t)$ and $v_{ij}(t)$ represent the speed of a particular vehicle in a section. These two variations will be used throughout this paper.

Since we are considering the microscopic details of the traffic flow for generating the macroscopic model, we can assume different traffic flow distributions to approximate the actual flow on the highway. For the most general case, we will assume that the traffic stream is randomly distributed along the section of highway. Also we have assumed that the speed command to the vehicles is time varying and is spatially distributed along the section, hence is different for each platoon in the section and is represented as $V(x_{i1},t)$[2]. In this section, headway command h is assumed to be constant and is absorbed in the transfer functions $W_1(s)$ and $W_2(s)$ [6].

Since our goal is to represent the instantaneous speed and density profiles in terms of the individual vehicle dynamics, we can simplify the calculations by making the following assumptions.

Assumption:

A–I The vehicles have similar closed loop characteristics, i.e.,

$$\sup_{\alpha,\beta} \|W_{1_\alpha} - W_{1_\beta}\|_\infty \leq \epsilon$$
$$\sup_{\alpha,\beta} \|W_{2_\alpha} - W_{2_\beta}\|_\infty \leq \epsilon \qquad \alpha, \beta \in \mathbb{L}$$

where ϵ is some small number.

From assumption **A–I**, we can make the following approximation:

$$\begin{aligned} W_{1_\lambda}(s) &= W_1(s) \\ W_{2_\lambda}(s) &= W_2(s) \qquad \lambda \in \mathbb{L} \end{aligned} \tag{4}$$

With the help of assumption **A–I**, we can extend the relationships developed for the speed and relative distance for vehicles within a single platoon, given in (3), to that for each vehicle in the given section as follows:

$$v(x_{ij},t) = [W_1(s)]^j V(x_{i1},t); \; j \in \mathcal{J}, \; i \in \mathcal{I} \tag{5}$$
$$X_r(x_{ij},t) = W_2(s)[W_1(s)]^{j-1} V(x_{i1},t). \tag{6}$$

[2]In previous section we were considering only a single platoon hence the speed command was represented as V.

In (5) and (6) the value of x_{ij} is calculated as:

$$x_{ij} = L - \left[\sum_{\alpha=1}^{i-1} \sum_{\beta=1}^{n_\alpha} (X_r(x_{\alpha\beta}, t) + l) + \sum_{\beta=1}^{j} X_r(x_{i\beta}, t) + \sum_{\beta=1}^{j-1} l \right], \ \alpha \in \mathcal{I}, \beta \in \mathcal{J} \quad (7)$$

where L is the length of the section and l is the length of the vehicle, assumed to be the same for all vehicles. For relation (7) to be well posed, it is assumed that the interplatoon distance, $X_r(x_{i1}, t)$, $i \in \mathcal{I}$, can be calculated from the available information.

In order to build a space continuum model of traffic flow on automated highways we need a continuous representation of the speed and density profile for a section of highway. However, the vehicles are located only at discrete locations denoted as x_{ij}. To overcome this problem we can use linear interpolation to define v and k for all values of x between any two vehicles. By using (5)-(7) we can obtain continuous speed, $v(x,t)$, and density distribution functions, $k(x,t)$, for the given section as follows:

$$v(x,t) \triangleq v(x_{ij}, t) + \left[v(x_{i(j-1)}, t) - v(x_{ij}, t)\right] \left[\frac{x - x_{ij}}{X_r(x_{ij}, t) + l}\right] \quad (8)$$

$$k(x,t) \triangleq k(x_{ij}, t) + \left[k(x_{i(j-1)}, t) - k(x_{ij}, t)\right] \left[\frac{x - x_{ij}}{X_r(x_{ij}, t) + l}\right] \quad (9)$$

$$x_{ij} \leq x \leq x_{i(j-1)} \ ; j \in \mathcal{J}, i \in \mathcal{I}$$

$$k(x_{ij}, t) \triangleq \frac{1}{X_r(x_{ij}, t) + l} \quad (10)$$

It should be noted that the definitions of speed and density distribution functions in (8) and (9) are valid for all values of x in the range, $x_{pn_p} \leq x \leq x_{11}$, where x_{pn_p}, x_{11} are the location of the vehicles closest and farthest from the origin $\mathcal{O}$ respectively. However, their definitions can be extended to all values of $x \in [0, L]$ by considering the boundary conditions and extrapolation of these distributions. The boundary conditions are:

$$v(0,t) = v_{in}(t) \qquad (11)$$
$$q(0,t) = q_{in}(t)$$

where v_i, q_i is the speed and flow rate respectively of the traffic entering the section shown in Figure 2. Since the subtraction in the value of j in (8) and (9) is modulo n_i, the following extrapolation can be made:

$$0 \leq x < x_{pn_p} \Rightarrow x_{ij} = x_{(p+1)1} = 0, \ x_{i(j-1)} = x_{pn_p}$$
$$x_{11} < x \leq L \Rightarrow x_{ij} = x_{11}, x_{i(j-1)} = x_{01} = L$$

Hence to use the definitions (8) and (9) outside the region $x_{pn_p} \leq x \leq x_{11}$, we have introduced fictitious vehicles at $x = 0$ and $x = L$, denoted as $x_{(p+1)1}$, x_{01} respectively. The speed at $x = 0$ is given by the boundary condition in (11), however, that at $x = L$ can be assumed to be the speed of the closest vehicle, i.e.,

$$v(x_{(p+1)1}, t) = v(0,t) = v_{in}(t) \qquad (12)$$
$$v(x_{01}, t) = v(L,t) = v(x_{11}, t).$$

The linear interpolation given in (8)-(9) is a good approximation for representation of the speed and density as continuous functions as long as the traffic flow rates are not negligibly small. Hence an inherent assumption in the definition of the speed and density distribution function is that the traffic flow rates are above a certain threshold.

Having developed a continuous approximation for the states of the automated highway, $[v, k]^\top$, we can develop update laws for these states by using the hydrodynamic traffic flow theory. According to this, the acceleration of an observer moving with the traffic stream is given as:

$$\dot{v}(x,t) = \frac{\partial}{\partial t} v(x,t) + v(x,t) \frac{\partial}{\partial x} v(x,t). \qquad (13)$$

It should be noted that well defined expressions for $\frac{\partial}{\partial t} v(x,t)$ and $\frac{\partial}{\partial x} v(x,t)$ can be obtained by using (8), (10), (5) and (6). Hence the acceleration at any point along the highway is a deterministic function of the known transfer functions $W_1(s)$ and $W_2(s)$. The justification for the assumption **A–I** is now clear, since no data from automatic highways is available to calibrate our model, it enables us to represent (13) as a deterministic function with no uncertain elements like human driving models.

The law of conservation of vehicles, which will be used to find the expression for $\dot{k}(x,t)$, is given as:

$$\frac{\partial}{\partial t} k(x,t) + \frac{\partial}{\partial x} q(x,t) = 0 \qquad (14)$$

where $q(x,t) = k(x,t)v(x,t)$ is the instantaneous longitudinal traffic flow rate. As discussed before, we will ignore the lateral traffic flow for this part of model. Hence, in (14) we have assumed that there is no on-ramp or off-ramp traffic. From (14) we have:

$$\dot{k}(x,t) = -k(x,t) \frac{\partial}{\partial x} v(x,t) \qquad (15)$$

To solve (13) and (15) uniquely, the required initial conditions are:

$$v(x, t_0) = g(x) \qquad (16)$$
$$k(x, t_0) = f(x)$$

where $f(.)$, $g(.)$ are assumed to be known at $t = t_0$. The update laws for continuous states $[v, k]^\top$ in (13), (15) along with their definitions in (8), (9) and a representation of individual vehicle states $[v_{ij}, k_{ij}]^\top$ in (5)-(7) and (10) form a complete subsystem model. This model will be referred to as the local macroscopic model and is summarized below for reference.

$$
\begin{aligned}
&\dot{v}(x,t) = \frac{\partial v(x,t)}{\partial t} + v(x,t)\frac{\partial v(x,t)}{\partial x}; v(x,t_0) = g(x)\\
&\dot{k}(x,t) = -k(x,t)\frac{\partial v(x,t)}{\partial x}; k(x,t_0) = f(x)\\
&q(x,t) = k(x,t)v(x,t)\\
&v(0,t) = v_{in}(t)\ ; q(0,t) = q_{in}(t)\\
&v(x,t) = v(x_{ij},t) + \left[v(x_{i(j-1)},t) - v(x_{ij},t)\right]\\
&\qquad \left[\frac{x - x_{ij}}{X_r(x_{ij},t) + l}\right]\\
&k(x,t) = k(x_{ij},t) + \left[k(x_{i(j-1)},t) - k(x_{ij},t)\right]\\
&\qquad \left[\frac{x - x_{ij}}{X_r(x_{ij},t) + l}\right]\\
&x_{ij} \le x \le x_{i(j-1)}\ ; j \in \mathcal{J}, i \in \mathcal{I}\\
&x_{ij} = L - \left[\sum_{\alpha=1}^{i-1}\sum_{\beta=1}^{n_\alpha}(X_r(x_{\alpha\beta},t) + l) + \right.\\
&\qquad \left.\sum_{\beta=1}^{j} X_r(x_{i\beta},t) + \sum_{\beta=1}^{j-1} l\right]\\
&x_{(p+1)1} = 0, x_{01} = L, v(x_{(p+1)1},t) = v(0,t),\\
&\quad v(x_{01},t) = v(x_{11},t)\\
&k(x_{ij},t) = \frac{1}{X_r(x_{ij},t) + l}\\
&v(x_{ij},t) = [W_1(s)]^j V(x_{i1},t)\\
&X_r(x_{ij},t) = W_2(s)[W_1(s)]^{j-1} V(x_{i1},t) \qquad (17)
\end{aligned}
$$

The model in (17) describes the dynamical behavior of a section of highway, as pointed out earlier, the global macroscopic model is an interconnected system of the local macroscopic model. In the next section we will develope the global macroscopic model applicable to a single lane.

4 Global Macroscopic Model: Single Lane

While developing the local macroscopic model, we have considered only a single section of a lane in the given highway system. The only external input to the subsystem model in (17) is the speed command $V(x_{i1}, t)$, as the headway command is assumed to be constant. To model a single lane highway system shown in Figure 3, as an interconnected system we need a set of global inputs which include boundary

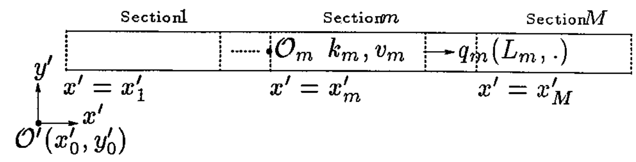

Figure 3: A single lane automated highway system.

and initial conditions. In the following we will present the required global inputs to connect the contiguous sections to form a single lane of highway.

The notation specific to the single lane macroscopic model is:

m : section number within a lane, $m \in \mathcal{M} = \{1, \ldots, M\}$, where M is the total number of sections,

$\mathcal{O}'$: Origin for global distance measurements, located at a fixed point (x'_0, y'_0),

x' : distance measured with respect to origin $\mathcal{O}'$ along the direction of flow,

$\mathcal{O}_m$: Origin for local distance measurements, located at $x' = x'_m$ with respect to $\mathcal{O}'$,

x : distance measured with respect to origin $\mathcal{O}_m$,

$v_m(x,t)$, $k_m(x,t)$, $q_m(x,t)$: instantaneous speed, density and traffic flow rate distribution functions for section m,

$\mathbb{G}$: domain of the global macroscopic model, $\mathbb{G} = \mathcal{M}$.

4.1 Global Inputs

We have formulated the problem of modeling the highway shown in Figure 3 as an interconnected system, where the elements of the system are sections. The set of equations in (17) is a representation of the states, $[v_m, k_m]^\top$ and output q_m of a particular element $m \in \mathbb{G}$. The only external input present in the model is the speed command $V(x_{i1}, t)$ which is assumed to be generated locally within a section. However, for a representation of the complete system, some inputs are required to provide the global connectivity. For example, the boundary conditions given in (17) can be rewritten as:

$$
\begin{aligned}
v_m(0,t) &= v_{(m-1)}(L_{(m-1)},t), \qquad (18)\\
q_m(0,t) &= q_{(m-1)}(L_{(m-1)},t).
\end{aligned}
$$

Similarly, the initial conditions in this case become:

$$
\begin{aligned}
v_m(x,t_0) &= g_m(x), \qquad (19)\\
k_m(x,t_0) &= f_m(x),
\end{aligned}
$$

where t_0 is the initial time and $f_m(.)$, $g_m(.)$ are known functions. As described earlier that the exact way in which the set of global inputs can be derived from the available information is implementation dependent, hence will be covered in the next part of this study for a specific system configuration.

Hence, the local macroscopic model in (17) together with the modified initial and boundary conditions given in (19), (18) respectively represents the model for the single lane highway system shown in Figure 3. Having developed the necessary conditions to connect the contiguous sections to form a single lane, in the next section we will consider the effect of lane changes and on-ramp and off-ramp flow, which have been ignored so far in this study, to model a multi-lane automated highway system.

5 Global Macroscopic Model: Multi Lane

In this section we will model a multi-lane automated highway system as shown in Figure 4 by superimposing the effect of lateral flow on the models obtained by considering the longitudinal flow only in previous sections. This technique allows us to model a multi-lane highway as a collection of single lane highways connected together through the relations developed for lateral flow in this section.

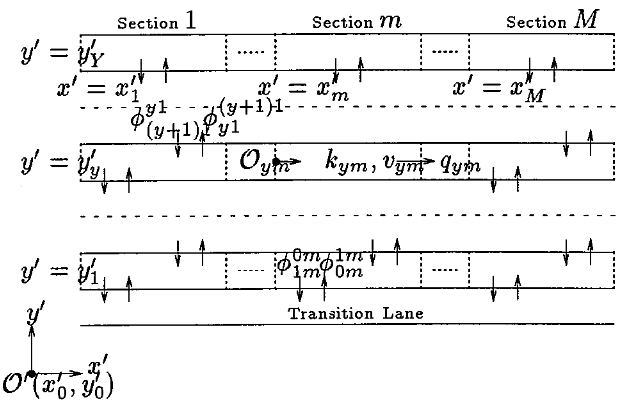

Figure 4: A multi-lane automated highway system.

As shown in Figure 4, by convention, we will consider the on-ramps and off-ramps to be always on the right most lane. In Figure 4 a transition lane is shown to identify the presence of incoming and outgoing traffic through the network, even though no physical lane may be present. In the following we will discuss notation specific to the multi-lane macroscopic model.

y : lane number, $y \in \mathcal{Y} = \{1, \ldots, Y\}$, where Y is the total number of lanes,

y' : distance measured with respect to origin $\mathcal{O}'$ perpendicular to the direction of flow,

$\mathcal{O}_{ym}$: Origin for local distance measurements, located at (x'_m, y'_y) with respect to $\mathcal{O}'$,

$v_{ym}(x,t)$, $k_{ym}(x,t)$, $q_{ym}(x,t)$: instantaneous speed, density and flow rate respectively for section m in lane y,

Φ_{ym} : average lateral flow rate for section m in lane y,

$\mathbb{G}$: domain of the global macroscopic model, $\mathbb{G} = \mathcal{Y} \times \mathcal{M}$.

In this study we assume that the lane changes are executed after coordination, either at local or at infrastructure level. This coordination requires that the operating conditions near the regions, where the lane change requests are initiated, be analyzed to select a strategy, if any, to execute these requests. These strategies depend on the upstream density of the two affected sections, their speed differentials etc. The complete discussion of selecting an optimal strategy which has minimum impact on the capacity and safety of the system can be found in [7] and will not be covered here.

For modeling purposes, we assume that the exact outcome of the strategy chosen by the roadway will manifest in the form of a change in the speed and/or headway command around the affected region. As described earlier, the only input to the local macroscopic model in (17) is the local desired speed command. Till now the headway command is assumed to be constant, hence did not appear in the model. However, during lane changes the headway command is not constant. Any change in headway command will change the coefficients of transfer functions $W_1(s)$, $W_2(s)$ and cause some transients to occur during this change. In [6], it has been shown that, for time headway policy, the transients are bounded and decay exponentially; a similar analysis can be done for fixed distance headway policy. In either case, we can rewrite (5) and (6) as:

$$v(x_{ij}, t) = [W_1(s,h)]^j V(x_{i1}, t) \quad (20)$$
$$X_r(x_{ij}, t) = W_2(s,h)[W_1(s,h)]^{j-1} V(x_{i1}, t) \quad (21)$$

where dependence of W_1 and W_2 on headway is shown explicitly. Hence any changes in the speed and headway commands caused by the requested lane changes will show up automatically in the model in terms of a change in the states of the system around the region affected by these processes. In addition to the dynamic effect of lane changes, the steady state effect will show up in the form of change in the size of two interacting platoons, which is assumed to be known at all times. In this context, a quantity which may be used for design purposes is the average lateral flow rate for a section, defined as:

$$\Phi_{ym}(t) \triangleq \phi_{ym}^{(y-1)m}(t) + \phi_{ym}^{(y+1)m}(t) - \phi_{(y-1)m}^{ym}(t) - \phi_{(y+1)m}^{ym}(t) \qquad (22)$$

where ϕ_{source}^{target} denotes the lateral flow from *source* section to the *target* section in two consecutive lanes. Each component in (22) can be obtained by averaging the successful lane change operations between two consecutive lanes within a specified interval of time. In this definition we have assumed that simultaneous multiple lane changes are not allowed.

In the next part of this study we will use this model to analyze different traffic flow scenarios on automated highways.

6 Conclusion

In this paper we have developed a model that describes the macroscopic behavior of automated highways in terms of the kinematics of individual vehicles. The model captures the details of microscopic control laws, which are deterministic in nature, in a form which can be used for analysis and design of control laws to improve system level performance. A structured modeling approach was used so that the same model can be used for different automated highway concepts by changing the global connectivity conditions, which are implementation dependent. The model is currently being used to analyze several automated highway concepts for stability and performance.

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