PLATOON MODAL OPERATIONS UNDER VEHICLE AUTONOMOUS ADAPTIVE CRUISE CONTROL MODEL

by

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Platoon Modal Operations Under
Vehicle Autonomous Adaptive Cruise Control Model

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Committee Chairman: Antoine G. Hobeika

Civil Engineering

(ABSTRACT)

This paper presents a theoretical development of adaptive cruise control models and platoon operation logic for Automated Highway Systems in the Advanced Vehicle Control Systems (AVCS). Three control modes, constant speed, emergency and vehicle-following, are defined based on the minimum safe stopping distance, and applied to the platoon operations.

Desired acceleration model is built for the different cruise control mode by considering the relative velocity, the difference between the relative distance and desired spacing, and the acceleration of the preceding vehicle. A control system model is proposed based on
the analysis of vehicle dynamics. The contribution of uncontrolled forces from the air, slop and friction to the vehicle acceleration is considered.

Application of control models for two successive vehicles is simulated under the situations of speed transition and emergency stopping. Proper control parameters are determined for different operation mode subject to the conditions: collision avoidance and stability. Same criteria are utilized to the platoon simulation in which the operation logic is regulated so that the platoon leader is operated under either emergency mode or constant speed mode depending upon the distance from the downstream vehicle, while the intraplatoon vehicles are forced to operate under vehicle-following mode. Three cases under speed transition, emergency stopping and platoon leader splitting are simulated to determine the stable control parameters. Lane capacity analysis shows the tradeoff between safety and efficiency for platoon modal operations on freeway with guideline or automated highway.
ACKNOWLEDGMENTS

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*NOTE: Volumes greater than 1000 L shall be shown in m³.*

#### Approximate Conversions to SI Units

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These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements*
1. Introduction

As the traffic volume on the roadway keeps growing and the construction of new transportation facility is restricted, attention is focused on improving the existing roadway capacity and increasing vehicle safety. Intelligent Vehicle Highway Systems (IVHS) is such a strategic program that it will smarten the traveler by providing better and more travel information, the vehicle by control enhancement and assistance, and the infrastructure by advanced traffic management. Advanced Vehicle Control Systems (AVCS) plays an important role in IVHS. Its main purpose is to enhance the driver control ability to make up the shortcoming caused by the restriction of human driving on the roadway efficiency and safety [1].

Intelligent cruise control (ICC) or adaptive cruise control (ACC) technology is applied in the vehicle to provide the driver with longitudinal control ability to automatically follow a downstream vehicle or stop without collision in emergency case. The macro-benefit under vehicle intelligent cruise control is to make traffic flow stable and increase the flow rate. This thesis is to study the vehicle adaptive control laws and establish macro-level platoon operation algorithm based on overall stability, safety and efficiency.
This thesis is organized by three main chapters. Chapter two presents the literature review including manual car-following model, automated vehicle control model, and intelligent cruise control model. An autonomous vehicle cruise control law is proposed in Chapter three. Three vehicle cruise operation modes are also proposed based on the minimum safe stopping distance policy. Platoon operation logic is established in Chapter four. Three traffic situations are simulated to determine the control parameters under each control mode. Finally, the lane capacity analysis shows the tradeoff between roadway capacity and vehicle safety under platoon modal operation.

This thesis only considers the theoretical and ideal analysis either on vehicle adaptive cruise law or on platoon operations. Due to complication of the real traffic situation and implementation of this technology, further research should be conducted and models and outputs might be revised.
2. Literature Review

Either manual or automatic control of a vehicle has to study the response of following vehicle against the change of position or velocity from the preceding vehicle. In manually following drive, the driver's behavior determines his control action: either pushing the gas pedal for propulsion or braking. The study on the human behavior of vehicle following was started in 1950's[2][3] and finally perfected by General Motor researchers in 1960's [4][5][6]. Limited researches on manual car-following theory have been conducted after mid-1960s [3]. The studies on the vehicle automatic control have been undertaken since 1970s, but much effort were made for automated transit vehicles [7][8][10]. Owing to the difference on the control feedback and controller design, the proposed control laws varied from one to one.

In 1980s and 1990s, as the traffic volume keeps increasing, the development of new transportation facilities is limited, and consequently the traffic congestion on highway becomes more and more intolerable all over the world, some strategic programs were initiated in Europe, Japan and United States for improving the highway capacity and safety. Some intelligent cruise control laws are proposed by California PATH and European PROMETHEUS researches [17][27][28][29][30][31]. The function of the
adaptive cruise control or automated headway control is to supplement manual control with capability of automatically maintaining minimum or desired headway. Since the automated control laws are based on the manual car-following theory, three categories of literature are reviewed for this research, which are shown as the following:

1. Car-following theories for manual driving. Papers are mainly selected from 1950s to 1960s;
2. Automated vehicle control models for both automated transit and passenger vehicles. Papers are selected from 1970s;
3. Recent development of intelligent cruise control models. Papers are selected mainly from PATH and European PROMETHEUS researches.
2.1 Manual Car-following Model

Some notations and definitions are summarized below before presenting the development of manual car-following models. Let n and n+1 denote the leading and following vehicle, respectively. Other notions are as follows:

\[ L_n = \text{length of the leading vehicle} \]
\[ L_{n+1} = \text{length of the following vehicle} \]
\[ X_n = \text{position of leading vehicle} \]
\[ X_{n+1} = \text{position of following vehicle} \]
\[ X_n = \text{speed of leading vehicle} \]
\[ X_{n+1} = \text{speed of following vehicle} \]
\[ \Delta t = \text{reaction time}. \]

Pipes proposed that distance headway was a linear function of the velocity of the following vehicle. If the length of the vehicle is was assumed as 20 feet, the distance headway was shown in the following equation:

\[ d_{\text{min}} = 1.36 [ X_{n+1}(t) ] + 20 \]
The minimum safe time headway was obtained in the following equation:

\[ h_{n+1} = 1.36 + \frac{20}{X_{n+1(t)}} \]

Forbes assumed that driver needed a reaction time to deceleration and applied the brake. The minimum time headway was equal to the reaction time plus the time required for the leading vehicle to traverse a distance equivalent to its length. This relationship was expressed in the following equation where reaction time was 1.5 seconds and length of vehicle 20 feet.

\[ h_{\text{min}} = 1.5 + \frac{20}{X_{n(t)}} \]

The minimum headway was expressed in the following equation:

\[ d_{\text{min}} = 1.5[x_{n(t)}] + 20 \]

General Motor researchers proposed that the driver's response was the function of sensitivity and stimuli. The relationship was expressed in the following equation:

\[ \text{response} = f(\text{sensitivity, stimuli}) \]
The improvement on the model was contributed to the sensitivity term. The early linear car-following model was:

\[ \dot{X}_{n+1(t+\Delta t)} = \alpha [X_{n(t)} - X_{n+1(t)}] \]

where \( \alpha \) is the inverse of reaction time and \( \dot{X}_{n+1(t+\Delta t)} \) is the acceleration of the following vehicle after a reaction time.

The final car-following model was perfected by improving the sensitivity through the distance headway and the velocity of the following vehicle. By introducing \( m \) and \( l \) exponents, the modified car-following model is expressed in the following equation:

\[ \dot{X}_{n+1(t+\Delta t)} = \alpha_{lm} \left( \frac{\dot{X}_{n+1(t+\Delta t)}}{[X_{n(t)} - X_{n+1(t)}]^m} \right)^l [X_{n(t)} - X_{n+1(t)}] \]

This model generalized the driver's behavior under different traffic streams based on the combination of parameters. The limits of local and asymptotic stability were also defined as the product of the reaction time and sensitivity value, which is shown in the following equation:

\[ C = \alpha(\Delta t). \]
2.2 Automated Vehicle Control Laws

Vehicle longitudinal control is necessary to regulate the velocity and position of individual vehicle [16][17][18][19][20]. Based on the information for the leading vehicle, the control system have the vehicle maintain proper velocity and spacing between successive vehicles or apply emergency braking to avoid collision. Some research was conducted in this field during 1970s for the automated guideway transit system or automated highway system [12][13][14][16][23]. The automated transit control has some similarities with vehicle automatic control, so it will be helpful to get an understanding of it.

The traditional automated vehicle control was called block control which was used to maintain minimum headway between vehicles in rapid rail transit. This method was only suitable for large headway between 20-30 seconds [8]. For operation under short headway, vehicle-following and point-following concept was proposed and developed [11][15][21] [22]. According to different control policies, the wayside computers gave appropriate command to automatically maintain the minimum safe stopping distance from the leading vehicle. Garrard et al proposed three basic spacing policies for the vehicle operation:

1. Constant separation. Spacing was fixed and does not vary with velocity;
2. Constant time headway. Time headway between consecutive vehicles was constant while spacing linearly varied with velocity;

3. Constant safety factor. The desired spacing was proportional to the safe stopping distance.

The command acceleration was assumed as a linear function of the velocity difference of two successive vehicles and the difference between the commanded and actual spacing; that is,

\[ a_{c_{n+1}} = H(s) [X_n(s) - X_{n+1}(s)] + G(s) [D_{c_n}(s) - D_k(s)] \]

where

- \(D_{c_n}\) = command spacing
- \(a_{c_{n+1}}\) = command acceleration of the \((n+1)th\) vehicle
- \(s\) = Laplace operator
- \(D_k\) = actual spacing between vehicles
- \(H(s), G(s)\) = control parameters.

Corresponding to the three basic spacing policies, the commanded spacing was expressed in the following equation:
\[
D_{cn} = \begin{cases} 
D \\
X_{n+1}h - L_n \\
KD_{stop} = \frac{K X_{n+1}}{2a_s}
\end{cases}
\]

Three expressions denote constant separation, constant time headway, and constant safety-factor where K was the safety factor and \(a_s\) the maximum emergency deceleration rate. Simulation results indicated that constant safety-factor and constant time headway had better operational advantages than constant separation policy which might lead to an unstable flow. Some of the papers presented researches on the maximum emergency deceleration and minimum stopping distance [9][16][19][21].

Vehicle emergency operation had been the focus of many researches [22][23]. Chiu, Stupp and Brown [24] considered variable-gains approach for short headway operation and decreasing high sensitivity to initial conditions. Rouse and Hoberock [26] proposed emergency control models for platoon operations under vehicle following laws. The control law for the platoon leader was assumed to be the function of difference between desired velocity and actual velocity. Dynamic position error was defined and tested to check whether collision happened. Through trial-and-error in emergency simulation, the proper control parameters were obtained in order avoid platoon oscillatory behavior.
2.3 Intelligent Cruise Control Models

Intelligent cruise control models have been studied in recent several programs [27][28][29][30][31]. However, development of these models are largely depend on the previous achievements including above manual car-following theory and automated vehicle or transit control models.

PROMETHEUS researchers [29][30][31] defined that purpose of intelligent cruise control was to automatically or assistantly control throttle or brake in order to keep with the desired speed-distance relation. Based on the flow rate, the "progressive" criterion was chosen as the speed-distance pattern of intelligent cruise control. It is expressed in the following equation:

\[ d_s = L + v\tau \]

where

\[ d_s = \text{stopping distance between vehicles} \]
\[ L = \text{equivalent length of vehicle} \]
\[ \tau = r - \frac{b}{2j} \]
\[ r = \text{reaction time} \]
\[ b = \text{maximum deceleration} \]
\[ j = \text{jerk} \]

The corresponding cruise control model was shown in the following equation:

\[ c = K(d - d' - gv_{n+1} + hv_n) \]

where
\[ c = \text{control feedback command} \]
\[ K = \text{overall control gain} \]
\[ d = \text{actual spacing between successive vehicles} \]
\[ d' = \text{minimum distance (equal to 11m)} \]
\[ g, h = \text{control gains.} \]

Simulation indicated that low overall gain would produce platoon instability while higher value allowed for platoon stable control.

California PATH researchers proposed the following intelligent cruise control models based on the first order control feedback:

\[ c_i(t) = c_p \delta_i(t) + c_v \delta_i(t) + k_v v_i(t) + k_a \alpha_i(t) \]

where
\[ Ci(t) = \text{commanded engine input for } i\text{th vehicle} \]
\[
\delta_i(t) = x_{i-1}(t) - x_i(t) - (l_i + s_{ai} + \lambda_2 v_i(t)) \\
\dot{\delta}_i(t) = v_{i-1}(t) - v_i(t) - \lambda_3 a_i(t)
\]

\[c_p, c_v, k_v, k_a = \text{design control constant}\]

A safety distance policy was proposed for the above control model which is expressed in the following equation:

\[S_{ai} = L v_i\]

Where \(L\) was vehicle length. The suggested value of maximum acceleration was ranged from 0.4g to 0.8g and maximum jerk limit 7.8g/s. Through comparing with different human driving models, simulation results showed that proper design and implementation of intelligent cruise control could smoothen traffic flow and increase roadway capacity. Sheikholeslam and Desoer [28] applied a non-linear model to vehicle dynamics and analyzed platoon operations with non-uniform vehicles. They proposed similar longitudinal control model.

Flow benefits under autonomously intelligent cruise control were investigated [32][33] and the results showed that the theoretical flow rate could be greater than 9000 veh/hr, but quickly down to 5500 veh/hr due to the stream disturbance. If the flow in the transition lane was considered, the effective flow rate per lane was reduced to 2700 veh/hr.
3. Control Laws For Different Modes
3.1 Concept of Adaptive Cruise Control

Goals of Adaptive Cruise Control

Due to the restrictions of human driving, it is difficult to further improve the existing roadway capacity and vehicle safety without the assistance or enhancement from the advanced technologies. In the Advanced Vehicle Control Systems or Automated Highway Systems, adaptive cruise control technology is chosen to help human driver with the ability of automatically longitudinal control.

The initial implementation of automatic cruise control does not consider the communications between vehicles. However, besides the equipped computer-controller system, the sensor system is also on-board which can detect the necessary data and deliver to the vehicle control system. The relative velocity and relative distance between leading and following vehicles are important parameters needed to collect and applied to the control laws. If a proper data processing device is connected with the on-board sensor, the acceleration of the leading could be calculated quickly. The driver still needs to steer for lateral control since the automatic headway control is restricted to the longitudinal range. Due to shortening of the headway (less than 1 second theoretically) and quick response
(0.1–0.01 reaction time) to the downstream stopping vehicles or stationary obstructions, the roadway capacity and safe insurance could be greatly improved.

Therefore, through the implementation of adaptive cruise control in vehicles, the following goals are expected to achieve:

1. Vehicle can maintain the minimum or desired headway between the successive vehicles under different control situations;

2. Vehicle has the ability to avoid collision and ensure the maximum safety operation in case of the sudden stopping of the leading vehicle;

3. Based on the proper platoon operation logic, the platoon has a stable control and stop-and-go traffic is avoided under the circumstances of either emergency stopping or speed transition.

**Definition of Adaptive Cruise Control**

Conclusively, adaptive cruise control can be defined as the autonomously automatic control that assists drivers to automatically maintain the minimum or desired headway and have the ability to avoid collision in different operation scenarios under the comfort consideration. In this stage, communications or data exchanges among vehicles are not necessary. This technology sets up the foundation of efficient and safe platoon operation and future's cooperative driving.
The automatic control process is realized by control laws, the function of sensoerd data, such as relative speed, distance or acceleration from the preceding vehicle, and presetting parameters, such as desired speed, spacing, maximum acceleration limit, etc. To build such control law, the following factors should be considered:

1. Minimum safe stopping distance that allows vehicle to stop without collision in case of emergency operation;

2. Thresholds to determine the vehicle operation modes, that is, cruising, vehicle-following and emergency stopping;

3. Application to the platoon operation and reasonable tradeoff between efficiency and safety. Based on the control law, the maximum platoon safety insurance and roadway capacity should be achieved;

4. The platoon stability in case of speed transition, vehicle splitting and merging;

5. Resistance to the sensor error. False or biased data as a result of on-board sensor error should be considered in the control law in order to avoid collisions.
3.2 Modes for Adaptive Cruise Control

Three modes are proposed for the autonomously adaptive cruise control. The first is constant speed mode in which vehicles travel at desired constant speed. The distance from the downstream vehicle should be great enough so as that the following vehicle can stop without collision under any circumstances. The second is emergency control mode. In this mode, if the leading vehicle stops at the deceleration between the maximum value and infinite (instantaneous stopping), the following vehicle will stop at the emergency deceleration without collision. The third is vehicle-following mode. Under this mode, the following vehicle maintains a safe stopping distance from the leading vehicle so that it can stop at emergency or maximum deceleration without collision if the leading vehicle stops at the deceleration less than or equal to the maximum deceleration.

The classification of three modes is the basis for analyzing of platoon operation and lane capacity later on. The safe stopping distance may guarantee the safety of the following vehicle, but shorter spacing or headway usually means higher efficiency or capacity. This is the reason to apply the adaptive or intelligent cruise control in the vehicle operation. In above modes, emergency control mode can ensure the higher safety but the lower capacity. The detailed analysis is shown on next sections.
3.3 Safe Stopping Distance Policies

According to the above classification, the values of deceleration play an important role in the control modes, thus we have to consider travel regimes with different decelerations to determine the safe stopping distance that can be applied to the control modes. It is obvious that the constant speed mode requires the maximum spacing from the downstream vehicle for the purpose of safe operation. The spacing for emergency operation should be greater than the vehicle-following mode. The following assumptions are made to simplify the analysis process in order to model the safe stopping distances for different travel regimes:

1. Vehicle travels in file on guideline. From this it is inferred that only vehicle following or free traveling is considered for control law, while vehicle merging, splitting, overtaking and lane-changing are ignored;

2. Vehicles are equipped with sensors which can detect relative velocity and distance from its preceding vehicle with a short reaction (detection) time;

3. The leading vehicle stops with an uniform deceleration which is either high finite value or infinite (instantaneous stop). The values of maximum or emergency deceleration are the same for both leading and following vehicles.

4. The deceleration for the following vehicle is assumed to be the trapezoidal profile for both speed transition and emergency stopping maneuver. The profile is shown on figure 3.1;

5. The errors of sensors are ignored, and all control systems and components are precisely reliable.
(4) The deceleration for the following vehicle is assumed to be the trapezoidal profile for both speed transition and emergency stopping maneuver. The profile is shown on figure 3.1;

(5) The errors of sensors are ignored, and all control systems and components are prefect reliable.

![Figure 3.1 Deceleration profile for the following vehicle](image1)

![Figure 3.2 Velocity profiles for leading and following vehicles](image2)
From above assumptions, velocity profiles for both leading and following vehicle are shown on the figure 3.2.

![Diagram showing vehicle following situation](image)

**Figure 3.3 Vehicle following situation**

According to distance relationship shown on figure 3.3, we get the following motion equation:

\[ D_s + d_{i-1} = d_i + D_t + L \]  \hfill (1)

where

- \( D_s \) = distance required between the successive vehicles
- \( D_t \) = distance between the rear of the leading vehicle to the front bump of the following vehicle
- \( L \) = vehicle length assumed to be same for both vehicle
- \( d_{i-1}, d_i \) = traveling distance during \( t \) before complete stopping
- \( t_r \) = sensor reaction time.
From equation (1)

\[ D_i = D_{i-1} + L + d_i - d_{i-1} \]  \hspace{1cm} (2)

where

\[ d_i - d_{i-1} = \int_0^t (V_{i(t)} - V_{i-1(t)}) \, dt \]

Based on the deceleration and velocity profiles, we get the following equations:

\[ d_i = \int_0^t V_i \, dt + \int_0^t \frac{V_i}{2} \, \frac{a_i}{j_i} \, dt + \int_{t_i}^{t_{i+1}} a_i \, dt \]

\[ d_i = V_i t_r + \int_{t_r}^{t_r + \frac{t_i}{j_i}} \int_{t_r}^{t_r + \frac{t_i}{j_i}} j_i (t - t_r) \, dt + \frac{V_i^2}{2a_i} \]

\[ d_i = V_i t_r + \frac{V_i^2}{2a_i} + \frac{V_i}{2} \, \frac{a_i}{j_i} \]

where

\[ j_i \text{ = jerk for vehicle } i, \]

\[ V_i \text{ = velocity at time } (t_r + \frac{a_i}{j_i}). \]
Thus,

\[ D_s = D_i + L + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_i}{j_i} + \frac{V_i}{a_i} \right) - \frac{V_{i-1}^2}{2a_{i-1}} \]  

(5)

To avoid collision, the following conditions should be met:

\[ D_i \geq 0 \]

and

\[ D_s \geq L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_i}{j_i} + \frac{V_i}{a_i} \right) - \frac{V_{i-1}^2}{2a_{i-1}} \]  

(6)

The different combination of \( a_i \) and \( a_{i-1} \) forms the different travel regimes. It is assumed that \( j \) is equal to the jerk limit. The following table shows the different regimes for the successive vehicle.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Decele</th>
<th>Decele</th>
<th>Minimum safe distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>leading</td>
<td>Follow</td>
<td></td>
<td>Control mode</td>
</tr>
<tr>
<td>1</td>
<td>infinite ( a_e )</td>
<td></td>
<td>S-sensored distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( D_1 \leq S )</td>
</tr>
<tr>
<td>2</td>
<td>( a_e )</td>
<td>( a_e )</td>
<td>Constant Speed</td>
</tr>
<tr>
<td></td>
<td>( D_2 = L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_e}{j_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{2a_e} )</td>
<td>( D_2 \leq S \leq D_1 )</td>
<td>Emergency</td>
</tr>
<tr>
<td>3</td>
<td>( a_n )</td>
<td>( a_e )</td>
<td>( D_3 \leq S \leq D_2 )</td>
</tr>
<tr>
<td></td>
<td>( D_3 = L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_n}{j_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{2a_n} )</td>
<td>Vehicle-following</td>
<td></td>
</tr>
</tbody>
</table>
The different combination of \( a_i \) and \( a_{i-1} \) forms the different travel regimes. It is assumed that \( j \) is equal to the jerk limit. The following table shows the different regimes for the successive vehicle.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Minimum safe distance</th>
<th>Control mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>leading Follow</td>
<td>[ D_1 = L_i + \frac{V_i}{2} \left( 2\Delta t + \frac{a_e}{j_e} + \frac{V_i}{a_e} \right) ]</td>
<td>( D_1 \leq S )</td>
</tr>
<tr>
<td>( a_e )</td>
<td>[ D_2 = L_i + \frac{V_i}{2} \left( 2\Delta t + \frac{a_e}{j_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{2a_e} ]</td>
<td>( D_2 \leq S \leq D_1 )</td>
</tr>
<tr>
<td>( a_e )</td>
<td>[ D_3 = L_i + \frac{V_i}{2} \left( 2\Delta t + \frac{a_e}{j_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{a_e} ]</td>
<td>( D_3 \leq S \leq D_1 )</td>
</tr>
</tbody>
</table>

According to the classification of control mode in section 3.1, if the sensed distance is greater than \( D_1 \), which is the worst situation and thus the most conservative spacing, the following vehicle should be operated at constant speed mode. If the distance less than the most conservative spacing but greater than \( D_2 \), vehicle is operated at emergency mode. If the distance less than \( D_3 \) but greater than \( D_3 \), it is operated at vehicle-following mode while \( D_3 \) is the minimum spacing that vehicle should maintain to ensure the least safety.
3.4 Vehicle Dynamic Model

As vehicle travels on gradient, the forces acting on it can be classified as two kinds: controlled or applied force, usually propulsive or braking, and uncontrolled force, usually from wing, friction and gradient either resistant or propulsive. Let $a$ denote the vehicle acceleration. According to Newton's second law, we have the following equation:

$$ma = f_c - f_u$$

(7)

where

$a$=vehicle acceleration,
$m$ = mass of the vehicle,
$f_c$ = controlled or applied force produce by engine
$f_u$ = uncontrolled force produce by its mechanical system or external factors.

It is noted that the controlled force is the output by the engine through commanded input based on specific control law. The uncontrolled force include the forces caused by aerodynamics, slop and mechanical rolling system and can be expressed as follows:

$$f_s = f_a + f_s + f_m$$

(8)
where

\( f_a \) = air resistance,

\( f_s \) = gravity force caused by slope,

\( f_m \) = force caused by mechanical system.

The air resistance's the function of velocity square and expressed as:

\[
f_a = C_a V_i^2
\]  \hspace{1cm} (9)

where \( C_a \) is the coefficient of air resistance and related to front area of the vehicle.

The slope force can be expressed as follows:

\[
f_s = mg \sin \alpha
\]  \hspace{1cm} (10)

where \( \alpha \) is the angle of the slope. Owing to the small angle of the slope, we have the following approximation.

\[
\sin \alpha \approx \tan \alpha \approx i
\]  \hspace{1cm} (11)

where \( i \) is the gradient.

Mechanical resistance includes rolling resistance and friction losses. It is the basic vehicle resistance and expressed as follows:
\[ f_m = (C_{m1} + C_{m2}V_i)mg \]  \hspace{1cm} (12)

where \( C_{m1} \) and \( C_{m2} \) are the coefficients related to rolling and friction.

From (9)(10)(11)(12), we rewrite the (8) as follows:

\[ f_u = C_a V_i^2 + (C_{m1} + C_{m2}V_i)mg + mgi \]

or

\[ f_u = m(C_a V_i^2 + C_m V_i + C_s) \]  \hspace{1cm} (13)

where

\[ C_a = \frac{C_a}{m} \]
\[ C_m = C_{m2}g \]
\[ C_s = (C_{m1} + i)g \]

From (13), the uncontrolled force is the function of vehicle velocity.
3.5 Control Laws

As assumed before, all vehicles are equipped with on-board sensors which can detect the relative velocity and distance from the leading vehicle. Acceleration of the leading vehicle could be sensed if they can communicate each other. The acceleration or deceleration can be automatically generated by the automatic system which gives command for propulsion or breaking in terms of different control laws. The choice of mode for the following vehicle is based on the distance from the preceding vehicle, therefore, the proposed control model is as follows:
Figure 3.4. Control flow chart for different modes

The proposed control law is assumed so that the desired or commanded acceleration for the following vehicle is the function of relative velocity, relative distance, following velocity, leading acceleration, desired distance, and desired following velocity. It is expressed as follows:
\[ a_{ci} = k_v (V_i - V_{i-1}) + k_d (D_d - \Delta X) + k_s (V_{d} - V_i) + k_a a_{i-1} \]  \hspace{1cm} (14)

where

\( a_{ci} \) = commanded acceleration for ith vehicle,

\( D_d \) = desired distance between leading and following vehicles,

\( V_d \) = desired cruise speed for ith vehicle,

\( \Delta X = X_i - X_{i-1} \) actual distance,

\( a_{i-1} \) = leading vehicle acceleration'

\( V_i \) = following speed'

\( k_v, k_d, k_s, k_a \) = control constant (gains) related to different factors.

**Constant Speed Mode**

In this mode, vehicle travels at the desired speed. The control logic is only based on the sensed distance from the downstream vehicle and not related to other parameters, therefore, the control gains in equation (14) become zero except the desired speed, that is,

\[ k_v = k_d = k_a = 0 \]

and the expression of desired acceleration becomes as follows:

\[ a_{ci} = k_s (V_{di} - V_i) \]  \hspace{1cm} (15)

or
\[ a_a = k_i V_{di} - k_i V_i \]  

(16)

This is common nonuniform acceleration model. The first term, \( k_i V_{di} \), is the maximum acceleration and \( V_{di} \) the maximum speed that vehicle can reach. In real-life control process, the first term is the acceleration limit, and the second the desired cruise speed.

**Emergency Control Mode**

In this mode, the desired distance is the second most conservative stopping distance. The sharp change of deceleration of the leading vehicle will result the response of the deceleration of the following vehicle.

**Vehicle-following Mode**

In this mode we try to assume that the desired acceleration of the following vehicle is not sensitive to the acceleration of the leading vehicle for it is not expected that the following vehicle quickly respond to the change of acceleration of the following vehicle in the close following distance in order to avoid the oscillation transmission. The commanded acceleration by (15) becomes as the following equation:[25][26]

\[ a_a = k_v (V_i - V_{i-1}) + k_d (D_{di} - d_i) + k_i (V_{di} - V_i) \]  

(17)
3.6 System Control Model

From the previous analysis of vehicle dynamics, vehicle acceleration is the result of controlled force and uncontrolled force. Having obtained the desired acceleration and the uncontrolled force, we can get the controlled force or engine input, that is,

\[ f_{ci} = m_i\alpha_{ci} + f_{ui} \]  (18)

where

\[ f_u = m_i (C_a V_i^2 + C_m V_i + C_s) \]

\[ \alpha_{ci} \text{= defined in (14)} \]

It is assumed that the engine dynamics follows the first order feedback longitudinal control, then we have the nonlinear differential equation, namely,

\[ f_{ci} = -\frac{f_{ci}}{\tau_i} + \frac{g_i}{\tau_i} \]  (19)

where
\( \dot{f}_{ci} \) = controlled force rate

\( g_i \) = engine input

\( \tau_i \) = engine time constant and function of speed.

From (19) and (18), we can get the feedback input \( g \):

\[
g_i = f_{ci} + \tau_i \dot{f}_{ci}
\]

(20)

where

\( \dot{f}_{ci} = m \dot{a}_{ci} + f_{wi} \), controlled force rate.

Other parameters are defined before. As a matter of fact, if acceleration and jerk limits are considered, their counterparts, controlled force and force rate should, should be considered. Let \( f_{lim}, \dot{f}_{lim} \) denote the force limit and force rate limit. The complete control system law is as following:

\[
g_i = \begin{cases} 
p_{ci} + \tau_i \dot{f}_{ci} & \left| \tau^{-1}(p_{ci} - \dot{f}_{ci}) \right| < f_{lim} \\
p_{ci} + \tau_i f_{lim} & \left| \tau^{-1}(p_{ci} - \dot{f}_{ci}) \right| \geq f_{lim} \end{cases}
\]

(21)

where

\[
p_{ci} = \begin{cases} 
f_{ci} & f_{ci} < f_{lim} \\
f_{lim} & f_{ci} \geq f_{lim} \end{cases}
\]

(22)

\[
f_{ci} = m \dot{a}_{ci} + f_{wi}
\]

(23)
\[ a_{\alpha} = k_v (V_i - V_{i-1}) + k_s (D_{\alpha} - d_i) + k_s (V_d - V_i) + k_d a_{i-1} \]  
\[ (24) \]

\[ f_{ui} = m_i (C_{d\alpha} V_i^2 + C_{m} V_i + C_z) \]  
\[ (25) \]
4. Platoon Operations and Traffic Simulation

In this chapter, the application of cruise control mode to the platoon operation is explored. Both interplatoon and intraplatoon operation logic are considered in order to realize the objectives: increasing road capacity and safety. Traffic simulation is performed to examine the platoon stability and to choose proper control parameters. A lane capacity formula is proposed in 4.6.
4.1 Platoon Operation Logic

It is necessary to repeat the some related assumptions made in the previous sections.

(1) Study is limited in a signal lane without passing, merging, splitting, etc.
(2) Uniformed vehicles are equipped with autonomous adaptive cruise controller and on-board sensors. Communications among vehicles are not necessary.
(3) Perfect vehicle dynamic system and sensor-computer-command system.

For interplatoon operation, one platoon should maintain minimum safe distance from the preceding one so as to ensure any collision within one platoon not to propagate to others. Therefore, the separation from the trailing platoon to the preceding should be greater than or equal to the most conservative stopping distance in order to avoid chain collision and to assure the maximum safety for every vehicle in the platoon. This requires the leader of the platoon is logically operated at two modes: constant speed or emergency control. Under these two modes the leader vehicle will stop with emergency deceleration without collision as the preceding platoon stops either instantaneously or with deceleration greater than the emergency or maximum allowable value. The critical distance for constant speed mode is $D_l$. If the safety factor is considered, the distance becomes $K*D_l$, where $K$ denotes safety factor and greater than or equal to $l$. In other words, the leader of the platoon ,if the sensed distance $S \geq K*D_l$, could be operated at constant speed mode and the condition is shown as follows:
constant mode choice if \( S \geq K \cdot D_1 \), where

\[
D_1 = L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_e}{J_e} + \frac{V_i}{a_i} \right)
\]  

(26)

The choice of emergency control mode is based on the sensed distance, the maximum distance \( KD_1 \), and the minimum distance \( KD_2 \), that is,

emergency mode choice if \( KD_2 \leq S \leq KD_1 \), where

\[
D_2 = L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_e}{J_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{2a_e}
\]

(27)

All vehicles in the platoon other than the leader are controlled under the vehicle-following mode. It is required that the vehicle stop with emergency deceleration without collision if the preceding vehicle stops with deceleration less than the emergency value but greater than the normal value. Therefore, the vehicle control mode choice is expressed as follows based on the sensed distance \( S \):

Vehicle-following mode choice if \( KD_3 \leq S \leq KD_2 \), where

\[
D_3 = L_i + \frac{V_i}{2} \left( 2 \Delta t + \frac{a_e}{J_e} + \frac{V_i}{a_e} \right) - \frac{V_{i-1}^2}{2a_e}
\]

(28)

The lane capacity analysis is performed in the next section and shows the benefits of such operational logic.
4.2 Simulation for Two Successive Vehicle

Analysis of two successive vehicles is the basis of simulation of platoon operation. In this section, the motion of the following vehicle under vehicle-following mode and emergency mode is simulated. In each mode, the responses of the following vehicle are recorded for two situations of the leading vehicle: (1) speed transition, and (2) emergency stopping.

Through trial-error approach, the determination of the control parameters is subject to two constraints:

1. Collision avoidance,
2. Stability, no oscillation for velocity and acceleration.

The following profiles are observed to examine above two conditions: acceleration, velocity, distance, velocity difference, and distance difference.

The acceleration profile of the leading vehicle is assumed as trapezoidal shape for both speed transition and emergency situation. The input parameters are as follows:

The initial velocity for both vehicle = 30 m/s;
The length of vehicle plus separation after stopping = 6 m;
The sensor reaction time = 0.1 s;
Emergency deceleration of the following vehicle = 0.5g;
Emergency jerk = 0.4g/s.

Based on the distance equation in 3.3, the steady state distance is calculated as follows:

For vehicle-following mode, the deceleration of the leading vehicle is assumed as 0.5g. The steady state distance is equal to 27.75 m;
For emergency mode, the deceleration of the leading vehicle is assumed as 1g. The steady state distance is 73.67 m.

The result of the simulation under emergency mode indicates that (1) as Kv increases, the distance between vehicles will increase. This means that the following vehicle will stop with greater deceleration and far from the leading vehicle. The range of the value is between 1.0 and 1.8; (2) Kd is very sensitive to the stability. The maximum value is 0.3. Fig 4.6 to 4.10 shows that the velocity and acceleration jump up and down as Kd is greater than 0.3; (3) The value of Ks has an effect on the safety. The range lesser than 0.5 will insure the collision avoidance; (4) Ka value has the least contribution either to stability or safety. As a matter of fact, it could be from 0 to 1.0. The simulation outputs for stable and unstable cases are shown through figure 4.1 to figure 4.10. The control parameters used in the graphs are list in the following table 4.1.
Table 4.1 Control Parameters Selected for Simulation of Two Successive Vehicles

<table>
<thead>
<tr>
<th>Parameters (emergency mode)</th>
<th>Stable control</th>
<th>Unstable control</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_v$</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$K_d$</td>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>$K_s$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$K_a$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The following set of parameters is used to simulate the speed transition situation:

$$K_v=1.2, \ K_d=0.8, \ K_s=0.02, \ K_a=0.02$$

Five periods are selected to represent the acceleration, deceleration and constant speed travel situation for the leading vehicle. The responses for the following vehicle are shown through figure 4.11 to 4.15.
Velocity Profile for Emergency Stopping under Emergency Control Mode

Figure 4.1 Following Vehicle under emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Figure 4.2 Following vehicle under emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Profile of Emergency Response of Following Vehicle under Emergency Mode

Figure 4.3 Following vehicle under emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Velocity Profile for Emergency Stopping under Emergency Control Mode

Figure 4.4 Following vehicle unstable control under emergency mode with $K(v)=1.4$, $K(d)=0.45$, $K(s)=0.01$, $K(a)=0.5$
Acceleration Profile of Emergency Response of Following Vehicle under Emergency Mode

Figure 4.5 Following vehicle unstable control under emergency mode with $K(v) = 1.4$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Profile of Emergency Response of Following Vehicle under Emergency Mode

Figure 4.6 Following vehicle unstable control under following mode with $K(v) = 1.4$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$
Velocity Profile for Emergency Stopping under Following Control Mode

Figure 4.7 Following Vehicle under following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.01$, $K(a) = 0.5$
Figure 4.8 Following vehicle under following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Profile of Emergency Response of Following Vehicle under Vehicle-following Mode

Figure 4.9 Following vehicle under following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.01$, $K(a) = 0.5$
Velocity Profile for Speed Transition under Following Control Mode

Figure 4.10 Following Vehicle under vehicle-following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.02$, $K(a) = 0.01$
Acceleration Profile of Speed Transition under Vehicle-Following Mode

Figure 4.11 Following vehicle under following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.02$, $K(a) = 0.01$
Distance Profile of Speed Transition for Following Vehicle under Following Mode

Figure 4.12 Following vehicle under following mode with $K(v) = 1.2$, $K(d) = 0.8$, $K(s) = 0.02$, $K(a) = 0.01$
Velocity Profile for Speed Transition under Emergency Control Mode

Figure 4.13 Following Vehicle under emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.02$, $K(a) = 0.6$
Figure 4.14 Following vehicle under Emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.02$, $K(a) = 0.6$
Distance Profile of Speed Transition for Following Vehicle under Emergency Mode

Figure 4.15 Following vehicle under Emergency mode with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.02$, $K(a) = 0.6$
4.3 Platoon Operation under Speed Transition

With the preparation of operation logic and the simulation of two vehicle, the platoon operation under speed transition is simulated from one steady state to another in this section.

A five-vehicle-platoon is forced to decelerate from the initial steady state with 30 m/s of velocity to 15 m/s. The criteria for determining the control parameters are almost same as those used in simulation of two vehicles, that is, platoon stability and safety. The platoon leader is assumed to travel under constant speed mode with 0.5g of maximum deceleration. Five profiles are observed including velocity, acceleration, distance, velocity difference, and distance difference. Both stable and unstable control situations under different parameters are shown through figure 4.16 to figure 4.25.

The results of simulation indicated that (1) Kv is not sensitive to the travel distance, but it has an critical effect on stability. Its value should be less than 1.4; (2) Kd affects platoon safety and is less than 1.9; (3) Ks should less than 1.2 in order to avoid the unstable situation. Figure 4.20 through 4.25 showed such situation as the value of Ks was changed to 1.35; (4) The value of Ka has little contribution to either stability of safety if it is less than 2.0. As a matter of fact, these results are consistent with analysis in two vehicle
simulation for the vehicle following mode. The values of control parameters are summarized in the following Table 4.2.

### Table 4.2 Values of Control Parameters under Vehicle-following Mode

<table>
<thead>
<tr>
<th>Control parameters for vehicle-following mode</th>
<th>Value interval</th>
<th>Values selected in graph for stable control</th>
<th>Values selected for unstable control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kv</td>
<td>&lt;1.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Kd</td>
<td>&lt;1.9</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Ks</td>
<td>&lt;1.2</td>
<td>0.2</td>
<td>1.35</td>
</tr>
<tr>
<td>Ka</td>
<td>0~2.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Velocity Profile of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.16 Platoon stable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 0.2$, $K(a) = 0$
Acceleration Profile of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.17 Acceleration profile for platoon stable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 0.2$, $K(a) = 0$
Distance Profile of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.18 Distance profile for platoon stable control with K(v) = 1.2, K(d) = 1.8, K(s) = 0.2, K(a) = 0
Distance Difference Profile between Vehicles for Speed Transition from 30 m/s to 15 m/s

Figure 4.19 Desired and actual spacing profile for platoon stable control with \( K(v) = 1.2, K(d) = 1.8, K(s) = 0.2, K(a) = 0 \)
Velocity Difference Profile between Vehicles of Platoons Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.20 Velocity error for platoon stable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 0.2$, $K(a) = 0$
Velocity Profile of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.21 Platoon unstable control with $K(v)=1.2$, $K(d)=1.8$, $K(s)=1.35$, $K(a)=0$
Figure 4.22 Acceleration profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 1.35$, $K(a) = 0$
Distance Profile of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.23 Distance profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 1.35$, $K[a] = 0$
Distance Difference profile between Vehicles for Speed Transition from 30 m/s to 15 m/s

Figure 4.24 Desired and actual distance difference profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 1.8$, $K(s) = 1.35$, $K(a) = 0$
Velocity Difference Profile between Vehicles of Platoon Response for Speed Transition from 30 m/s to 15 m/s

Figure 4.25 Velocity Difference for platoon unstable control with K(v) = 1.2, K(d) = 1.8, K(s) = 1.35, K(a) = 0
4.4 Platoon Emergency Control

When there is an obstruction or a vehicle stopping on the downstream road, the platoon should take emergency stopping without collision. During this period, all of the vehicles should stop stably and smoothly.

In emergency case, the platoon leader is assumed to operated under emergency mode. If it is operated under constant speed mode, it has the ability to stop for worst case. Therefore, only the emergency mode for the leader is considered for simulation, while intraplatoon vehicles are operated under vehicle-following mode. The downstream vehicle is assumed to travel with 30 m/s velocity and then stops with maximum deceleration, 1g. The steady state distance between platoon leader to the preceding vehicle is calculated as 60 m and the distance between intraplatoon vehicles 30m. The initial steady-state velocity is assumed to be 30 m/s. The steady-state configuration is shown on the following Figure 4.26.

Fig 4.26 Platoon configuration in steady state
The simulation results show that $K_d$ is very sensitive to platoon stable control and $K_s$ has an great effect on the safety. The values of control parameters under emergency mode are summarized in the following table 4.3.

<table>
<thead>
<tr>
<th>Control parameters in emergency mode</th>
<th>Value range</th>
<th>Values selected for stable control</th>
<th>Values selected for unstable control</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_v$</td>
<td>$&lt;1.4$</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$K_d$</td>
<td>$&lt;0.35$</td>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>$K_s$</td>
<td>$&lt;0.2$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$K_a$</td>
<td>$&lt;2.0$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The velocity, acceleration, distance, velocity difference and distance profiles are shown on Figure 4.27 through Figure 4.36 for stable and unstable platoon control.
Velocity Profile of Platoon Response for Emergency Stopping

Figure 4.27 Platoon stable control with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Acceleration Profile of Platoon Response for Emergency Stopping with Maximum Acceleration 1G

Figure 4.28 Acceleration profile for platoon stable control with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Profile of Platoon Response for Emergency Stopping with Preceding Acceleration 1G

Figure 4.29 Distance profile for platoon stable control with \( \text{K}(\nu) = 1.2, \text{K}(d) = 0.3, \text{K}(s) = 0.01, \text{K}(a) = 0.5 \)
Figure 4.30 Spacing profile for platoon stable control with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.01$, $K(a) = 0.5$
Velocity Difference Profile between Vehicles of Platoon Response for Emergency Stopping with Maximum Preceding Acceleration 1G

Figure 4.31 Velocity difference for platoon stable control with $K(v) = 1.2$, $K(d) = 0.3$, $K(s) = 0.05$, $K(a) = 0.5$
Figure 4.32 Platoon unstable control with $K(v) = 1.2$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$.

Velocity Profile of Platoon Response for Emergency Stopping with Maximum Preceding Acceleration 1G.
Acceleration Profile of Platoon Response for Emergency Stopping with Maximum Acceleration 1G

![Graph showing acceleration profile over time for different vehicles.]

Figure 4.33 Acceleration profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Profile of Platoon Response for Emergency Stopping with Maximum Preceding Acceleration 1G

Figure 4.34 Distance profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$
Distance Difference Profile between Vehicles for Emergency Stopping with Maximum Preceding Acceleration 1G

Figure 4.35 Spacing profile for platoon unstable control with $K(v) = 1.2$, $K(d) = 0.45$, $K(s) = 0.01$, $K(a) = 0.5$
Velocity Difference Profile between Vehicles of Platoon Response for Emergency Stopping with Maximum Preceding Acceleration 1G

Figure 4.36 Velocity difference for platoon unstable control with $K(v) = 1.2$, $K(d) = 0.45$, $K(s) = 0.05$, $K(a) = 0.5$
4.5 Platoon Leader Splitting

In this section, the case for platoon leader splitting from the platoon is simulated. It is assumed that the leader travels under emergency control mode in the steady state. As the leader leaves, the second vehicle will become new leader; consequently, it has to switch from vehicle-following mode to emergency mode. Since the initial distance is greater than the steady-state distance, it will cause new leader to accelerate and finally reach to new steady-state traveling. In the simulation, the steady-state distance for emergency mode is set to be 75 m and 30 m for the vehicle-following mode. The steady-state velocity is 30 m/s. Figure 4.37 through Figure 4.39 show this process.
The simulation results are shown on the Figure 4.40 through Figure 4.44. The control parameters are selected as following: $K_v=1.2$, $K_d=0.17$, $K_s=0.01$, and $K_a=0$ for the emergency control mode.
Velocity Profile of Platoon Response for Platoon Leader Splitting

Figure 4.40 Platoon stable control with $K(v) = 1.2$, $K(d) = 0.17$, $K(s) = 0.01$
Acceleration Profile of Platoon Response for Platoon Leader Splitting

Figure 4.41 Acceleration profile for platoon stable control with $K(v) = 1.2$, $K(d) = 0.17$, $K(a) = 0.01$
Distance Profile of Platoon Response for Platoon Leader Splitting

Figure 4.42 Distance profile for platoon stable control with $K(v) = 1.2$, $K(d) = 0.17$, $K(s) = 0.01$
Position Difference between Vehicles for Platoon Leader Splitting

Figure 4.43 Spacing profile for platoon stable control with $K(v) = 1.2$, $K(d) = 0.17$, $K(s) = 0.01$
Damped Velocity Difference Profile for Platoon Leader Splitting

Figure 4.44 Velocity difference for platoon stable control with $K(v) = 1.2$, $K(d) = 0.17$, $K(s) = 0.01$
4.6 Simulation Process

Simulation approach is applied to this project. Through the simulation, we can imitate the real-life vehicle movement and test the logic without implementation of the theory. The goals of simulation are to obtain proper control parameters in each control mode, to observe the outputs to insure platoon traveling in stable condition, and to assure the collision avoidance when vehicle responds to emergency stopping.

Simulation Model

According to the previous analysis of system cruise control process in Chapter 3.5, as actual distance between vehicles is measured and compared with minimum safe distance, the equipped computer-controlled system will give a command to the vehicle to either accelerate or decelerate depending upon the difference between measured distance and minimum safe distance and desired mode. At that moment, the acceleration model (17) in Chapter 3.5 is executed and give out specific value of acceleration or deceleration until vehicle reaches steady state. In simulation process, equation (17) could be re-written as following differential equation.
\[
\frac{d^2 x_i}{dt^2} = k_v \left( \frac{dx_i}{dt} - \frac{dx_{i-1}}{dt} \right) + k_d [D_d - (x_i - x_{i-1})] + k_s (v_d - \frac{dx_i}{dt}) + k_a \frac{d^2 x_{i-1}}{dt^2}
\]

Let T denote simulation time step. We get the following equations which can be used in adaptively describing each vehicle movement.

\[
a_{i(t)} = k_v (v_{i(t)} - v_{i-1(t)}) + k_d (D_d - (x_{i(t)} - x_{i-1(t)}) + k_s (v_d - v_{i(t)}) + k_a a_{i-1(t)}
\]

\[
v_{i(t+T)} = v_{i(t)} + T a_{i(t)}
\]

\[
x_{i(t+T)} = x_{i(t)} + T \frac{v_{i(t)} + v_{i(t+T)}}{2}
\]

where \(i = 2, ..., n\) if the platoon has \(n\) vehicles.

**Simulation Flow Chart**

From the equations used in the simulation, we see that it is a circulating system where the computed outputs, velocity and distance, are again used in the next input if the vehicle does not reach the desired distance and velocity. Control parameters play an important role in this process. Different values will produce different acceleration or deceleration and result platoon traveling in stable or instable condition. Through the simulation, we can determine the proper control parameters considering stability, acceleration limit, jerk limit, and collision avoidance. The following flow chart Figure 4.46 shows this process.
Simulation Tool

Spreadsheet is used in this simulation process. The time step is 0.5 second considering the accuracy and working load. Simulation time is usually set as 50 to 100 seconds depending upon each scenarios. The input of control parameters is test-and-error process. The final output of the control parameters is obtained under the satisfaction of those constraints, however, other figures also show those parameters which will make platoon operation in instable condition.
Figure 4.46 Simulation Flow Chart
4.7 Simulation Output Analysis

Platoon Stability
Platoon stability is an important index for passenger comfort and vehicle safety. Through traffic simulation based on the proposed logic and models, we see that different values of control parameters could result in a different pattern of platoon traveling. From Figure 4.22, if Ks is changed from 0.2 to 1.35, it will give a up-and-down command of acceleration and deceleration to the vehicle. In macro-level, the vehicle and platoon will travel in an unstable condition. Sometimes, it will probably produce large value of acceleration or deceleration. From Figure 4.33, the maximum acceleration reaches 35 m/s², which is unacceptable for the human tolerance, so control parameters should be properly selected. All figures illustrate two alternatives: one is platoon traveling in stable condition, and another shows that platoon is traveling in an unstable condition if control parameters are not correctly chosen.

Safety and Acceleration Limit Analysis
Beside considering stability, the simulation results also indicate if the vehicle can avoid collision under the selected control parameters. This could be observed from the outputs of distance profiles. If the distance between two adjacent vehicles is less than the vehicle length, collision will happen when there is an emergency braking or speed changing. This is the most important criteria to select control parameters. Although none of figures
shows the collision situation, it occurs a lot as doing trial-and-error analysis to select proper control parameters.

Acceleration and deceleration limit is also a criteria used in the traffic simulation. In Figure 4.28, maximum deceleration is as high as 7 m/s\(^2\). This is almost close to gravity acceleration and beyond human's tolerance, but we can still reduce the value through lots of times of trial. Please note that all of output figures just show that platoon could travel in stability and under acceleration limit following the proposed model and logic, and those control parameters are only example values under which platoon can be either in stability or instability. Searching for optimal solution of platoon stability or acceleration limit needs lots of work and seems worthless because some of other practical factors should be seriously considered before such kind of parameters, models and logic are implemented in the intelligent cruise control devices and platoon operation logic. Those factors include sensor error, data processing, communication between vehicles and road-side, vehicle system control reliability, etc.. Researches on these factors affecting the control model and platoon operation in the future's automated highway system are very important but already beyond this thesis.
4.8 Lane Capacity Analysis

In order to analyze the lane capacity, the following assumptions are made for the ideal and saturated situation.

(1) Vehicles are operated strictly at the modes stated above, that is, emergency control for the platoon leader and vehicle-following for in-platoon vehicles;
(2) Every platoon has the same number of uniformed vehicles with length of $L$.
(3) Traveling platoon has the same nominal line speed $V_p$.

The emergency spacing is assumed to be $KD_2$ and vehicle-following spacing $KD_3$. The platoon configuration is shown on figure 4.45.

![Platoon configuration diagram](image)

Figure 4.45 Platoon configuration
Let $V_p$ be the nominal line speed. From the above configuration and assumption, the saturated spacing headway is:

$$\text{Spacing headway} = (N-1)D_3 + L + (D_2 - L)$$

$$= (N-1)D_3 + D_2$$

The minimum time headway of platoon is as follows:

$$h_{\text{min}}^p = \frac{(N-1)D_3 + D_2}{V_p} \quad (29)$$

Let $C$ denote the lane capacity. Therefore $C$ could be expressed as follows:

$$C = \frac{3600N}{h_{\text{min}}^p} \quad (30)$$

Substitute (29) into (30), we obtain the following model:

$$C = \frac{3600NV_p}{(N-1)D_3 + D_2} \quad (31)$$

It is noted that the variable $N$ has an important effect on lane capacity. California PATH researchers took it as the average number of vehicles in platoons. The greater value of $N$ means a longer platoon, which will lead to lose the emergency control mode between platoons. This will have negative effect on the safety operation. However, smaller $N$ will
decrease the lane capacity and lose the function of alleviating traffic congestion. Thus, the
determination of N value is based on the tradeoff between road efficiency and safety. As a
matter of fact, the determination of vehicle numbers in platoon is closely related to other
advanced highway management technologies such as ramp metering, vehicle splitting and
merging, etc. This means that improvement of roadway efficiency and safety can not be
realized only by intelligent cruise control technology, but also the integration of IVHS
technologies. However, it is evident from this research that the intelligent control
technology does improve the capacity and safety to some extent. This will be shown in the
following theoretical calculation and analysis. For simple reason, we just make assumption
of the N value in this study. The exploration of the optimal solution is already beyond this
thesis.

Initial Data Input to Calculate Capacity

\[ \Delta t = 0.1 \text{s} \]
\[ a_e = 0.5g \]
\[ j_e = 0.4g/s \]
\[ V = 25 \text{ m/s} \]
\[ a_n = 0.2\text{--}0.4g \]
\[ L = 8 \text{ m} \]
\[ K = 1.0 \]

The lane capacity for different platoon size is shown on the Figure 4.47.
Lane Capacity for Different Size of Platoon

Figure 4.47 Lane Capacity under Different Size of Platoon
Capacity Analysis under N=1

If platoon size is one vehicle, it means that vehicle travels either in emergency control mode or constant speed mode. We will lane capacity change under different jerk limit and reaction time.

Since N=1, we can assume that D_2=D_3. We re-write the capacity equation as follows:

\[
C = \frac{3600Nv_p}{ND_2 - D_2 + D_2} \\
= \frac{3600Nv_p}{ND_2} \\
= \frac{3600v_p}{D_2}
\]

We assume that vehicles travel in emergency mode and has the same speed, then we get the following equation.

\[
D_2 = L_i + \frac{V}{2} (2 \Delta t + \frac{a_e}{j_e})
\]

Substituting the distance equation into capacity equation, we get

\[
C = \frac{3600V}{L + V \Delta t + V \frac{a_e}{2 j_e}}
\]

Case 1: acceleration 0.5g, jerk 0.4 g/s, reaction time 0.1 s.

The capacity equation is expressed as follows.

\[
C = \frac{3600V}{8 + 0.725V}
\]
We calculate some of capacity values for different speed.

\[ C_{v=10} = 2360 \text{ veh/hr} \]
\[ C_{v=20} = 3200 \text{ veh/hr} \]
\[ C_{v=30} = 3630 \text{ veh/hr} \]

Case 2: acceleration 0.5g, jerk 4g/s, reaction 0.1 s.

The capacity equation becomes as follows.

\[ C = \frac{3600V}{8 + 0.1625V} \]
\[ C_{v=10} = 3740 \text{ veh/hr} \]
\[ C_{v=20} = 6400 \text{ veh/hr} \]
\[ C_{v=30} = 8388 \text{ veh/hr} \]

Case 3: acceleration 0.5g, omit jerk, reaction time 1s for manual control.

The capacity equation becomes as follows.

\[ C = \frac{3600V}{8 + 1.0V} \]
\[ C_{v=10} = 2000 \text{ veh/hr} \]
\[ C_{v=20} = 2571 \text{ veh/hr} \]
\[ C_{v=30} = 2842 \text{ veh/hr} \]

Case 4: acceleration 0.5g, omit jerk, reaction time 1.5s.

The capacity equation becomes as follows.

\[ C = \frac{3600V}{8 + 1.5V} \]
\[ C_{v=10} = 1565 \]
$C_{V_{\infty}} = 1895$

$C_{V_{\infty}} = 2038$

All four cases are illustrated in the following diagram Figure 4.48 for continuous speed change.
4.9 Sensor Error

Sensor plays a critical role in the process of automated vehicle control. Through the on-board sensor equipment, the relative velocity, distance even acceleration from the preceding vehicle can be detected and applied to the computer-controller system. However, there always exist sensor errors caused by either technical problems or external circumstances such as weather, road curve, etc.. If we ignore these errors, the biased data transmitted to the controller might cause the command mistake and lead to accident. In this section, the distribution of sensor error will be assumed and the mean will be utilized to the control model.

It is assumed that the sensor errors have an effect on the measured data: relative velocity and distance. Since the acceleration of the leading vehicle is transmitted by data processor, the error effectiveness is not tempoarily considered. Let $\delta_d, \delta_v$ denote the percentage errors on relative spacing and velocity with mean of $\mu_d, \mu_v$ and standard deviation of $\sigma_d, \sigma_v$. The probability function is in the following equation:

\[ F(\delta_d) = \mathcal{N}(\mu_d, \sigma_d) \]

\[ F(\delta_v) = \mathcal{N}(\mu_v, \sigma_v) \]
In the real situation, the sensor error randomly occurs. Let the probability of sensor error be a random number between 0 and 1, and it is denoted by $r$. $r$ can be obtained based on the above equations.

We can utilize the obtained value to modify the control model by substituting the error terms to measured data. The distribution of error percentage is shown on the figure 4.47. Further study on sensor is recommended in the future's research.
5. Conclusions and Recommendations

Through the development of adaptive cruise control model and simulation of traffic operations in terms of platoon modal operation algorithm, we obtain the following conclusions:

1. The vehicle adaptive cruise control law has the function of the relative velocity, difference of the desired minimum stopping distance and the relative distance, and difference of desired cruise speed and actual speed. The acceleration of the leading vehicle has little effect on the vehicle stable control or safety of the following vehicle;

2. The adaptive cruise control is designed into three operational modes: constant speed, emergency control, and vehicle-following based on the minimum stopping distance policy. According to this sequence, performance of vehicle safety increases but roadway capacity decreases. Subject to the safety and efficiency, platoon modal operation algorithm is proposed so that the platoon leader is always operated under either constant speed or emergency mode, while intraplatoon vehicles are operated under vehicle-following mode. The implementation of this operational algorithm is conducted through sensoring the distance from the downstream vehicle and comparing
with the desired distance to instruct the driver which mode he should use or automatically switch one mode to another;

3. Every control parameter in the vehicle cruise control mode has a value range in order to ensure the collision and oscillation avoidance. Proper selection of these value results in vehicle or platoon stable control under the limits of maximum acceleration or deceleration. This also proves that the developed control model could be well used in the adaptive cruise control technology.

However the above findings are based on many assumptions which might cause some results to deviate from the real traffic situation or implementation unreality. Besides the technical aspects in mechanical or electrical engineering, the following topics should be at least recommended for further study in transportation engineering in order to successfully apply intelligent cruise control technology in AHS and integrate with other technologies in IVHS program:

1. More vehicles should be simulated to examine the control parameters. Some thresholds need to be set to judge the platoon stability;

2. In the mix traffic including ICC equipped vehicles and non-equipped vehicles, how to operate the equipped vehicle under the influence or disturbance of nonequipped vehicles by changing the control laws should be further studied. This is the key issue to implement such technology to the real situation;
3. How to integrate the intelligent cruise control with other technologies of control laws should be included in the further study. As mentioned in the chapter four, roadway platoon operations are not only issue of intelligent cruise control but associated with other control methods.
6. Reference


27. A. Ioannou, C. C. Chien and J. Hauser, *Autonomous Intelligent Cruise Control*, Southern California Center for Advanced Transportation Technologies, University of Southern California, Los Angeles, California


7. VITA

JINGSHENG YAN

Date of Birth: July 25, 1963

CAPABILITIES & ACCOMPLISHMENTS

TRAFFIC ENGINEERING AND OPERATIONS
• Evaluated and tested new logic for NETSIM by traffic simulation for arterial streets, interchanges, freeways, and urban networks
• Analyzed the impact of pedestrian demand on delays of right turn vehicles at actuated controllers to examine the pedestrian logic in the NETSIM model
• Assessed and tested Expert Signal, a software package for optimization and evaluation of actuated controllers, through a comparison of its signal timing with EVIPAS and HCS
• Developed bicycle traffic flow models, which have been applied to the prediction of intersection traffic flow patterns in the Urban Area Control Techniques project
• Proposed a traffic operation improvement plan, whose implementation reduced the vehicle delay by 30 percent and traffic accident rate by 20 percent

IVHS AREA
• Proposed an adaptive vehicle cruise control model
• Developed a platoon operation algorithm for automated highway systems
• Assessed electronic pre-clearance service for truck operations in weight stations by simulation approaches

TRANSPORTATION PLANNING
• Modeled travel demand forecasting in the Transportation Planning for Lianyungang area
• Planned transportation facilities including the highway system, transit system, urban street network, and bicycle route for the City of Lianyungang
• Planned a mass transit system from Dulles Airport to CBD, Washington D.C. by QRSII
• Selected the best trip generation model by statistical analysis using SAS

ROADWAY AND BRIDGE DESIGN
• Designed a 2-mile-long street including its geometric, pavement structure, intersections, drainage, and super-elevation, etc.
• Designed a 180-feet-span arch bridge with calculation of its upper structure and foundation

EXPERIENCE

RESEARCH FELLOW
Turner-Fairbank Highway Research Center, FHWA, McLean, VA, July 1993-present
Responsibilities:
• Assist chief engineers in IVHS research and project management activities
• Test TRAF family traffic software and related supporting programs
• Categorize urban interchanges based on their functions, control types, and geometric designs
• Develop procedures for the evaluation of capacity and level-of-service for different types of interchanges by simulation approach

ASSISTANT ENGINEER
Responsibilities:
• Conducted traffic engineering analysis for problem areas to determine the necessary corrective and future actions in traffic operation and planning
• Reviewed city traffic control plans and calibrated control parameters
• Performed detailed travel demand modeling for the long range transportation planning
• Updated and planned the City's transportation facilities including highway, transit system, urban street networks, and bicycle routes
• Represented the Planning Division as a liaison with other government and private agencies

RESEARCH ASSISTANT
Tongji University, Shanghai, China, January 1986 to May 1988
• Developed non-auto traffic control strategies for the Urban Traffic Control Techniques project, the first real-time traffic control system in China
• Participated in the survey and interview for trip generation in the Comprehensive Transportation Planning for Shanghai Metropolitan Area

COMPUTER SKILLS
• Proficiency in applying the following software packages to traffic studies and planning: HCS, NETSIM, TRANSYT-7F, QRSII, MINUTP, FRESIM, CORSIM, CORFLO, EVIPAS, ExpertSig, DYNAMO, SAS
• Extensively utilized BASIC, and FORTRAN77 for programming, and dBASE IV, Microsoft Word 2.0, Excel 4.0, WP5.1 for data management and word processing

EDUCATION
Virginia Polytechnic Institute & State University, Blacksburg, VA
M.S.C.E., Transportation Engineering, GPA 3.81/4.00 (June 1994)

Tongji University, Shanghai, China
M.S.C.E., Traffic Engineering, GPA 3.69/4.00 (May 1988)
B.S.C.E., Urban Roadway and Highway Engineering, GPA 3.33/4.00 (July 1985)

PUBLICATIONS & REPORTS
• Evaluation of Expert Signal and Summary of Beta User Results, project report submitted to the IVHS Division, FHWA, November 1993
• Planning and Design of a Mass Transit System from Dulles Airport to CBD, Washington, D.C., project report, December 1992
• Strategies for Improving the City Traffic Flow Conditions-Traffic Operations and Planning, Urban Traffic Operations and Management, December 1990