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## **Coordination Layer Control Design for Automated Trucks and Buses**

**Xiao-Yun Lu**  
**Sungmoon Joo**  
**J. Karl Hedrick**

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This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

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# Executive Summary

This project is to preliminarily study the coordination layer control and decision making for automated trucks and buses. The most challenging issues for the maneuverability of truck/bus are:

- (a) The overall system model for longitudinal control is highly nonlinear;
- (b) Large time delays in power-train and actuators, particularly, control command to torque production delay, engine torque to wheel torque production delay, braking system (air brake, transmission retarder and Jake brake) delay;
- (c) Their acceleration capability is severely limited, which is due to the low mass/power ratio compared to other vehicles;
- (d) Large internal/external disturbances from gear shifting, wind (aerodynamic dragging), road unevenness and road grade.

Maneuver design and coordination algorithm need to take those factors into consideration. Practical achievement in this project includes the following three parts:

## **I. Automated Ground Vehicle Maneuver Coordination**

A systems approach is used for research in the sense that each automated vehicle is considered as a subsystem and the overall system is composed of a finite number of subsystems. Some of those subsystems are inter-connected (neighboring vehicles are coupled). The configuration of the overall system is dynamically changing because the couplings are changing as time elapses. However, the complete design of coordination layer is huge task and the research conducted in this project is preliminary.

- (1) Mathematical modeling for coordination layer control and decision making;
- (2) Multiple vehicle maneuver coordination and optimal trajectory planning.

## **II. Maneuver Design for Automated Truck/Bus**

Although maneuver design for passenger cars has been conducted in previous work and showed in 97-Demo [33], they are not suitable for Heavy-Duty Truck (HDT) and Buses any more because truck/bus control system performance is severely limited by its acceleration capabilities, or equivalently, control is easy to saturate. Work conducted in this part includes:

- (1) To investigate truck/bus acceleration/deceleration capability under automated control for single vehicle and for vehicle following on flat road and on a slope;
- (2) Practical String Stability for automated truck/bus vehicle following;
- (3) Automated vehicle maneuver design and implementation:
  - Two HDTs short distance following
  - Transition between manual and automatic driving of a HDT

- Vehicle deceleration to stop in vehicle following mode
- Splitting
- Joining

### III. Simulation Package Development

As other simulation packages, the purpose for work in this part is to develop model based platform for control design and real-time code development. This is the most economic, safe and efficient and thus scientific way for control system development. Work in this part include:

(1) Using available optimization tool to solve some simple trajectory planning problem of a single vehicle;

(2) Development of simulation package which integrates the following maneuvers and their coordination when operated for three HDTs. In the simulation, the maneuvers are considered as discrete event. These maneuvers include:

- Transition between manual and automatic driving
- Vehicle following after transition to automatic driving mode;
- Splitting
- Joining
- Lane changing
- The third truck merge from behind of two truck platoon to form a 3 truck platoon (following)
- Vehicle deceleration to stop in vehicle following mode.

It is to emphasized that, the acceleration capability of a fully loaded HDT drops significantly when speed increases. This is a severe constraint which needs taken into consideration for any practical maneuver design. It is even more severe to the merging algorithm developed in [26]. However, by proper choice of design parameter, the problem is solved in simulation. Because vehicle acceleration capability and other implementation related issues are taken into consideration, the algorithm developed in the simulation is likely to be implementable on bus/truck.

# Chapter 1

## Preface

Coordination of maneuvers of multiple automated vehicles is an active research area from a system point of view. The vehicles include automated robot, un-manned air vehicles (UAVs), automated or semi-automated military vehicles on land, in the air and the water. This project is to develop the maneuvers of automated road vehicles, particularly, trucks and buses. From a systems point of view, if we consider each vehicle a subsystem, the overall system is composed of a finite number of inter-connected subsystems. The relationship between each pair of subsystems are changing, which is determined by the relative speed and location of each vehicle. This means that the overall system configuration is dynamically changing. This is the characteristics of such a system different from other inter-connected system such as those encountered in industrial assembly line.

Coordination of vehicle maneuvers can be considered localized by isolating the system as composed of only those vehicles involved in the maneuver. Other vehicles which are not involved will not be included in the system. The purpose of the coordination is to make all the vehicles in the system to behave coherently, efficiently, safely, and optimally.

In present highway system, vehicle maneuver is carried out based lane choice, perception, decision and command. Lane choice is determined by driver's behavior and traffic situation; Driver's perception of current driving environment is the main factor for decision making for vehicle maneuvering control: vehicle speed, acceleration/deceleration, steering, stop, etc.. In turn, this decision is made based on the following factors: Generally accepted driving rule which is to be followed by all the drivers. It involves desired vehicle speed, following distance, signaling for maneuvering, traffic signs, and driver's personnel preference (a mixture of competition and cooperation). Instead of centralized control and coordination for maneuvers, all the drivers involved abide by the same rule for driving and negotiate when maneuvering. There are many uncertainties involved in current highway system, which makes highway

traffic unpredictable, particularly, bottleneck (including incident and accident) which causes severe traffic congestion.

For automated vehicle system, multiple vehicle maneuvers always need hierarchical and centralized control. Thus a centralized coordination is unavoidable in the future for automated vehicles. This is based on the following considerations.

(1) Vehicle automation is evolving rapidly to higher and higher level. Nowadays, with the widely use of cheap computer processors, many parts of a modern vehicle are automatically controlled, such as engine, transmission, braking, temperature, fueling, valve timing, power steering, driving-by-wire. Automation is not just restricted to vehicle system itself, but also the driver assistance system. This involves CC (Cruise Control), ACC (Adaptive Cruise Control), Lane departure warning, front collision warning and avoidance.

(2) The development and widely use of DSRC (Dedicated Short Range Communication) between vehicles will not only make such a coordination feasible but also will become an important impetus for locally centralized coordination;

(3) A centralized hierarchical control system can make the traffic deterministic and cooperative, which effectively eliminate all the uncertainties.

The following figure (Figure 1.1) shows the general picture for the coordination of maneuvers of automated vehicles.

The results of this project can be used for local coordination of maneuvers for automated vehicle system, automated people mover systems, and automated train system. As along multiple vehicle are driving in a limited environment, coordination is necessary to make the overall system *safe, coherent and efficient*.

The lowest layer, *regulation layer*, is the control system on each vehicle, which executes a series of commands to fulfill the tasks determined by the desired maneuver (reference trajectory tracking) assigned by a *coordination manager*. A coordination layer is *event driven* in the sense that a request of a maneuver from a vehicle may be random in time, space and type. The task for coordination manager is to make the maneuver to be performed deterministically in both space and time. This is the only possible way to make all the things under control and thus to guarantee safety. Above the coordination layer are the *link layer manager* and *network layer manager* which are for the linkage between two adjacent sections and different highways respectively, which are not to be discussed here [38].

In the past 10 years, regulation layer controllers have been developed, particularly, longitudinal control for vehicle following [2, 6, 31, 33, 34] and lateral control [30, 37] for lane keeping and lane changing. The maneuvers include car speeding up, splitting, joining, lane changing to join to the end of a platoon, slowing down and stop. *Automated vehicle merg-*

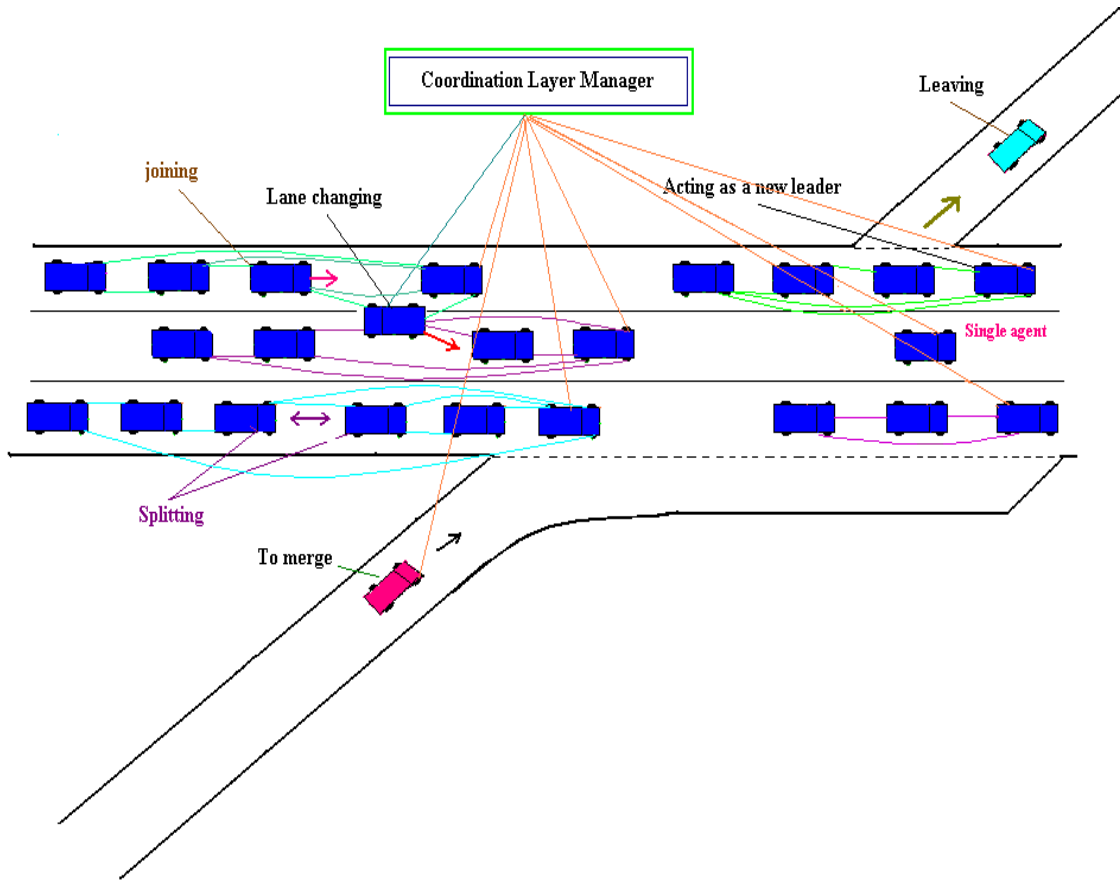


Figure 1.1: Maneuver coordination of ground vehicles

ing developed in [14, 24] is another step forward in maneuver development which enables a dynamic interaction between a vehicle from on-ramp and a platoon of vehicles.

A maneuver is *safe* if there is no danger of time and space overlap. In fact, any crash is caused by time and space overlap. This is a crucial safety factor of the mathematical principle for the decision making in a coordination layer. Although each event (maneuver performing) may happen discretely, they are imbedded in a continuous time-space infrastructure. Furthermore, they should happen optimally according to some performance criteria such as minimum time, fuel consumption and emission, maximum safety and throughput. From this point of view, these event should come from a optimal discrete solution of a continuous a model.

In the current highway system if vehicles are completely controlled by the driver, possibility of application of the maneuver coordination to improve safety and efficiency still

exist. For example, coordinated free lane change or infrastructure-supported merge. Control design technologies developed for vehicle following can be used for *driver assistance system* for cars and Heavy-Duty Trucks in a short term, to mention a few.

This final report is organized as follows. Chapter 2 presents mathematical frameworks for coordination layer modeling for control and decision making; Chapter 3 study practical string stability for automated vehicle following; Chapter 4 to discuss HDT control for short distance following including implementation related issues; Chapter 5 presents in detail the design and implementation of transition maneuvers between manual driving and automatic driving, which is the most important one for the interaction between the driver and the vehicle control system; Chapter 6 to discuss some other maneuvers design, optimization and coordination, including joining, splitting and merging; Chapter 7 describes simulation development both in Matlab and in C. The purpose to use C is for real-time code development for control and maneuver coordination for automated HDTs.



# Chapter 2

## Coordination Layer Modeling

*Summary:* This chapter is to establish a mathematical model for Coordination Layer control and decision making for Automated Trucks and Buses. The main function of the coordination manager is to coordinate all the maneuvers of each vehicle such that they are performed coherently, safely and efficiently. A hybrid system model is used to unify both coordination layer and regulation layer. In the model, the upper level corresponding to the coordination layer is a programming problem which is to generate discrete optimal solution. Each solution determines some parameters of a reference trajectory of a specified maneuver for lower level control system (regulation layer). It decides when and where to execute the maneuver. The regulation layer is to track the reference trajectory provided by the coordination layer and eventually to produce command to the execute lower level control (throttle and brake) comes out of a feedback loop.

### Notations

The following notations are used throughout this Chapter:

$t$  – time variable

$x(t) = [x_1(t), \dots, x_n(t)]$  – state variable of control system

$x^{(ref)}(t) = [x_1^{(ref)}(t), \dots, x_n^{(ref)}(t)]^T$  – reference state for the control system

$u$  – control variable

$k = [k_1, \dots, k_q]^T$  – control system design parameter vector

$J$  – performance index

$T_0, T_1$  – maneuver start/end time instant

$\theta$  – road grade (slope)

$(x^{(ref)}, v^{(ref)}, a^{(ref)})$  – reference distance, speed and acceleration

$\bar{d}_i(v, \theta), \bar{a}_i(v, \theta)$  – maximum deceleration/acceleration capability

$v(t)$ – subject vehicle speed, measurable

$s_{ij}(t)$ – the geometrical distance (may be 1 or 2–dimensional) between vehicle  $i$  and vehicle  $j$

## 2.1 Coordination Layer Modeling

### 2.1.1 Main Functions

A coordination layer manager for an AHS, as depicted in Figure 1.1, is to coordinate all the maneuvers of all vehicles in a specified section of AHS. A maneuver can be requested randomly by a vehicle according to the needs of its passenger(s) or arranged by the coordination layer to improve traffic throughput or safety. To achieve this, it must have the following functions:

1. Real-time wireless networking all the relevant vehicles: receiving requests for maneuvering and sending back its decision and control command;
2. Based on the request from relevant vehicle(s), states of vehicles in a vicinity and the maneuverability of the vehicle, to decide the type of maneuvers and the corresponding starting time, position and time limit for the maneuver according to safety, compatibility and etc.;
3. Monitoring the execution of the specified maneuvers;
4. Higher level fault detection and management including emergency handling;
5. Transition between the two coordination managers of adjacent sections in the highway.

### 2.1.2 Principles for Decision Making and Control in Coordination Layer

Coordination layer modeling, analysis and design should abide by the following general principles:

*Safety*: It is the key factor for AHS. To ensure safety in coordination layer, all the following conditions must be satisfied:

- (a) Software: All the algorithms should be mathematically correct and reliably implemented. There are proper protection procedures and redundancies to ensure reliability;
- (b) Hardware: Reliable with proper redundancies;
- (c) Fault tolerant: There is a higher level fault detect and management system to deal with all possible faults including emergency handling;

*Compatibility:* Time and space (vehicle position) are the main concern for maneuvers. It guarantees that there is no conflict in time and position between the maneuvering vehicle and vehicles in a vicinity. Besides, there should be a safe distance between any two vehicles at any time instant.

*Maneuverability:* In coordination layer, constraints from acceleration/deceleration capability of an individual vehicle and the string stability margin should not be violated.

*Optimality :* For safety, time gap between two vehicles and two platoons should be large enough. However, to increase throughput and to reduce fuel consumption and pollution, inter-vehicle distance need to be reduced. There is trade-off to be properly balanced.

*Simplicity:* Mathematical modeling, decision making algorithm and control design should be simple to reduce computation time for real-time implementation;

### 2.1.3 A Hybrid System

A type of hybrid control system relevant to coordination and regulation layers is proposed as follows:

$$\begin{aligned}
 & \min_{\alpha, T} J [x^{(ref)}(\alpha, T_0, T_2)] \\
 h(\alpha, T_0, T_2) & \leq 0 \\
 T_0 & \leq t \leq T_2 \\
 x^{(ref)} & = \zeta(\alpha, t, k) \\
 \|x^{(ref)}\| & \leq x^{(ref)}
 \end{aligned} \tag{2.1.1}$$

$$\begin{aligned}
 \dot{x} & = f(x, t, u) + \Delta(t) \\
 u & = u(x, x^{(ref)}, t, k)
 \end{aligned} \tag{2.1.2}$$

where  $\alpha = (\alpha_1, \dots, \alpha_m)$  is the set of parameters to be determined in coordination layer, and  $u = u(x, x^{(ref)}, t, k)$  is a feedback control which is designed with some robust methods.  $k$  is the set of parameters to be determined in control design. It is known in advance that, with bounded disturbances

$$\begin{aligned}
 \|\Delta\| & \leq \rho \|x\| + l \\
 \rho, l & \geq 0
 \end{aligned}$$

the feedback system is robustly stable (ultimate bounded).

The upper layer is for coordination, which is composed of a mathematical programming problem with properly selected performance index. The constraints determine a convex set with proper function  $h(\dots)$ .

It is assumed that the control design parameter vector  $k = [k_1, \dots, k_p]$  is determined in control design phase. In this way, the coordination layer optimal decision making problem is separated from the robust stability problem of regulation layer control system. This does not exclude the possibility that one can use any optimal or sub-optimal control approach in regulation layer design.

### 2.1.4 Vehicle Coupling Criteria

To study the inter-relationship between any two automated/autonomous vehicles in a system, it is necessary to determine if they are coupled or independent. For ground vehicles, it should be considered in both lateral and longitudinal directions in general. For example, in a platoon, one vehicles follows the other. Here "follow" means the information related to front vehicle such as relative distance/speed/acceleration is used in the feedback control of the following vehicle. All the vehicle in a platoon are coupled. Now the problem is when the front vehicle's information should be taken into consideration. It is suggested that some results in vehicle collision warning and avoidance (safety-base) are used as coupling criteria. Of course, some other criteria may be added to then but the safety based criteria are fundamental.

Suppose vehicle  $i$  is coupled with vehicle  $j$ . There are two possible ways to define the coupling between two vehicles.

(1) *Static coupling criterion*: Vehicle  $i$  and vehicle  $j$  are close enough to be considered coupled. For simplicity, a constant number  $D_{\max} > 0$  is specified. If

$$s_{ij}(t) = \|(x_i(t) - x_j(t), y_i(t) - y_j(t))\| \leq D_{\max} \quad (2.1.3)$$

then they are considered coupled. Otherwise, they are independent of each other.

(2) *Dynamic coupling criterion*: Specify a relative distance, speed and acceleration dependent function

$$\xi(s_{ij}(t), \dot{s}_{ij}(t), \ddot{s}_{ij}(t))$$

which is a type of threat assessment criterion between vehicles [40]. If

$$\xi(s_{ij}(t), \dot{s}_{ij}(t), \ddot{s}_{ij}(t)) \leq 0 \quad (2.1.4)$$

then two vehicles are considered coupled. Otherwise, they are independent.

In this preliminary research, the static coupling criterion will be used for simplicity.

## 2.1.5 Separability Principle

It is necessary to consider the separability principle between coordination layer and regulation layer, which is related to the stability of overall system. Firstly, it is noted that, from a system point of view, the link between coordination layer and regulation layer can be depicted as the following figure (Figure 2.1).

Coordination of Cooperative Subsystems: with Dynamically Changing Inter-connection

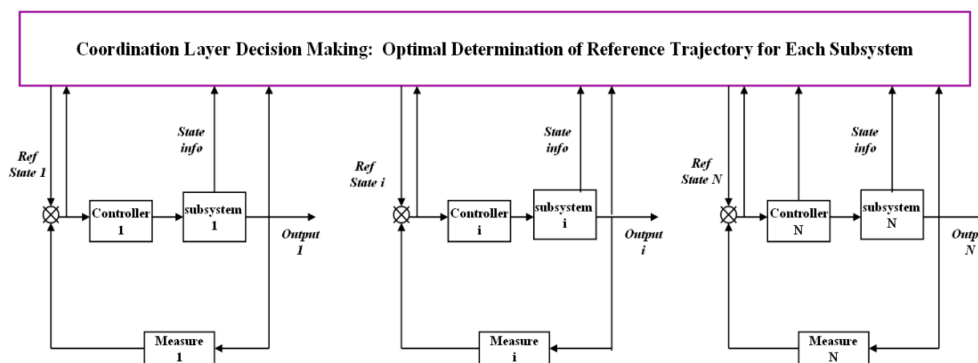


Figure 2.1: Coordination of a system composed of a finite number of subsystems

From a control system point of view (in a narrower sense), for a given reference trajectory  $x^{(ref)}(t)$ , the control variable  $u(t)$  is selected such that each closed-loop system is ultimately bounded (stable in some sense) irrespective of internal/external disturbances and measurement noises. Now for a dynamically changing system, trajectory planning is in real-time. To design a controller to track an arbitrary trajectory such that the overall system is stable is a not very difficult for Linear Time Invariant (LTI) system. For nonlinear systems, this is almost impossible in most cases. To address this issue generally, it is required to investigate

the system controllability/accessibility [7, 8], which is out of the cope of this project. Here we propose some sufficient conditions for the systems resulting from the relevant vehicle dynamics. Here it is further required that

- (a)  $x^{(ref)}(t)$  is absolutely and uniformly continuous with respect to  $t$ ;
- (b)  $x^{(ref)}(t)$  satisfies

$$\|x^{(ref)}\| \leq X^{(ref)} \quad (2.1.5)$$

for known bound  $X^{(ref)} > 0$ .

**Remark 2.1** (1) Those assumptions are not unreasonable. In fact, to make the vehicle behave smoothly for driving stability and the comfort of the driver, it is reasonable to have condition (a); (2) In practical trajectory planning, it is feasible to achieve such reference trajectory for all the normal maneuvers.

It is noted that, under those assumptions, the stability issue is restricted to the lower regulation layer feedback subsystem only. Besides, the problem of coordination is separated distinctively from the control design in the regulation layer. In fact, if the optimal robust control of (2.1.2) is formulated as a nonlinear  $H_\infty$  problem [9]. It ends up with a nonlinear Hamiltonian-Jacobi-Isaac Inequality (nonlinear partial differential inequality) which is difficult to solve. Our approach, however, separate the control problem with the trajectory planning problem. Any robust control design method can be used to choose the control variable  $u(t)$ .

## 2.2 Coordination of Automated Vehicles

For coordinating a system composed of multiple automated vehicles (subsystems), the regulation layer is typically composed of

- (a) vehicle dynamics
- (b) a feed-forward control for each vehicle
- (c) a feedback control for each vehicle

In general, ground vehicles has  $6DOF$ . Strictly speaking all the  $6DOF$  should be involved if we consider vehicle driving stability. However, for trajectory planning purpose for guidance of ground vehicles, it is sufficient to consider a movement on the plane. So the degree of freedom is reduced to 4. As examples, we will show how to use the general model (2.1.1)

## 2.2.1 Longitudinal Motion Only

For simplicity, the problem can be considered for longitudinal motion only if a vehicle is assumed to stay in the lane only. Maneuvers belong to this category include: joining, splitting, longitudinal transition, etc., which only involves movement in the same lane. In such cases, it is sufficient to consider longitudinal control.

The vehicle dynamics for longitudinal control includes engine, powertrain, drivetrain and tire dynamics. The feed-forward control determines desired maneuver. Each maneuver corresponds to an algorithm for trajectory planning. Each algorithm contains some design parameters which affect the stability, performance and demanding of the feedback control. It is those parameters that define the link between the regulation layer and the coordination layer, which are to be manipulated by the latter.

A typical vehicle longitudinal dynamics model can be simplified as:

$$\begin{aligned}\dot{x} &= v + \Delta_1 \\ \dot{v} &= \frac{1}{M} (u - C_a v^2 - F_r) + \Delta_2\end{aligned}$$

where  $C_a$  – aerodynamic drag coefficient,  $F_r$  – total rolling resistance,  $M$  – vehicle mass.

$$\begin{aligned}x_e &= x^{(ref)} - x \\ v_e &= v^{(ref)} - v \\ a_e &= a^{(ref)} - a \\ \dot{x}_e &= v_e \\ \dot{v}_e &= a^{(ref)} - \frac{1}{M} (u - C_a v^2 - F_r) \\ x_e(0) &= L^{(ref)} \\ v_e(0) &= 0\end{aligned}\tag{2.2.1}$$

from which  $u$  is determined by a proper control design method

$$u = u(k, x^{(ref)}, v^{(ref)}, a^{(ref)})$$

where  $k = [k_1, \dots, k_p]$  is a set of control design parameters.

Any longitudinal maneuver algorithm provides a reference trajectory for vehicle  $i$

$$\begin{aligned}x^{(ref)}(t) &= f_1(t, v, \mu) \\ v^{(ref)}(t) &= f_2(t, v, \mu) \\ a^{(ref)}(t) &= f_3(t, v, \mu) \\ \mu &= [\mu_1, \mu_2, \dots, \mu_m]\end{aligned}$$

where  $\mu$  is a set of parameters which may include

- (a) vehicle state  $(x, v, a)$ , maneuver status and fault mode
- (b) time headway or distance headway
- (c) state of nearby vehicles of the same lane
- (d) maneuver status of nearby vehicles in different lanes
- (e) road information (grade, tire slip, ...)

As a simple example, consider the longitudinal controllers designed for vehicle following in [2, 25]. For the given automated control, the vehicle has the acceleration/deceleration capability at certain speed  $v_i$  with road grade  $\theta$ . Trajectory planning is to find a continuous (or continuously differentiable) trajectory  $\left( L_i^{(ref)}, v_i^{(ref)}(t), a_i^{(ref)}(t) \right)$  such that

$$\begin{aligned} a_{\min}(v_i, \theta) &\leq a_i^{(ref)}(v_i, \theta) \leq a_{\max}(v_i, \theta) \\ 0 &\leq v_i^{(ref)}(\theta) \leq v_{\max}(\theta) \\ D_{\min} &\leq L_i^{(ref)} \leq D_{\max} \end{aligned} \quad (2.2.2)$$

The first constraints gives acceleration and deceleration bounds; The second constraints give speed constraints; In the third constraint,  $D_{\min}$  – is safety related constant and  $D_{\max}$  is the coupling criterion parameter as in (2.1.3).

The performance index should be chosen for each maneuver according to its characteristics. The main factors to be involved will include part or all listed in last section. A preliminary suggestion of performance index is

$$\begin{aligned} J &= \left\{ b_1 (T_1 - T_0) + \frac{b_2}{L^{(ref)}} + b_3 \left| a_i^{(ref)}(v, \theta) \right| \right\} \\ b_1 + b_2 + b_3 &= 1, \quad b_i \geq 0, \quad i = 1, 2, 3 \end{aligned}$$

where  $b_1, b_2$  and  $b_3$  are known weighting factors. It is to be minimized with respect to some parameters subject to the constraints (2.2.2).

## 2.2.2 Maneuver Involving both Longitudinal and Lateral Movement

Maneuvers in this category involve lane changing and lane departure which can be conducted in normal cases or in the case of collision avoidance. Now the vehicle dynamics will include lateral, longitudinal and yaw motions [15].

$$\begin{aligned} \dot{v}_x &= \frac{1}{M} (F_x - C_x v_x^2 + F_{roll} + \delta_f F_{y_f}) + v_y \dot{\Psi} \\ \dot{v}_y &= \frac{1}{M} (F_{y_f} - C_y v_y^2 + F_{y_r}) - v_x \dot{\Psi} \end{aligned}$$



$$\ddot{\Psi} = \frac{1}{I_z} (L_{w_f} F_{y_f} - L_{w_r} F_{y_r})$$

where  $v_{x,y}$  – longitudinal/lateral velocity

$M$  – vehicle mass

$\Psi$  – yaw angle

$F_x$  – longitudinal tire traction force

$F_{y_f}$  – Front tire lateral traction force

$C_{x,y}$  – longitudinal/lateral drag coefficient

$F_{y_r}$  – rear tire lateral traction force

$\delta_f$  – steering angle

$L_{w_{f,r}}$  – distance from CG to front/rear axle

$I_z$  – moment of inertia about vertical axle through the CG

The synthetic inputs of the system are  $F_x$ ,  $\delta_f$ ,  $F_{y_f}$  and  $F_{y_r}$ . The trajectory planning problem is to specify the following state variables:

$x^{(ref)}$ ,  $y^{(ref)}$  – longitudinal and lateral position

$v_x^{(ref)}$ ,  $v_y^{(ref)}$  – longitudinal and lateral speed

$\Psi^{(ref)}$  – desired yaw angle

$\dot{\Psi}^{(ref)}$  – desired yaw rate

One can specify similar constraint conditions as those in (2.2.2).

## 2.3 Network Structure

Wireless communication networks are crucial for automated vehicles. The fundamental function of the communication system is message passing: sending and receiving messages in real-time, which are used for synchronization and control (Figure 2.2 and Figure 2.3).

### 2.3.1 Wireless Networking

Several wireless communication systems such as Utilicom, WaveLAN, DSRC (Dedicated Short Range Communication) radio systems are used at California PATH between vehicles and between the coordination layer and the vehicles. The structure of the system is in Figure 2.2. For WaveLAN system, the physical layer is the radio system which is a PCMCIA WaveLAN card. In our application, the real-time operating system is QNX. The data link layer is composed of components of communication devices for enhance the reliability of the medium. The network layer is for dynamic network configuration and routing, which is necessary

### Wireless Communication System Structure

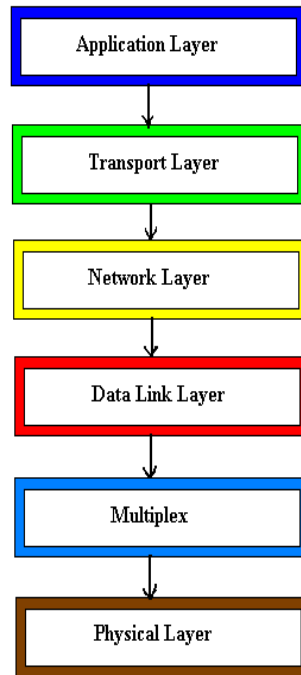


Figure 2.2: Wireless communication system structure

because a vehicle may merge from on-ramp, join, change lane or leave a platoon. The transport layer is for message splitting, handling and creating multiple transport addresses on the host. Wireless *Token Ring* Protocol (WTRP) is used for medium access control for ad-hoc networks [13].

The advantages of this distributed medium access control protocol are

- (a) Quality of service: This is guaranteed in terms of bounded latency and reserved bandwidth.
- (b) Efficiency: It completely excludes the possibility of retransmission due to collisions;
- (c) Robustness against single node failure: It can gracefully recover from single and multiple transmission failure.
- (d) Dynamic configuration of rings: It support for flexible topologies in which nodes can be partially connected and not all nodes need to have a connection with a master

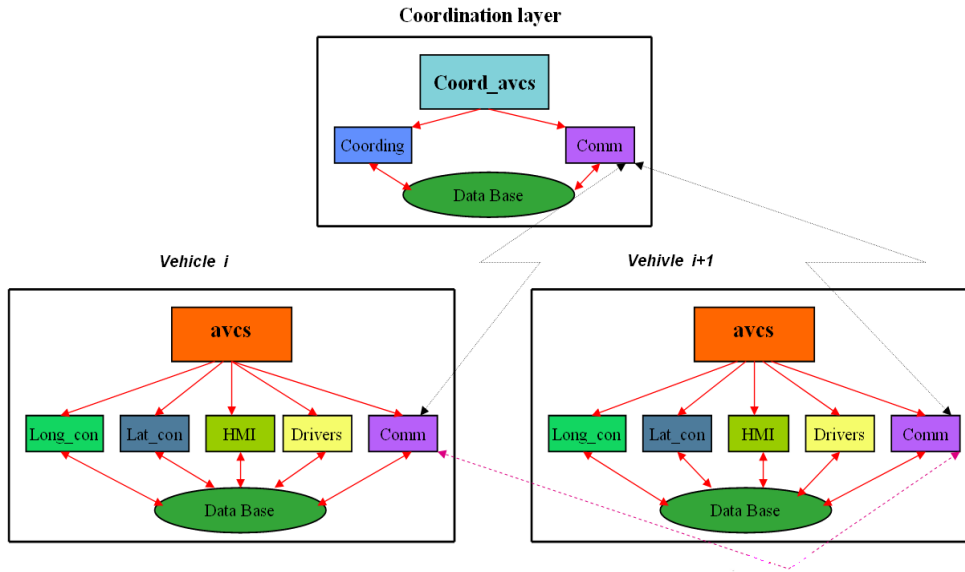


Figure 2.3: Wireless communication between subsystems

(e) Support different topologies: Multiple ring dynamic configuration is permitted.

With those capabilities, a dynamic link can be established among all the relevant vehicles involved in a regulation layer as well as the link between each platoon with coordination layer. Such a network can be implemented with a single physical set or two separate sets.

## 2.4 Remarks

This chapter reports some preliminary research results for coordination layer control and decision making for automated trucks and buses. Each vehicle represent a regulation layer. All the vehicles in a specified section of a coordination layer are networked with wireless communication system. The main functions for the coordination system are to coordinate in real-time all the vehicles such that all the maneuvers are executed coherently, safely and

efficiently. Any maneuver of a vehicle is determined by a reference trajectory of the regulation layer. Some parameters in the reference trajectory need to be determined by coordination layer according to the state of the vehicles involved, the traffic situation, safety constraint (headway) and road geometry. Those parameters are the link between the coordination layer and the regulation layer.

The main task of a coordination layer involves decision making with some control ingredients. The main tasks of the regulation layer mainly involves control with some decision making in a lower level. These two layers can be unified into a mathematical model called hybrid system. Upper part of the hybrid system corresponding to the coordination layer is a linear (nonlinear) programming problem depending on the choice of performance index. The lower level is a feedback control system.

# Chapter 3

## Practical String Stability for Vehicle Following

*Summary:* Among all vehicle maneuvers, multiple vehicle following is the fundamental maneuvers. This is because highway system is the place with the most high traffic density. Any vehicle has to interact with the vehicles of its immediate front and rear. If a vehicle finish a maneuver, then it will return to the vehicle following mode. The most important problem for vehicle following is the string stability of the finite number of vehicles considered coupled due to following.

This chapter discusses string stability issues for multiple vehicle following. With the increase of vehicle size, for example from a car to a bus or truck, the time delay accumulation from the lead vehicle to the vehicles behind increases significantly. Such accumulated time delay is the essential difficulty for automated vehicle following.

Most previous work on string stability does not take into consideration of the accumulated time delays. This chapter will show how such time delay plays a critical role in multiple vehicle following. Some effective ways to compensate for it are suggested. Basically, this requires that any vehicle need to know the information from leader vehicle as well as the vehicle in the immediate front. Wireless communication between vehicles is an effective solution to it.

### 3.1 Introduction

*String stability* describes the dynamic interaction between vehicles in short inter-vehicle distance following in longitudinal motion. Previous work in [35] defines the *string stability*

as an *asymptotic stability* of the overall system which is composed of a finite number of inter-connected sub-systems (a single vehicles) with the same or similar dynamics. Necessarily, each closed-loop controller must be asymptotically stable. This is the ideal case for the dynamic behavior of a series of sub-system inter-connected in a string.

Time delays will naturally cause measurement and actuation discrepancies. Due to such discrepancies in addition to model mismatch, measurement noises and external disturbances, each sub-system can only achieve ultimate boundedness in stability [11, 17], which coincides with experimental work. To require strict attenuation of tracking error down stream (direction from the first vehicle to the last vehicle) in the platoon is too restrictive. Practically, *string stability* in vehicle following can only require that distance and speed tracking error will not propagate or has limited propagation down stream in a platoon. However, for theoretical analysis, the definition for *string stability* in [35] is reasonable.

In [36], string stability for many vehicle following strategies has been considered. Time lag is involved but not pure time delay. [16] considered both time lag caused by actuators and pure time delay caused by inter-vehicle communication. Due to the complication of the problem formulated, it is impossible to consider arbitrary design parameters. i.e. It only show that the system is string stable/unstable when some particular control parameters are chosen.

In this chapter, two time delays are taken into consideration. The control strategies are feedback linearization plus linear (PID and a type of sliding mode) control. A different parameterization approach is adopted compared to those in [16, 36]. These approaches greatly simplify the problem for both theoretical analysis and practical implementation.

String stability mainly depends on following strategies as discussed in [21] while the latter on information available from the preceding vehicles. If each vehicle follows its immediate preceding vehicle only, it is *Adaptive Cruise Control* (ACC) (implicitly, no communication). It will be shown mathematically that ACC mode cannot achieve string stability for all linear controller. However, if certain amount of information from leader vehicle (passed over with communication ) is used, string stability can be achieved irrespective of the time delays.

The rest of the chapter is organized as follows. Section 2 introduces string stability in vehicle following and its mathematical criteria. Section 3 addresses string stability analysis. Section 4 presents test results. Section 5 is for concluding remarks.

### Notations

$x_i(t)$  or simply  $(x_i)$  – position of vehicle  $i$  in longitudinal direction. All the vehicles are with respect to a inertia frame.

$v_i(t), a_i(t)$  – speed and acceleration of vehicle  $i$

$h_{p1}$  – time delay for obtaining front range

$h_{p2}$  – time delay for obtaining preceding vehicle's speed and acceleration

$L_i$  is the desired inter-vehicle distance with vehicle length accounted for

$l$  – subscript for the leader vehicle

$\varepsilon_i(t)$  – distance tracking error

$E_i(s)$  – Laplace transform of distance tracking error  $\varepsilon_i(t)$

$\|\cdot\|_1$  –  $l_1$ -norm

$\|\cdot\|_\infty$  –  $H_\infty$ -norm

## 3.2 String Stability for Vehicle Following

This section will provide mathematical criteria for string stability in vehicle following.

### 3.2.1 Problem Statement

Let

$$\begin{aligned}\varepsilon_i(t) &= x_i(t) - x_{i-1}(t) + L_i \\ \dot{\varepsilon}_i(t) &= v_i(t) - v_{i-1}(t) \\ \ddot{\varepsilon}_i(t) &= a_i(t) - a_{i-1}(t)\end{aligned}$$

$E_i(s)$  is the Laplace transformation of  $\varepsilon_i(t)$ .  $G(s)$  is the transfer function of the closed-loop dynamics  $g(t)$  of sub-system  $i$ , which is the same for each vehicle with

$$G(s) = \frac{E_i(s)}{E_{i-1}(s)} \quad (3.2.1)$$

The string stability for a platoon of  $n$  vehicles requires that

$$\|\varepsilon_1\|_\infty \leq \|\varepsilon_2\|_\infty \leq \dots \leq \|\varepsilon_n\|_\infty$$

From linear system theory

$$\begin{aligned}\|\varepsilon_i\|_\infty &\leq \|g(t)\|_1 = \int_0^\infty |g(\tau)| d\tau \\ \|g * \varepsilon_i\|_\infty &\leq \|g(t)\|_1 \|\varepsilon_i\|_\infty \\ \|G(s)\|_\infty &\leq \|g(t)\|_1\end{aligned} \quad (3.2.2)$$

Thus the inter-connected system is string stable if  $\|g(t)\|_1 < 1$  and string unstable if  $\|G(s)\|_\infty > 1$ . To practically check it, one may evaluate  $\|g(t)\|_1$ .

### 3.2.2 Following Strategy and String Stability

Due to feedback linearizability of vehicle dynamics, it is sufficient to consider the following simplified model for string stability analysis

$$\begin{aligned}\dot{x}_i &= v_i \\ \dot{v}_i &= u_i\end{aligned}\tag{3.2.3}$$

where  $u_i$  is the synthetic force. Two types of control strategies will be considered.

#### 1. Sliding Model Control

Let the sliding surface be defined as

$$S_i = \alpha \dot{\varepsilon}_i + \alpha q \varepsilon_i + (1 - \alpha)(v_i - v_l) + (1 - \alpha)q(x_i - x_l + \sum_{j=2}^i L_j)$$

where  $\alpha \in [0, 1]$  is the interpolation parameter. Two extreme cases are:  $\alpha = 1$  - Each vehicle follows the preceding vehicle only and no lead vehicle information is used;  $\alpha = 0$  - Each vehicle follows the leader vehicle only. However, the most interesting cases correspond to  $0 < \alpha \leq 1$ .

One can choose general sliding reachability condition  $\dot{S}_i = -\gamma_i(s)$  as in [17]. For special case of  $\gamma_i(s) = \lambda S_i$  ( $\lambda > 0$ ), the controller is solved out as

$$\begin{aligned}u_i^{(d)} &= \alpha \ddot{x}_{i-1} + (1 - \alpha) \ddot{x}_l - \alpha(q + \lambda) \dot{\varepsilon}_i - \alpha \lambda q \varepsilon_i \\ &\quad - (1 - \alpha)(q + \lambda)(v_i - v_l) - \lambda q (1 - \alpha) \left( x_i - x_l + \sum_{j=2}^i L_j \right)\end{aligned}\tag{3.2.4}$$

The design parameters  $(q, \lambda, \alpha)$  are to be chosen such that

- (a) The closed loop controller for each vehicle is stable;
- (b) The overall system is string stable.

#### 2. PID Control

Now considering the interpolation of two PID controllers. The errors are with respect to the preceding vehicle and the leader vehicle respectively.

$$\begin{aligned}u_i^{(d)} &= \alpha U_i^1 + (1 - \alpha) U_i^2 \\ U_i^1 &= K_D \frac{d}{dt} v_{i-1} - K_P (v_i - v_{i-1}) - K_I \int_0^t (v_i(\tau) - v_{i-1}(\tau)) d\tau \\ U_i^2 &= K_D \frac{d}{dt} v_l - K_P (v_i - v_l) - K_I \int_0^t (v_i(\tau) - v_l(\tau)) d\tau\end{aligned}\tag{3.2.5}$$

The closed loop stability requires that

$$K_D \zeta^2 + K_P \zeta + K_I = 0$$



be Hurwitz, where one can always normalize  $K_D = 1$  for stability.

The following relationship shows that if a special sliding reachability condition  $\dot{S}_i = -\lambda S_i$  is used, the sliding mode control is a special case of PID control with:

$$x_i(t) = \int_0^t v_i(\tau) d\tau, \quad x_i(0) = \sum_{j=2}^i L_j$$

$$K_P = q + \lambda, \quad K_I = \lambda q, \quad K_D = 1$$

### 3.2.3 Time Delays

In practice, there are two types of time delays: time lag and pure time delay. A time lag can be represented by inserting a first order dynamics

$$\tau \dot{u}_i + u_i = u_{id}$$

which links the controller (3.2.4) and upper level vehicle model (3.2.3) with  $\tau = 0.15[s]$ .

There are two fundamentally different cases for pure time delays.

**Case 1:** *With inter-vehicle communication*

Relative distance  $(x_i - x_{i-1})$  is estimated from distance sensor reading, which causes pure time delay of  $h_{p1} \approx 0.25[s]$  where  $0.1[s]$  comes from radar/Lidar sensor delay (physical and radar internal signal processing) and  $0.15[s]$  is due to signal processing in feed-forward control.  $(v_{pre}, a_{pre})$  is passed over by communication which causes time delay about  $h_{p2} \approx 0.1[s]$  in which  $0.02[s]$  is the communication cycling period and  $0.08[s]$  is due to the speed and acceleration sensor delay.

**Assumption 3.1:** The communication system passes information from the leader vehicle to each vehicle and from each vehicle to its follower simultaneously with one step time delay  $0.02[s]$ .

**Assumption 3.2:** Pure sensor time delay on vehicle  $i$  with respect to the preceding vehicle is the same for all the vehicles.

**Case 2:** *Without inter-vehicle communication*

All the three elements in  $[(v_i - v_{i-1}), (a_i - a_{i-1}), (x_i - x_{i-1})]$  are estimated from measurement with Doppler radar, Lidar and video camera. In this case:  $h_{p1} \approx 0.25[s]$ ,  $h_{p2} = 0.35[s]$ . No leader vehicle information is available.

### 3.2.4 Transfer Function Expression

To use frequency analysis approach to calculate the  $H_\infty$  gain, the transfer function for the closed-loop system of each vehicle is calculated as follows.

$$\begin{aligned}
\tau \frac{d^3 \varepsilon_i}{dt^3} + \ddot{\varepsilon}_i &= u_i^{(d)} - u_{i-1}^{(d)} \\
&= -\alpha K_P \dot{\varepsilon}_i - \alpha K_I \varepsilon_i - K_I (1 - \alpha) \varepsilon_i \\
&\quad - (1 - \alpha) K_P (v_i(t) - v_{i-1}(t)) + \alpha \ddot{x}_{i-1}(t - h_{p2}) \\
&\quad - \alpha \ddot{x}_{i-2}(t - h_{p2}) + \alpha K_P (\dot{x}_{i-1}(t - h_{p2}) - \dot{x}_{i-2}(t - h_{p2})) \\
&\quad + \alpha K_I (x_{i-1}(t - h_{p1}) - x_{i-2}(t - h_{p1}))
\end{aligned}$$

Using Laplace transformation on both sides to get

$$G(s) = \frac{E_i(s)}{E_{i-1}(s)} = \frac{\alpha K_I e^{-h_{p1}s} + \alpha s e^{-h_{p2}s} (s + K_P)}{\tau s^3 + s^2 + K_P s + K_I} \quad (3.2.6)$$

## 3.3 String Stability Analysis

This section analyzes the string stability with respect to the two typical following strategies above.

### 3.3.1 Vehicle Following without Communication (ACC)

Vehicle following without communication implies that all the information of the front vehicle is detected by remote sensors such as radar. The overall system can be depicted as in Figure 3.1.

In (3.2.6), set  $\alpha = 1$  which is equivalent to using preceding vehicle information only. The control law (3.2.5) becomes

$$u_i^{(d)} = \ddot{x}_i - K_P \dot{\varepsilon}_i - K_I \varepsilon_i \quad (3.3.1)$$

It is obtained that

$$G(s) = \frac{K_I + s e^{-(h_{p2}-h_{p1})s} (s + K_P)}{\tau s^3 + s^2 + K_P s + K_I} e^{-h_{p1}s}$$

For feedback stability, it is necessary and sufficient that

$$D(s) = \tau s^3 + s^2 + K_P s + K_I$$

be Hurwitz, which is equivalent to the parameter constraints:

$$\begin{aligned}
K_I &> 0 \\
K_P - \tau K_I &> 0
\end{aligned} \quad (3.3.2)$$

### Vehicle Following without Communication

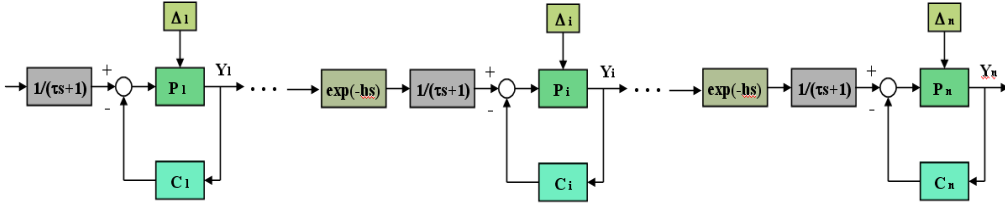


Figure 3.1: Both pure time delay and time lag appear between subsystems and such time delays accumulate

Because  $e^{-h_p s}$  does not effect the value of  $|G(j\omega)|$  and thus it is ignored. Let  $h_p = h_{p2} - h_{p1} > 0$  for simplicity. Thus

$$G(j\omega) = \frac{K_I + j\omega (\cos(\omega h_p) - j \sin(\omega h_p)) (j\omega + K_P)}{-\tau j\omega^3 - \omega^2 + K_P j\omega + K_I}$$

Now it is necessary to evaluate  $\|G\|_\infty = \max_\omega |G(j\omega)|$ .

For considering only very small  $\omega > 0$  and  $2nd$  order truncation in the Taylor series:

$$\begin{aligned} G(j\omega) &\approx \frac{K_I + j\omega (1 - j\omega h_p) (j\omega + K_P)}{-\omega^2 + K_P j\omega + K_I} = 1 + \frac{\omega^2 h_p K_P}{(K_I - \omega^2) + K_P j\omega} \\ &= 1 + \frac{\omega^2 h_p K_P (K_I - \omega^2)}{(K_I - \omega^2)^2 + K_P^2 \omega^2} - \frac{K_P j\omega}{(K_I - \omega^2)^2 + K_P^2 \omega^2} \end{aligned}$$

One can observe that for feedback control law (3.3.1) with constraints (3.3.2), if  $\omega > 0$  is chosen very small such that  $\omega^2 < K_I$  arbitrarily,  $h_p > 0$  will lead to

$$\frac{\omega^2 h_p K_P (K_I - \omega^2)}{(K_I - \omega^2)^2 + K_P^2 \omega^2} > 0$$

which means that the real part is positive and greater than 1. This implies from (3.2.2) that

$$\|G\|_\infty = \max_\omega |G(j\omega)| > 1 \Rightarrow \|g(t)\|_1 > 1$$

This is summarized in the following theorem.

**Theorem 3.1.** For vehicle following in *ACC* mode (inter-vehicle range and range-rate are measured by radar), the system is string unstable for any linear controller of the type (3.3.1).

### 3.3.2 Vehicle Following with Inter-vehicle Communication

The system structure can be depicted as Figure 3.2.

Now (3.2.6) is directly considered with some information from the leader vehicle passed over by communication.  $G(s)$  has the form

$$G(s) = \frac{\alpha [K_I e^{-h_p s} + s e^{-h_p s} (s + K_P)]}{\tau s^3 + s^2 + K_P s + K_I}, \quad 0 < \alpha < 1$$

Similarly, feedback stability requires that the denominator be Hurwitz, which leads to the same constraint (3.3.2). Now  $G(s) = \alpha G_0(s)$  with

$$G_0(s) = \frac{K_I e^{-h_p s} + s e^{-h_p s} (s + K_P)}{\tau s^3 + s^2 + K_P s + K_I}$$

Although by Initial Value Theorem and Final Value Theorem

$$\begin{aligned} \lim_{t \rightarrow 0} g_0(t) &= \lim_{s \rightarrow \infty} s G_0(s) = 0 \\ \lim_{t \rightarrow \infty} g_0(t) &= \lim_{s \rightarrow 0} s G_0(s) = 0 \end{aligned}$$

where  $g_0(t)$  is the inverse Laplace transformation of  $G_0(s)$ , one can expect that  $g_0(t)$  is bounded, a rigorous proof is provided which can be used to calculate the bound for  $\alpha$ .

**Lemma 3.1** If the design parameters  $K_P, K_I$  are chosen so that poles  $s_k, (k = 1, 2, 3)$  are all simple, then there exists a positive number  $M > 0$  such that  $\|g_0(t)\|_1 < M$ .

### Vehicle Following with Communication

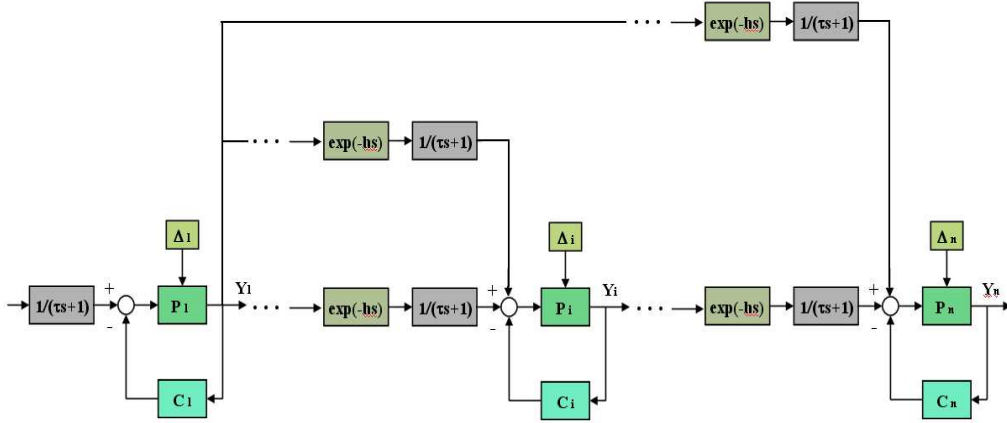


Figure 3.2: Accumulated time delay effectively reduced with inter-vehicle communication

**Proof:** By the definition of inverse Laplace transformation

$$\begin{aligned}
 g_0(t) &= \mathcal{L}^{-1}(G_0(s)) = \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} e^{st} G_0(s) ds \\
 &= \frac{1}{2\pi j} \lim_{R \rightarrow \infty} \int_{ABCDEA} e^{st} G_0(s) ds \\
 &= \frac{1}{2\pi j} \lim_{R \rightarrow \infty} \int_{ABCDEA} \left( \frac{K_I e^{s(t-h p_1)}}{\tau s^3 + s^2 + K_P s + K_I} \right) ds \\
 &\quad + \frac{1}{2\pi j} \lim_{R \rightarrow \infty} \int_{ABCDEA} \left( \frac{s(s+K_P) e^{s(t-h p_2)}}{\tau s^3 + s^2 + K_P s + K_I} \right) ds
 \end{aligned} \tag{3.3.3}$$

The integration can be evaluated along the contour  $\overline{ABCDEA}$  and take the limit for  $R \rightarrow \infty$  (Figure 3.3). By the *Residue Theorem* (p. 967 of [29])

$$g_0(t) = \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} e^{st} G_0(s) ds = \sum_{k=1}^3 \text{Res}_{s_k}(G_0(s))$$

where  $\text{Res}_{s_k}(G(s))$  is the residue corresponding to pole  $s_k$ , ( $k = 1, 2, 3$ ). For a simple pole  $s_k$ ,  $\text{Res}_{s_k}(G_0(s))$  is the coefficient of  $\frac{1}{s-s_k}$  in the Laurent expansion of  $G_0(s)$  at  $s_k$ , ( $k = 1, 2, 3$ ).

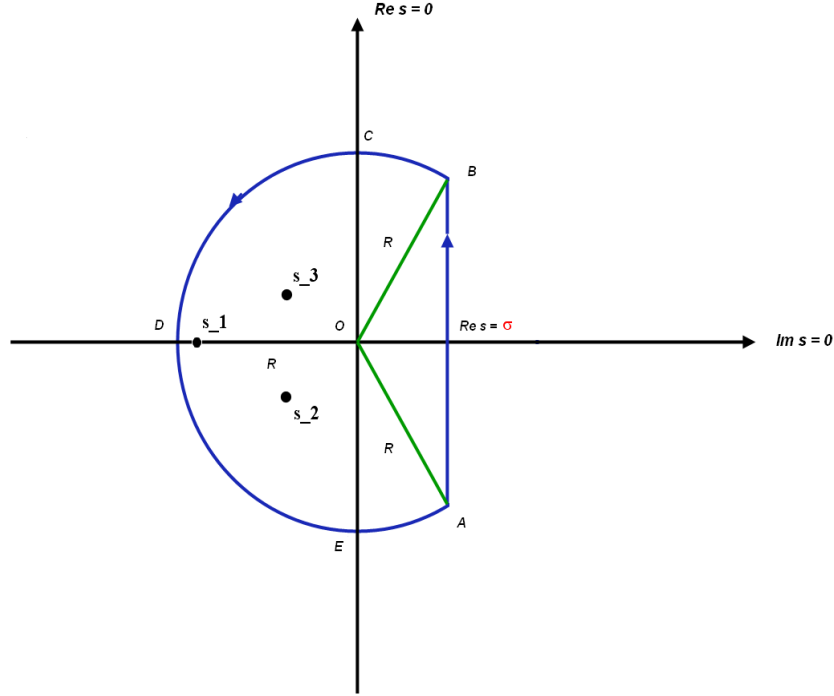


Figure 3.3: Integration along the contour

Let the first integrand in (3.3.3) be partitioned as

$$\frac{K_I e^{s(t-h_{p1})}}{\tau s^3 + s^2 + K_P s + K_I} = \frac{e^{s(t-h_{p1})}}{\tau} \left( \frac{a^{(1)}}{s-s_1} + \frac{a^{(2)}}{s-s_2} + \frac{a^{(3)}}{s-s_3} \right)$$

where  $a^{(i)}$  ( $i = 1, 2, 3$ ) are constants. Expanding  $e^{s(t-h_{p1})}$  as Taylor series at  $s = s_i$  to produce

$$\frac{e^{s(t-h_{p1})}}{\tau} \left( \frac{a^{(1)}}{s-s_1} + \frac{a^{(2)}}{s-s_2} + \frac{a^{(3)}}{s-s_3} \right) = \frac{1}{\tau} \left[ \frac{a^{(1)} e^{s_1(t-h_{p1})}}{s-s_1} \sum_{n=1}^{\infty} \frac{(t-h_{p1})^n (s-s_1)^n}{n!} + \frac{a^{(2)} e^{s_2(t-h_{p1})}}{s-s_2} \sum_{n=1}^{\infty} \frac{(t-h_{p1})^n (s-s_2)^n}{n!} + \frac{a^{(3)} e^{s_3(t-h_{p1})}}{s-s_3} \sum_{n=1}^{\infty} \frac{(t-h_{p1})^n (s-s_3)^n}{n!} \right]$$

Thus

$$\begin{aligned} & \int_{ABCDEA} \left( \frac{K_I e^{s(t-h_{p1})}}{\tau s^3 + s^2 + K_P s + K_I} \right) ds \\ &= \frac{2\pi j}{\tau} [a^{(1)} e^{s_1(t-h_{p1})} + a^{(2)} e^{s_2(t-h_{p1})} + a^{(3)} e^{s_3(t-h_{p1})}] \end{aligned}$$

Similarly treating the second integral in (3.3.3), if

$$\frac{s(s + K_P)}{\tau s^3 + s^2 + K_P s + K_I} = \frac{1}{\tau} \left[ \frac{b^{(1)}}{s - s_1} + \frac{b^{(2)}}{s - s_2} + \frac{b^{(3)}}{s - s_3} \right]$$

then

$$g_0(t) = \frac{1}{\tau} \left[ a^{(1)} e^{s_1(t-h_{p1})} + a^{(2)} e^{s_2(t-h_{p1})} + a^{(3)} e^{s_3(t-h_{p1})} \right] + \frac{1}{\tau} \left[ b^{(1)} e^{s_1(t-h_{p2})} + b^{(2)} e^{s_2(t-h_{p2})} + b^{(3)} e^{s_3(t-h_{p2})} \right]$$

Notice that  $s_i (i = 1, 2, 3)$  have negative real parts. Thus each term in  $g_0(t)$  is bounded for  $t \geq 0$ .

This completes the proof.  $\diamond$

**Theorem 3.2** . In vehicle following, if the linear control law (3.2.5) is used and if parameter  $K_P$  and  $K_I$  are chosen such that the transfer function  $G(s)$  has simple and stable poles, then there exists  $\alpha$ , with  $0 < \alpha < 1$  such that the overall system is string stable irrespective of the time delays.

**Proof.** By the lemma, one can choose  $\alpha$  such that  $0 < \alpha < \frac{1}{M}$ . Then  $\|g(t)\|_1 = \alpha \|g_0(t)\|_1 < 1$ . This completes the proof.  $\diamond$

**Corollary 3.1** Suppose that  $s_i = -\sigma_i + j\eta_i$  with  $\sigma_i > 0 (i = 1, 2, 3)$ . Then  $M$  can be estimated as

$$|g_0(t)| \leq M = \frac{1}{\tau} \left[ |a^{(1)}| e^{\sigma_1 h_{p1}} + |a^{(2)}| e^{\sigma_2 h_{p1}} + |a^{(3)}| e^{\sigma_3 h_{p1}} \right] + \frac{1}{\tau} \left[ |b^{(1)}| e^{\sigma_1 h_{p2}} + |b^{(2)}| e^{\sigma_2 h_{p2}} + |b^{(3)}| e^{\sigma_3 h_{p3}} \right]$$

which provides an upper bound for  $\alpha < \frac{1}{M}$ .

**Proof.** Directly from the proof of the Lemma.  $\diamond$

**Remark 3.1** In theory, when every vehicle follows the leader vehicle only, the overall system is always string stable. This following strategy sounds ideal but impractical. This is due to the following reasons:

(a) Real-time distance estimation ( $x_l - x_i$ ) of each vehicle with respect to the leader vehicle is difficult to obtain. If radar distance with respect to the preceding vehicle is used for the estimation of ( $x_l - x_i$ ), error accumulation may increase down stream in the platoon even if inter-vehicle communication is available.

(b) For safety, each vehicle must avoid conflict with its immediate front vehicle, which requires  $\alpha$  to be as large as possible. This suggests to choose  $\alpha = \frac{1}{M} - \varepsilon$  with  $\varepsilon (> 0)$  sufficiently small.

## 3.4 Concluding Remarks

This chapter studies the practical string stability problem for vehicle following. As a special case of inter-connected system, the overall system configuration is a serial connection of subsystem (automated vehicles) with time delays. Other maneuvers may lead to an interaction between two serially connected subsystems. For example, lane change usually lead a situation that one subsystem drop from a system (decoupling) and join the other system (coupling). Such a dynamically changing interconnection is an interesting reconfiguration property from a systems point of view. Such a dynamic reconfiguration characteristics bring new research topics for control system design and stability analysis. String stability comes from the assumption that the finite number of vehicles are coupled serially. But is we also consider the lateral interaction between vehicles in neighbor lanes, then the inter-connection between systems are of two dimensional. In this cases, control design for each subsystem and stability analysis for the overall system will be quite different. However, they are still in the category of inter-connected systems.



# Chapter 4

## Heavy-Duty Truck Following

*Summary:* This chapter presents implementation of truck longitudinal control for short distance following, which is a very difficult issue. The main difficulties are (a) low power/mass ratio; (b) time delay caused by and internal engine control and actuators like air brake; (c) Prominent disturbance during gear shifting, wind and slight road grade; To overcome those difficulties, a complicated nonlinear vehicle dynamics model has been adopted to reduce the model mismatch on one hand. On the other hand, robust stability margin is enhanced in control design phase. A reliable and precise distance measurement is critically required for automated vehicle following. This has been achieved by filtering and fusing both Doppler radar and laser radar with Kalman filter. Experimental work with two trucks shows that this approach is effective. Two heavily loaded trucks are used for constant inter-vehicle distance following test. The controller performance is good even for 3[m] inter-vehicle distance. Although, there are only two trucks tested, there is still a string stability problem because the leader truck is following a reference speed trajectory. The practical string stability study in previous work still apply. Experimental work has been presented.

### 4.1 Introduction

Based on the hardware structure of heavy duty trucks [4, 5, 12], previous work have considered in detail the modeling and longitudinal control design for a single automated truck [20, 22]. A complicated model is adopted there, (Figure 4.1) which include: turbo-charged diesel engine, torque converter, transmission, and braking system (engine brake, transmission retarder and pneumatic brake). Engine braking effect, which is caused by the mismatch between engine speed and wheel speed when fuel is released and drive-line is engaged, is

naturally unified with Jake (compression) brake effect as a special case. The structure of the controller can be divided into upper level control and lower level control. Upper level control uses sliding mode control to generate desired engine/brake torque from desired vehicle acceleration. Lower level control is divided into two branches: (a) Engine Control: From positive desired torque to desired fuel rate (or Torque Control Command). In the case of former, using a static engine mapping is used, which captures the intrinsic dynamic performance of the turbo-charged diesel engine; (b) Brake control is to generate, from negative desired torque, to Jake-Brake-on time period, applied pneumatic brake pressure, and applied voltage of transmission retarder. Such a complicated model has been validated by using closed-loop control of a single vehicle to track a pre-defined reference speed trajectory [22].

This chapter is to report the research and experimental work in longitudinal control of two or more trucks, which is basically short inter-vehicle distance following with radar/lidar distance sensing and using wireless communication to pass information between vehicles and between each vehicle with coordination layer manager.

The prominent difference between the controller of one vehicle and that of multiple vehicle following is the *string stability*. As discussed in [23] and the previous chapter, the biggest enemy for string stability is *time lag* and *pure time delay* caused by sensors and actuators. Truck hardware related to longitudinal control is very complicated with large time delays [22, 39]. For Freightliner Century trucks, time lag can be as large as 0.3[s]. Pure time delay for engine input-to-torque-production can be as large as 0.3[s]; For braking system, transmission retarder: 0.5[s]; Air brake: 0.6[s]; Engine brake: 0.15[s]. The synthetic approach in [23] is used to guarantee the practical string stability [23], and the stability and performance the following vehicle.

**Notations:** The following notations are used throughout this chapter.

$x_i(t)$  or simply  $(x_i)$  – position of vehicle  $i$  in longitudinal direction. All the vehicles are with respect to a inertia frame.

$v_i(t), a_i(t)$  – speed and acceleration of vehicle  $i$

$h_{p1}$  – time delay for obtaining front range

$h_{p2}$  – time delay for obtaining preceding vehicle’s speed and acceleration

$h_l$  – time delay for on-car sensor measuring and for communication system to pass the leader vehicle’s distance, speed and acceleration to other vehicles

$L_i$  is the desired inter-vehicle distance with vehicle length accounted for

$l$  – subscript for the leader vehicle

$M$  – vehicle mass

$\theta$  – road grade

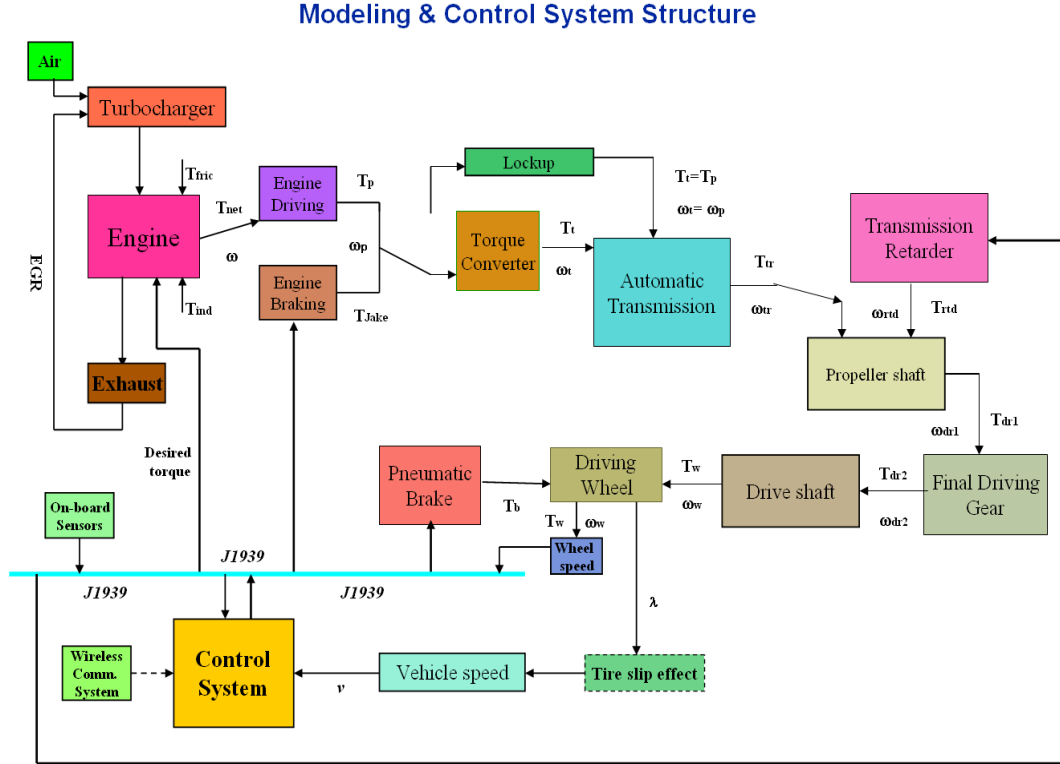


Figure 4.1: Multiple transition between manual and automatic control

$T_{des}$  – desired torque from upper level control

$T_{jk-j}$  – engine Jake brake torque when  $j$  cylinder is on, ( $j = 0, 2, 4, 6$ )

$T_b^{(des)}$  – desired brake torque

$T_{rtd}^{(des)}$  – desired transmission retarder torque

Due to page limit, other notations, if not listed, are referred to [22].

## 4.2 Control Systems

Due to the internal control system structure of Century Freightliner, brake (including Jake brake, transmission retarder and air brake) control and engine control are not directly accessible. Instead, it is necessary to send the control command (properly scaled) from J-1939 Bus to corresponding *Control Modules*.

## 4.2.1 Upper Level Control

For simplicity, suppose all the vehicles in the platoon has the same dynamics. Let the tracking errors are denoted as

$$\begin{aligned}x_e &= x_{i-1} - x_i \\v_e &= v_{i-1} - v_i \\a_e &= a_{i-1} - a_i\end{aligned}$$

Suppose the desired inter-vehicle distance is  $L = const.$  The sliding surface is chosen

$$s = v_e + k_1(x_e - L), \quad k_1 > 0$$

From any sliding reachability condition  $\dot{s} = -\gamma(s) = -\lambda s$  [22], the desired torque  $T_{des}$  can be solved out as

$$T_{des} = \frac{\bar{I}(\lambda s + k_1 v_e + a_{i-1})}{r_d r_g} + \frac{(r_d T_{rtd} + T_b + F_a h_r + F_r h_r + M g h_r \sin \theta)}{r_d r_g} \quad (4.2.1)$$

which generates the torque control command.

## 4.2.2 Lower Level Control

Due to internal engine control,  $T_{des} (> 0)$  is directly fed into the ECM (Engine Control Module). Detailed brake control design has been presented in [22]. The main logic to coordinate the EBS (Electronic Braking System - air brake), Jake brake and transmission retarder is to use engine brake with the highest priority, then the transmission retarder. Leave the air brake only used in braking to stop or in emergency cases. Suppose the total desired braking torque on all wheels are  $T_{brk\_total}$ .

A variable structure braking system control strategy has been implemented as follows.

If  $T_{brk\_total} \leq T_{jk\_0}$ , no pneumatic brake nor jake brake is necessary but throttle is released.

If  $T_{jk\_0} < T_{brk\_total} < T_{jk\_2}$ , No jake brake

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_0}$$

If  $T_{jk\_2} \leq T_{brk\_total} < T_{jk\_4}$ , Jake brake with 2 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_2}$$

If  $T_{jk\_4} \leq T_{brk\_total} < T_{jk\_6}$ , Jake brake with 4 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_4}$$

If  $T_{jk\_6} \leq T_{brk\_total}$ , Jake brake with 6 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_6}$$

### 4.3 Vehicle Acceleration/deceleration Capability

The following table are Truck acceleration capability practically achieved under automatic control which is also apply to Bus.

**Table 4.1**

$v$ [m/s]	max_acceleration [m/s <sup>2</sup> ] ( $M = 36,000kg$ )	max_acceleration [m/s <sup>2</sup> ] ( $M = 15894$ )
5.0	0.55	0.8
8.0	0.53	0.7
12.0	0.4	0.65
18.0	0.244	0.6
25.0	0.11	0.18
30.0	0.06	0.15

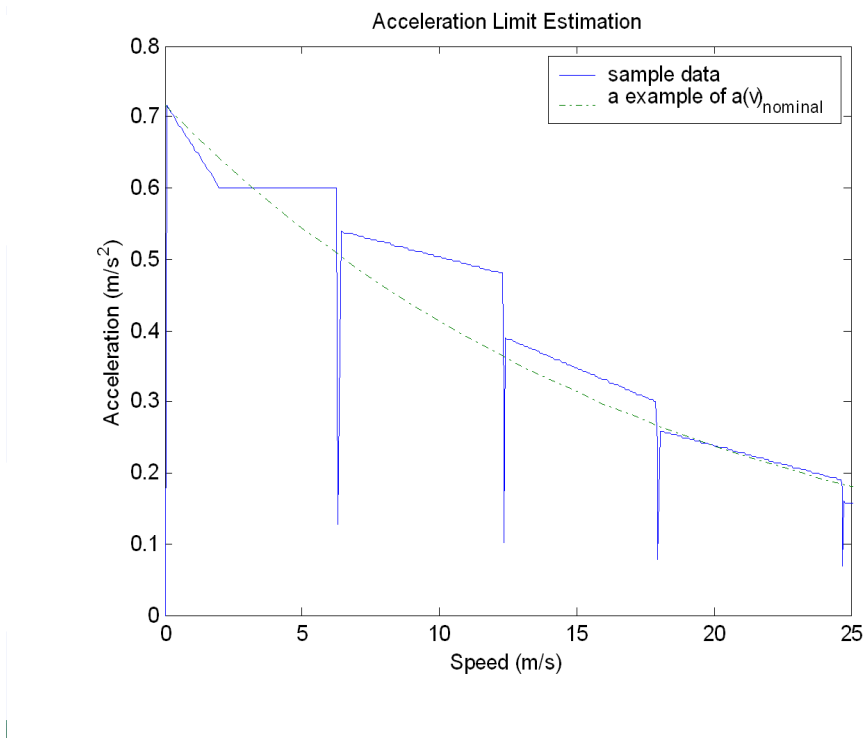


Figure 4.2: Estimation of acceleration limit for empty truck

Tractor/trailer Combination, Fully Loaded:  $M = 36,000kg$ .

Tractor/trailer Combination, Empty trailer:  $M = 15894kg$ .

Truck deceleration capability under automatic control is between  $0.45 \sim 1.1[m/s^2]$  for different combination of weight from trailer only to fully loaded combination.

Suppose the maximum acceleration of the vehicle ta speed  $v$  is  $a_{\max}(v)$  on flat road. Then the vehicle will have maximum acceleration capability on a road with grade  $\theta[rad]$

$$a_{\max}(v, \theta) = a_{\max}(v) - g \sin \theta$$

## 4.4 Other Implementation Issues

### 4.4.1 Measurement and Data Fusion

To achieve an accurate and reliable distance measure is critical for automated vehicle short distance following. As redundant sensors, a Doppler radar, Eaton Vorad (EVT-300) and Denso Lidar are used for this purpose. The characteristics of those systems are listed in Table 1.

**Table 4.2**

	<i>NENSO Lidar</i>	<i>EVT – 300</i>
<i>Meas. principle</i>	<i>Distance based</i>	<i>Relative speed</i>
<i>No. of tracks</i>	8	7
<i>Effective range</i>	$\sim 150[m]$	$\sim 120[m]$
<i>View angle</i>	$\pm 20[deg]$	$\pm 6[deg]$
<i>Azimuth resol.</i>	$0.01[deg]$	$0.1[deg]$
<i>Longitude resol.</i>	$0.01[m]$	$0.2 \sim 2.0[m]$
<i>Weather effect</i>	<i>Severe</i>	<i>Small</i>

The following algorithms are used for signal processing and data fusion.

#### 1. Target Association

The main problem for vehicle following using radar is to detect and track the target vehicle in the front. The controller requires to focus on distance measurement and estimation. To track the main target, i.e. the front vehicle, different laser beams may be used by lidar. Radar tracking may also change the target ID during tracking. Besides, radar distance will drop to zero when relative speed is or nearly zero. These characteristics determines that *target association* techniques are necessary. There is a difference between lidar and radar for target association which is based on their measurement principle.

*Algorithm for radar target association:* Let  $range[I]$ ,  $rate[I]$ , and  $az[I]$ ,  $I = 1, 2, \dots, 7$  denote radar distance, relative speed and azimuth measurement.  $track\_ID$  denote the track number for the front vehicle.

*Step 1.* To choose initial track: For  $J = 1, 2, \dots, 7$ , if  $range[J] > 1.0$  and  $range[J] < 100.0$  then  $track\_ID = J$ . If there are more than one track number satisfy these conditions, then using smallest one as the most likely target tracking.

*Step 2.* Target association: For radar, start from the initial track. At each step, let  $rate[track\_ID]$  and  $az[track\_ID]$  represent the detected front vehicle range and azimuth respectively. For sufficiently small parameter  $\varepsilon_1, \varepsilon_2 > 0$ , if

$$\begin{aligned} |rate[track\_ID] - rate[J]| &= \min_i \{|rate[track\_ID] - rate[i]|\} \\ |az[track\_ID] - az[J]| &= \min_i \{|az[track\_ID] - az[i]|\} \\ |rate[track\_ID] - rate[J]| &\leq \varepsilon_1 \\ |az[track\_ID] - az[J]| &\leq \varepsilon_2 \end{aligned}$$

then,  $range[J]$ ,  $rate[J]$  and  $az[J]$  are considered as the new measure of the track of the front target.

For single target tracking, this algorithm is reasonable. For multiple target tracking, the un-used measure should be put into new tracks and the above process is to be carried for each track established.

*Step 3.* Set  $track\_ID = J$  and go to the *Step 2*. If at least one of the last two conditions are violated, then a measurement error will be reported which may indicate that the radar target tracking has a problem.

For lidar, the above algorithm still apply except that, (a) the total number of track is 8; (b) The rate is changed to longitudinal distance and  $az$  is changed to lateral distance. The choice of parameters depends on design requirement.

## 2. Signal Processing

For both lidar and radar distance measurement in the established tracking, digital filters [28] are used for smoothing the distance measures. Particularly, the following filters are used:

(a) Recursive type:

$$\bar{x}_n = \lambda x_n + (1 - \lambda)\bar{x}_{n-1}$$

(b) Low pass filter:

$$\begin{aligned} x_1(n) &= 0.4320x_1(n-1) - 0.3474x_1(n-1) + 0.1210rg_m(n) \\ x_2(n) &= 0.3474x_1(n-1) + 0.9157x_1(n-1) + 0.0294rg_m(n) \\ y(n) &= 0.4984x_1(n-1) + 2.7482x_2(n-1) + 0.0421rg_m(n) \end{aligned}$$

where  $x_1(n), x_2(n)$  are filter state variables,  $rg_m(n)$  is range measure at time  $n$ .  $y(n)$  is filtered range at time  $n$ .

Figure 4.3 shows the radar raw data and filtered data after using the above filter.

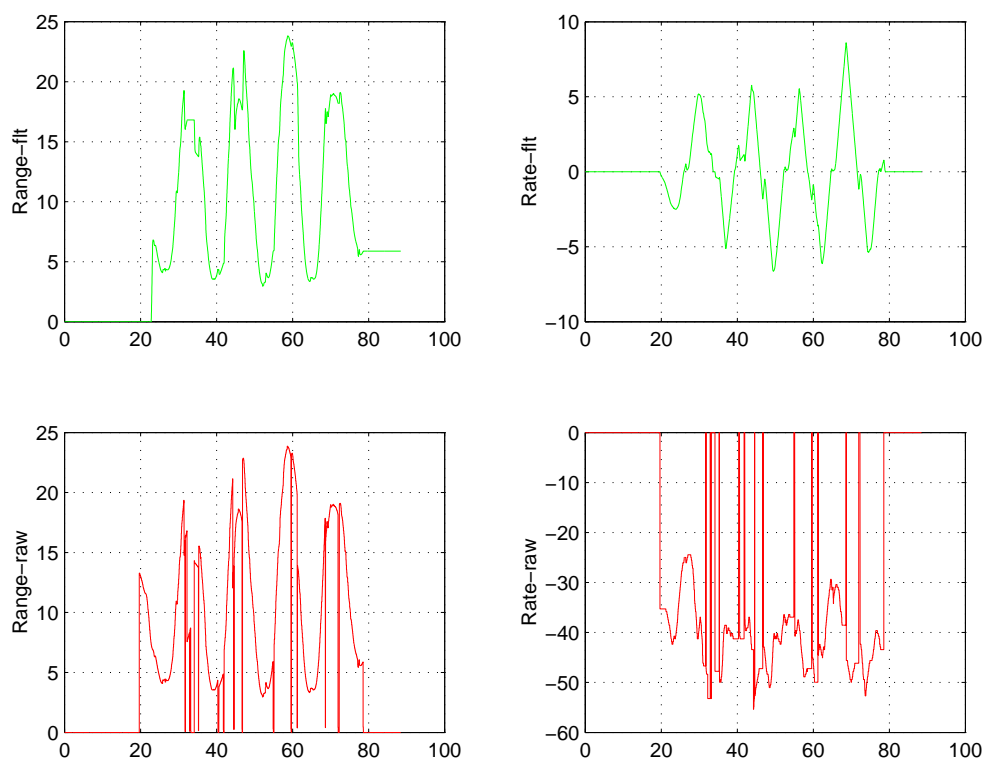


Figure 4.3: Eaton Vorad radar filtering

Lower: raw range and range-rate; Upper: filtered range and range rate

### 3. Data Fusion

The purpose for data fusion is to achieve a more reliable and accurate measure by means of sensor redundancy. Due to the characteristics of the two types of distance sensors, their measurement are complementary in some sense. The following three techniques are used in data fusion of radar and lidar.

(a) Using lidar distance measure to compensate for radar distance measure when relative vehicle speed is zero. In this case, radar measure will drop to zero while lidar still have a good measurement if the weather is reasonable. It is simply to use the average of previous step radar measure and current lidar measure to replace the lost radar measure. (b) If one set report error status, the measure naturally shift to the other. (c) A Kalman filter is used to fuse those two distance measures in normal cases [3].



Let  $y_L(n)$ , and  $y_R(n)$  denote the filtered lidar range and radar range respectively at time step  $n$ ; Let  $y_{LR}(n)$  denote the Kalman filter estimation of combined radar and lidar signal at time step  $(n - 1)$ . The Kalman filter is constructed as the following "predictor-corrector" structure:

$$\begin{aligned}\bar{x}(n) &= \frac{\sigma_{y_L(n)}^2}{\sigma_{y_L(n)}^2 + \sigma_{y_R(n)}^2} y_R(n) \\ y_{LR}(n) &= \bar{x}(n) + K(n) [y_L(n) - \bar{x}(n)] \\ K(n) &= \frac{\sigma_{y_R(n)}^2}{\sigma_{y_L(n)}^2 + \sigma_{y_R(n)}^2}\end{aligned}$$

where  $\sigma_{y_L(n)}^2, \sigma_{y_R(n)}^2$  are variance of lidar and radar distance measurement respectively.

Figure 4.4 shows the filtering and fusion of radar, lidar distance measurement. The following notations are used in the figure: `vrdrange`: Eaton Vorad radar range; `vrdrtr`: Eaton Vorad radar range rate; `lidrng`: Lidar range flt; `filtered K-F`: Fused distance using Kalman filter.

Explanation of the figure: Upper 1st plot: red is the raw radar range data and green is filtered radar range; 2nd plot: red is the radar range rate and the green is filtered radar range rate; 3rd plot: red is Lidar range raw data and the green is filtered lidar range; The lower plot: The green is filtered radar range (corresponding the green in the 1st plot), the magenta is filtered lidar range (corresponding to the blue in the 3rd plot) and the blue is the fused lidar and radar range by the Kalman filter. The abrupt change of radar range as indicated in the last plot does not affect the fused range.

## 4.4.2 Wireless Communication

802.11b wireless systems are used for inter-vehicle communication. The update rate is 20[ms]. The information passed from the leader vehicle to the following vehicles involve: vehicle speed, acceleration, pedal deflection, brake pressure, `maneuver_des`, `maneuver_id`, and fault mode;

`maneuver_des`: An integer to specify the desired maneuver of the vehicle assigned by the coordination layer manager;

`maneuver_id`: Practical maneuver the subject vehicle is doing;

`fault_mode`; An integer to represent different faults including: radar, lidar, communication, brake actuator, engine speed, vehicle speed, etc. For each critical component, there is a fault detect mechanism to report if they are working properly.

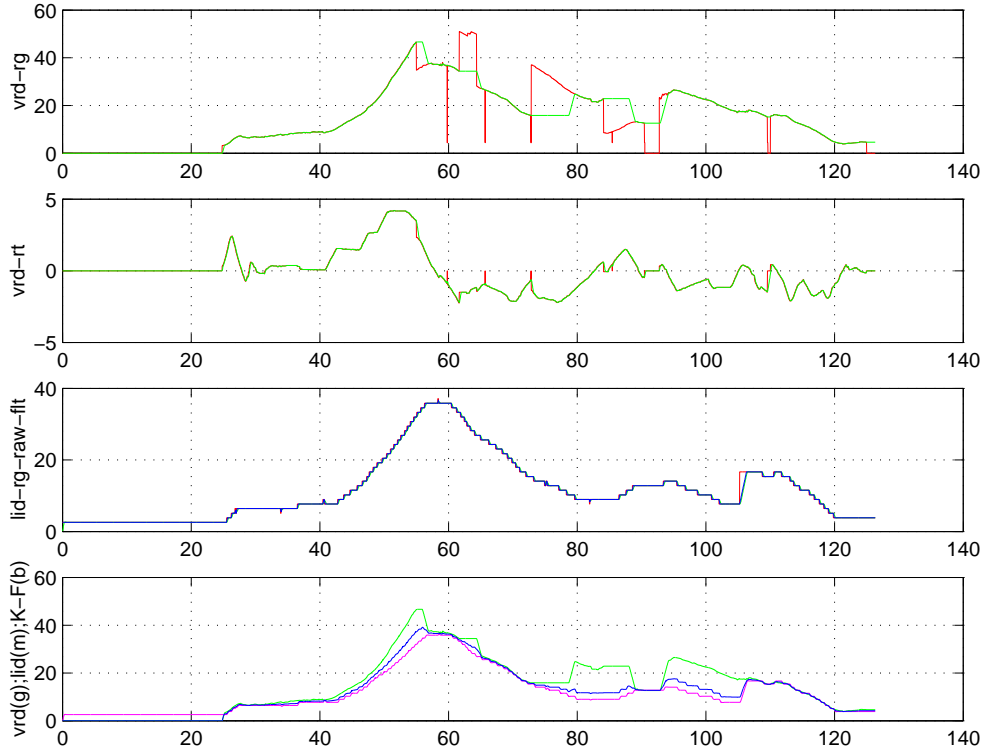


Figure 4.4: Kalman filter used for data fusion

## 4.5 Experimental Work

In the test, the first truck is fully loaded ( $M = 31795[kg]$ ) and the second truck is half loaded ( $M = 22226[kg]$ ). A nearly flat test track has total length  $2250[m]$ . Speed range tested is:  $5 \sim 55[mph]$ . Inter-vehicle distance tested is between:  $3 \sim 10[m]$

Combined braking system tested Air brake (EBS), Jake brake and Transmission retarder. The second truck has modified EBS Box with no minimal brake value, but the first truck has a minimal brake torque which produces deceleration of  $0.25[m/s^2]$ . This hardware constraint behaves as a prominent disturbance and affects the performance somehow.

Maximum deceleration range tested  $0.45 \sim 0.9[m/(s^2)]$ . For safety, the distance is intently increased when the desired distance is  $3[m]$  while the vehicle is braking to stop.

Each run has 3 figures.

Units & notations used in the following figures are:

spd: speed [mph]

dist: distance

dist\_err: distance error [m]

spd\_err: speed error [m/s]

Color used in plotting:

red - 1st vehicle

green - 2nd vehicle

The x-coordinate is time in second.

It is noted that, in the following figures, air brake pressure is intently plotted from  $-20[s]$  to show that air brake is applied before  $t = 0$  (the instant when the vehicle start to move). Other plots in each run are plotted from  $t = 0[s]$  instead.

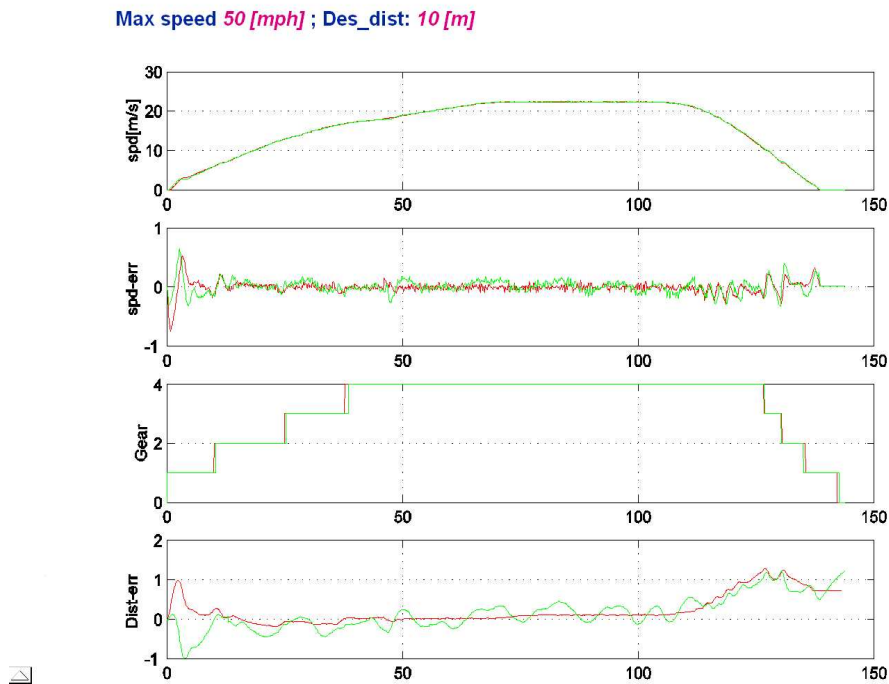


Figure 4.5:

## 4.6 Concluding Remarks

Based on the modeling and control design in previous work [20, 22], this chapter presents the implementation issues of longitudinal control of automated trucks for short distance

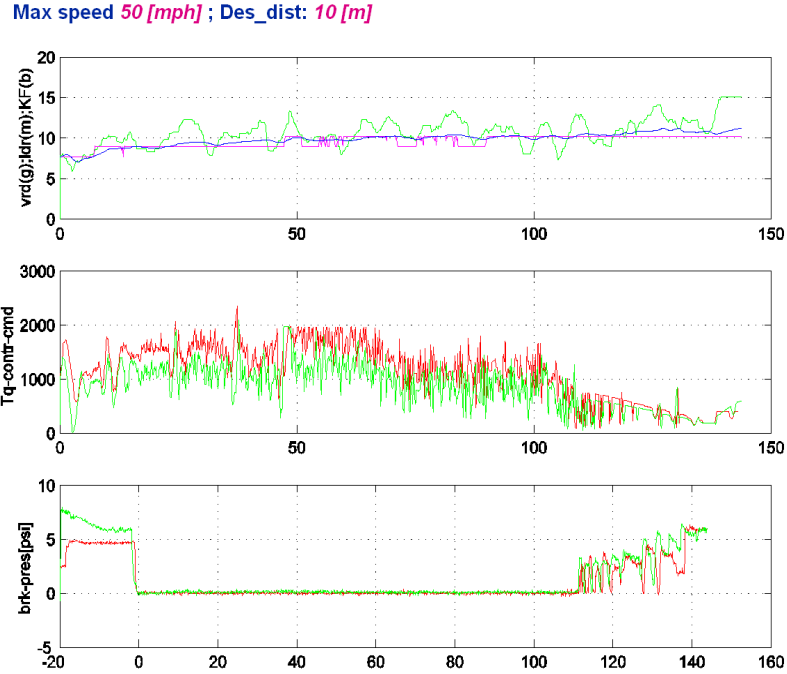


Figure 4.6:

following. Research results for practical string stability discussed in [23] or previous chapter is used here, which takes into consideration the time delays caused by sensors and actuators. The remaining issue for vehicle following are: distance measurement and estimation, wireless communication. Linear filter and Kalman filter are used for filtering and fusion of radar and lidar data in real-time. Although, there are only two trucks tested, considering that the first truck is following a reference trajectory, there is still a string stability problem. Extensive test has been done, which involves different following distance between  $3 \sim 10[m]$ , different acceleration and deceleration, and different maximum speed. Results show that the performance of the controller is good.

Work in this chapter will be extended to three or more trucks in the future.

Max speed 45 [mph] ; Des\_dist: 10 [m]

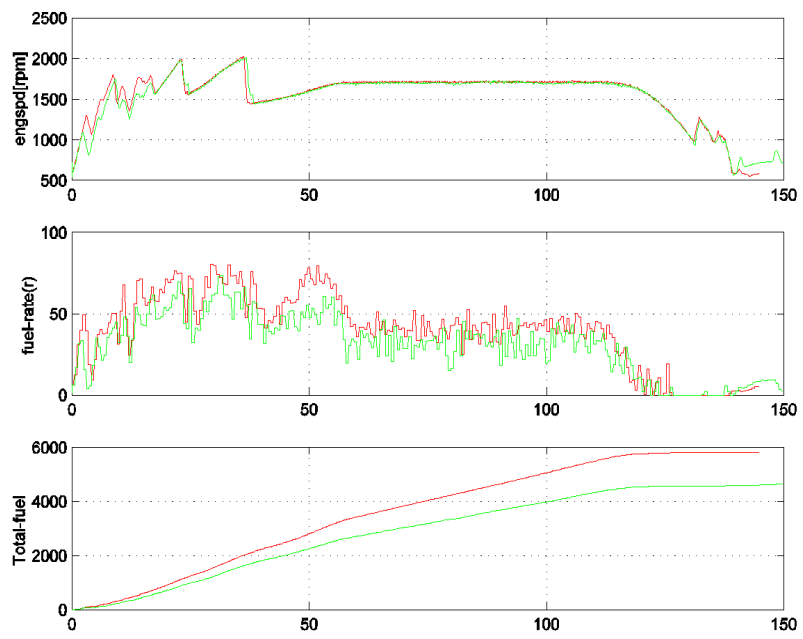


Figure 4.7:

Max speed 55 [mph] ; Des\_dist: 4 [m]

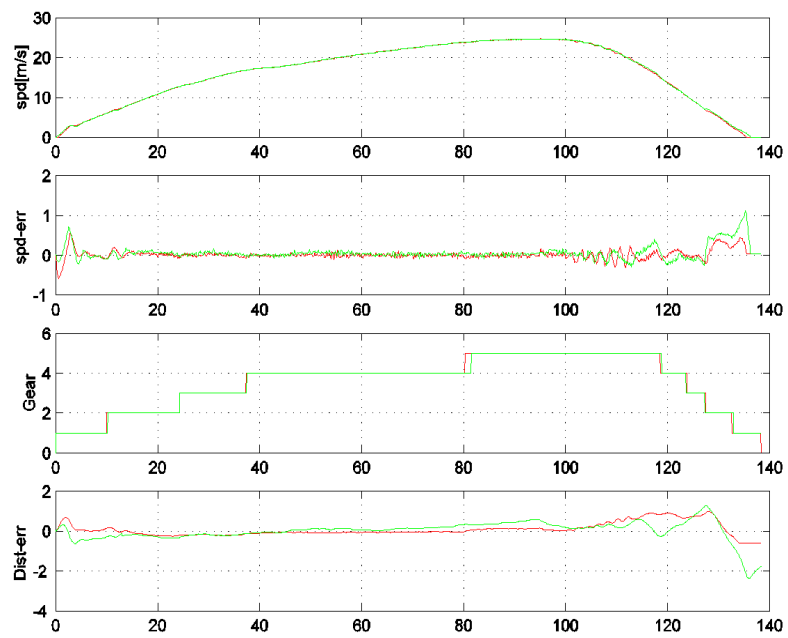


Figure 4.8:

Max speed 55 [mph] ; Des\_dist: 4 [m]



Figure 4.9:

Max speed 55 [mph] ; Des\_dist: 4 [m]

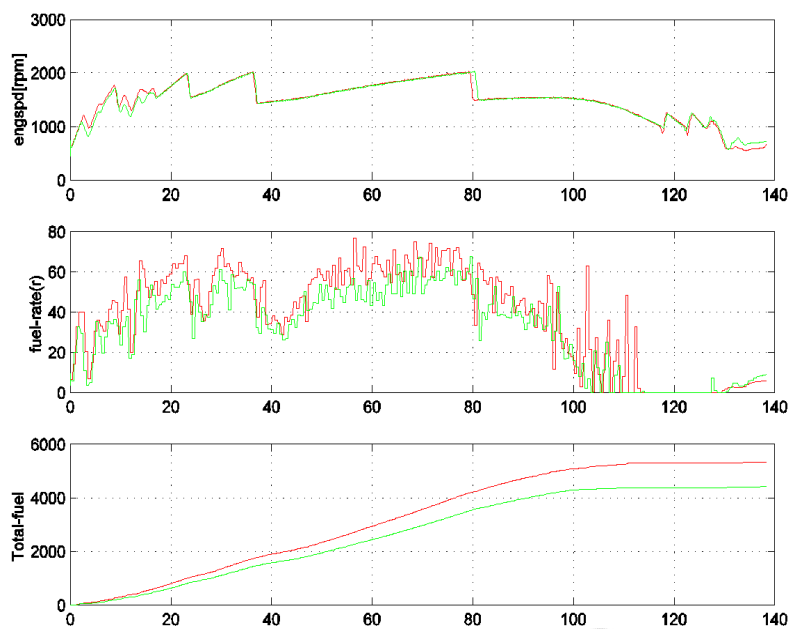


Figure 4.10:



# Chapter 5

## Transition Maneuvers

*Summary:* This chapter considers real-time algorithm and implementation for longitudinal control transition between manual and automatic driving for a single vehicle. This maneuver is fundamental for developing driver assistance system and for the driver to interact with the control system of the vehicle. From automatic to manual control is easy to achieve. The main control problem involved is the transition from manual to automatic. It may be divided into two phases: *control systems witching* and *dynamic trajectory planning*. The switching includes hardware switching, logical control and state variable initialization. Emphasis is put on trajectory planning with others briefly discussed. The mathematical problem is to find a continuously differentiable curve which is tangent to the manual control speed curve at the time instant of switching and also tangent to a reference speed trajectory for automatic control. The reference trajectory is known but the speed profile of manual driving is not known a priori. It is shown that there always exists such a curve, which can be composed of three pieces of sinusoidal curves, for example. Implementation related issues are briefly discussed. Dynamic trajectory planning here is another typical example encountered in vehicle coordination in the sense that the trajectory planning must be subject to appropriate constraints, mainly acceleration/deceleration capability, at different speed.

Experimental results on full scale passenger car and Heavy-Duty-Trucks are also presented.

### 5.1 Introduction

With the development of longitudinal and lateral control for automated highway systems (AHS) [6, 31, 33, 34, 37], or other kinds of intelligent transportation systems [18], one

problem that arises naturally is the transition between manual and automatic driving. Before entering AHS, all vehicles need transition from manual to automatic control. Here transition is understood as a procedure which brings manual control of a single vehicle (*single agent*) to completely automatic control. Multiple transitions between manual and automatic may also be necessary in practice in case the driver needs to takeover in some situations and transition back to automatic in other cases. The transition from automatic to manual is relatively easy from the control design point of view because the driver takes the responsibility for the dynamic response of the vehicle. The main control problem is the smooth transition from manual to automatic control. Here a transition maneuver is conducted for a single vehicle.

The transition procedure can be divided into two phases: control system switching and trajectory planning. The former includes hardware switching, logical control and state variable initialization. The crux is the trajectory planning, which is to find a continuously differentiable speed curve such that it is tangent to both the end point of the manual driving speed curve and some point on the automatically controlled reference trajectory. One main purpose of this chapter is to provide a general real-time algorithm for trajectory planning. Implementation and real-time testing will be addressed briefly.

This chapter is organized as follows: Section 2 specifies the control problem for the transition maneuver; Section 3 sets up mathematical models and provides real-time algorithms for transition of a single vehicle; Section 4 presents implementation and real-time test issues; Section 5 is for concluding remarks.

**Notations:** The following notations are used throughout of the chapter.

$t$  – time parameter

$t_0$  – time instant for the vehicle to transition from manual to automatic control

$v(t_0)$  – speed for the subject vehicle at  $t = t_0$

$a(t_0)$  – acceleration for the subject vehicle at  $t = t_0$

$v_{auto}(t)$  – reference speed profile for automated vehicle

$\tau$  – time parameter for reference speed profile

$a_{auto}(t) = \dot{v}_{auto}(t)$  (continuous)

$v_{ref}(t)$  – reference speed trajectory for the subject vehicle to be designed

$v_{ref}^{(1)}(t)$  – reference speed trajectory for  $t \in [t_0, t_0 + T_1)$

$v_{ref}^{(2)}(t)$  – reference speed trajectory for  $t \in [t_0 + T_1, t_0 + T_1 + T_2)$

$v_{ref}^{(3)}(t)$  – reference speed trajectory for  $t \in [t_0 + T_1 + T_2, t_0 + T_1 + T_2 + T_3]$

$a_{ref}(t) = \dot{v}_{ref}(t)$  (to be continuous)

$a_{ref}^{(i)}(t) = \dot{v}_{ref}^{(i)}(t)$ , ( $i = 1, 2, 3$ ) – (to be continuous)

$a_{max}(v)$  – is the maximum acceleration capability of the vehicle under automatic control

- $d_{\max}(v)$  – is the maximum deceleration capability of the vehicle under automatic control
- $\mathcal{C}^1$  – the set of continuously differentiable functions
- $T$  – time span for transition

## 5.2 Specification

The principles for longitudinal transition control are stated as follows.

1. It is for the operation of a single vehicle;
2. Its controller has a known  $\mathcal{C}^1$  speed profile. The continuity for acceleration curve is necessary for two reasons:
  - (2-a) For passenger vehicle, it is for comfort. Vehicle jerk is bounded only if acceleration is continuous;
  - (2-b) For heavy-duty vehicle, discontinuity of acceleration/deceleration is easy to cause control command saturation, which leads to the loss of controllability.
3. The driver should be able to transition from manual driving mode to a completely automatic driving mode for some bounded conditions of speed, acceleration and jerk based on safety and passenger's comfort;
4. Multiple transitions: The driver may execute multiple transitions between manual and automatic control modes if necessary in practice.

## 5.3 Transitions

The transition from manual to automatic control needs two steps:

Step 1: *Control system switching*: It involves hardware switching, logical control, vehicle state initialization and automatic closed-loop control activation. Here vehicle state includes all the state variables in control systems (hardware and software).

Step 2: *Trajectory planning*: This is necessary because there should be a smooth transition process between manual control and automatic control. An automatic closed-loop control system for a vehicle usually takes a known speed profile as a reference trajectory fed into the controller. This reference trajectory can be a pre-defined  $\mathcal{C}^1$  (continuously differentiable) function based on the vehicle acceleration/deceleration capability and the controller bandwidth. The initial conditions of the control system must fall into a specific region (stability margin) to ensure closed-loop stability, bounding the case in which the driver is permitted to switch from manual to automatic control.

### 5.3.1 Control System Switching

This process involves logical control and vehicle state initialization. To understand this, it is helpful to introduce the concept of the *vehicle state*, which is a vector composed of the following entries:  $v(t)$ —vehicle speed,  $a(t)$ — acceleration and  $b(t)$ — jerk ( $b(t) = \dot{a}(t)$ ).

For transition, a mutually exclusive three way logical control is necessary:

(1) Manual mode: It is necessary for a vehicle to run in a normal highway system, suburban area and before entering the AHS.

(2) Automatic mode: Driver cannot take over by simply pressing the throttle or brake pedal; This mode is necessary to exclude the possibility of driver's taking over in a condition under which he/she is not likely to be able to control the vehicle adequately.

short inter-vehicle distance platoon maneuver.

(3) Automatic mode, but the driver can overtake manually by pressing the accelerator or brake pedal in the following sense:

Throttle control:

$$fuel\ rate = \max \{pedal\ deflection, control\ command\}$$

Brake control:

$$brk.\ press. = \max \{pedal\ deflection, control\ command\}$$

This mode is necessary for transitions between manual and automatic and for emergency handling.

Logical control is very critical for transition between those modes. It guarantees that at any time instant, all the state variables and control algorithms must stick to one and only one mode.

For smooth transition from one mode to the other and to ensure stability of the control system, it is necessary and sufficient to set the initial state of the next mode as the final state of the current mode. Such logical control and initialization in real-time can be implemented with the following general mechanism which is applicable to transition between  $n$  exclusive modes.

Suppose a decision is made that the transition is from mode  $k$  to mode  $l$ , where  $l, k \in \{1, \dots, n\}$ . The following semantics implement the control system switch in real-time.  $sw\_i\_j$  is the switch for the Semaphores [1] while  $trans\_i\_j=ON$  means the state variables are to transition from state  $i$  to state  $j$ . The latter is the command issued by some hardware switch or Human Machine Interface.

(a) Variable declaration and initialization:

```
for i=1:n;
    mode_j_control = OFF;
    for j=1:n;
        sw_i_j=OFF;
        trans_i_j=OFF.;
    end
end
```

(b) Initialization and control for the transition process ( $t = t_0$ ):

```
sw_k_l=ON;
for i=1:n;
    for j=1:n;
        if (sw_k_l == ON)
            state_l is initialized as the final value of state k;
            transition start time is initialized;
            sw_k_l=OFF;
            mode_k_control = OFF;
            trans_k_l = ON;
        end
    end
end
```

(c) Temporary period ( $t \in [t_0, t_0 + T]$ ):

```
if (trans_k_l == ON;)
    using temporary trajectory planning;
    if (v_ref = v_auto && a_ref = a_auto)
        trans_k_l = OFF;
        mode_l_control = ON;
    end
end
```

(d) Execute *mode l* control algorithm ( $t > t_0 + T$ )

```
for i=1:n
    if (mode_l_control = ON)
        mode_l_control_algorithm;
        ...
    end
end
```

end

### 5.3.2 Trajectory Planning

Suppose the control mode transition is invoked at  $t = t_0$  and the trajectory smoothing will be finished at  $t = t_0 + T$  with  $T$  to be determined. From  $t > t_0 + T$  the automated vehicle is assumed to track its long-term reference trajectory. The transition (smoothing) reference trajectory for  $t \in [t_0, t_0 + T]$  is

$$\begin{aligned}
 v_{ref}(t_0) &= v_{man}(t_0) \\
 a_{ref}(t_0) &= a_{man}(t_0) \\
 v_{ref}(t_0 + T) &= v_{auto}(t_0 + T) \\
 a_{ref}(t_0 + T) &= a_{auto}(t_0 + T) \\
 -d_{\max}(v_{ref}) &\leq \dot{v}_{ref}(t) \leq a_{\max}(v_{ref})
 \end{aligned} \tag{5.3.1}$$

where  $v_{ref}(t)$  and  $a_{ref}(t)$  (continuous) are reference speed and acceleration of the subject vehicle respectively. In (5.3.1) the first two are for compatibility of initial conditions (tangent at point a in Figure 5.1) and the third and fourth are for compatibility of final conditions (tangent at point b in Figure 5.1). The last constraint comes from the control system and vehicle's physical acceleration/deceleration capability.

Now the mathematical problem for the temporary trajectory planing can be stated as follows: to find a  $T$  and a  $\mathcal{C}^1$  function  $v_{ref}(t)$  such that all the conditions in (5.3.1) are satisfied assuming that  $v_{auto}(t)$  is known.

There are altogether nine cases for trajectory planning which correspond to manual driving acceleration state at the time the transition is invoked:

$$a_{man}(t_0) \begin{cases} > 0 \\ = 0 \\ < 0 \end{cases}$$

and automated operation acceleration state at the completion of the smooth transition:

$$a_{auto}(t_0 + T) \begin{cases} > 0 \\ = 0 \\ < 0 \end{cases}$$

Now the trajectory planning is carried out in three disjoint subintervals

$$[t_0, T] = [t_0, t_0 + T_1) \cup [t_0 + T_1, t_0 + T_1 + T_2)$$

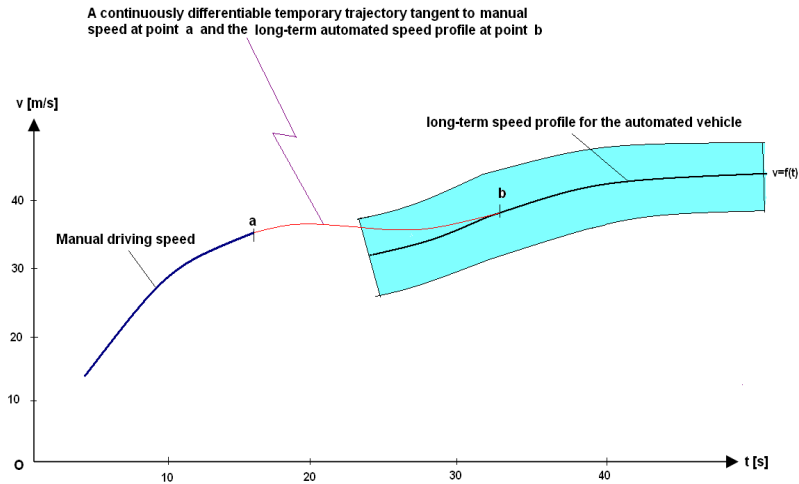


Figure 5.1: Temporary trajectory planning is necessary for transition.

$$\cup [t_0 + T_1 + T_2, t_0 + T_1 + T_2 + T_3]$$

$$T = T_1 + T_2 + T_3$$

$$T_i \geq 0, i = 1, 2, 3$$

where  $T_i (i = 1, 2, 3)$  are to be determined.

In the following approach, the temporary trajectory is composed of 3 sections of sinusoidal curves. This approach is adopted for the following reasons:

- (a) Such a general  $\mathcal{C}^1$  solution always exists;
- (b) It is easy to control the magnitude of  $\dot{v}_{ref}(t)$  by varying the magnitude and frequency of the sinusoidal functions;
- (c) It is easy for implementation.

1. For  $t \in [t_0, t_0 + T_1)$ ,  $v_{ref}^{(1)}(t)$  is chosen as

$$v_{ref}^{(1)}(t) = \begin{cases} v_{man}(t_0) \left[ 1 + \sin\left(\frac{\pi(t-t_0)}{2T_1}\right) \right] \\ \quad \text{if } a_{man}(t_0) > 0 \\ \\ v_{man}(t_0), \text{ if } a_{man}(t_0) = 0 \\ \\ v_{man}(t_0) \left[ 1 + \sin\left(\frac{\pi(t-t_0)}{2T_1} - \pi\right) \right] \\ \quad \text{if } a_{man}(t_0) < 0 \end{cases} \quad (5.3.2)$$

Clearly,

$$v_{ref}^{(1)}(t_0) = \begin{cases} v_{man}(t_0), \text{ if } a_{man}(t_0) > 0 \\ v_{man}(t_0), \text{ if } a_{man}(t_0) = 0 \\ v_{man}(t_0), \text{ if } a_{man}(t_0) < 0 \end{cases}$$

which implies that the transition is continuous at  $t = t_0$ .

Correspondingly

$$a_{ref}^{(1)}(t) = \begin{cases} \frac{\pi v_{man}(t_0)}{2T_1} \cos\left(\frac{\pi(t-t_0)}{2T_1}\right), \text{ if } a_{man}(t_0) > 0 \\ 0, \text{ if } a_{man}(t_0) = 0 \\ \frac{\pi v_{man}(t_0)}{2T_1} \cos\left(\frac{\pi(t-t_0)}{2T_1} - \pi\right), \text{ if } a_{man}(t_0) < 0 \\ t \in [t_0, t_0 + T_1) \end{cases}$$

For such choice

$$a_{ref}^{(1)}(t_0 + T_1) = \begin{cases} 0, \text{ if } a_{man}(t_0) > 0 \\ 0, \text{ if } a_{man}(t_0) = 0 \\ 0, \text{ if } a_{man}(t_0) < 0 \end{cases}$$

and

$$a_{man}(t_0) = \dot{v}_{ref}^{(1)}(t_0) = \begin{cases} \frac{\pi v_{man}(t_0)}{2T_1}, \text{ if } a_{man}(t_0) > 0 \\ 0, \text{ if } a_{man}(t_0) = 0 \\ -\frac{\pi v_{man}(t_0)}{2T_1}, \text{ if } a_{man}(t_0) < 0 \end{cases} \quad (5.3.3)$$

from which  $T_1$  is determined as follows

$$T_1 = \begin{cases} \frac{\pi v_{man}(t_0)}{2a_{man}(t_0)}, \text{ if } a_{man}(t_0) > 0 \\ 0, \text{ if } a_{man}(t_0) = 0 \\ -\frac{\pi v_{man}(t_0)}{2a_{man}(t_0)}, \text{ if } a_{man}(t_0) < 0 \end{cases}$$



It is noted that at  $t = t_0 + T_1$

$$v_{ref}^{(1)}(t_0 + T_1) = \begin{cases} 2v_{man}(t_0), & \text{if } a_{man}(t_0) > 0 \\ v_{man}(t_0), & \text{if } a_{man}(t_0) = 0 \\ 0, & \text{if } a_{man}(t_0) < 0 \end{cases}$$

$$a_{ref}^{(1)}(t_0 + T_1) = \begin{cases} 0, & \text{if } a_{man}(t_0) > 0 \\ 0, & \text{if } a_{man}(t_0) = 0 \\ 0, & \text{if } a_{man}(t_0) < 0 \end{cases}$$

which will be used later.

For such a plan,  $v_{ref}^{(1)}(t)$  is tangent to  $v_{man}(t)$  at  $t = t_0$ .

2. For  $t \in [t_0 + T_1 + T_2, t_0 + T_1 + T_2 + T_3)$ ,  $v_{ref}^{(3)}(t)$  will be chosen such that it is tangent to  $v_{auto}(\tau)$  at  $\tau = \tau_f$ , where both  $v_{auto}(\tau_f)$  and  $a_{auto}(\tau_f)$  are known. Note that  $\tau$  is the time parameter for the long term automated driving speed profile. For real-time implementation, it needs to be mapped to the real-time parameter  $t$ .  $\tau_f$  may be chosen to minimize  $\left|v_{auto}(\tau_f) - v_{ref}^{(1)}(t_0 + T_1)\right|^2 + \left|a_{auto}(\tau_f) - a_{ref}^{(1)}(t_0 + T_1)\right|^2$

For so chosen  $v_{auto}(\tau_f)$  and  $a_{auto}(\tau_f)$ , the reference trajectory in the third sub-interval can be chosen as

$$v_{ref}^{(3)}(t) = \begin{cases} v_{auto}(\tau_f) \left[ 1 + \sin\left(\frac{\pi(t - (t_0 + T_1 + T_2))}{2T_3} - \frac{\pi}{2}\right) \right] & \text{if } a_{auto}(\tau_f) > 0 \\ v_{auto}(\tau_f), & \text{if } a_{auto}(\tau_f) = 0 \\ v_{auto}(\tau_f) \left( 1 - \sin\left(\frac{\pi(t - (t_0 + T_1 + T_2))}{2T_3} - \frac{\pi}{2}\right) \right) & \text{if } a_{auto}(\tau_f) < 0 \end{cases} \quad (5.3.4)$$

$$\tau_f = t_0 + T_1 + T_2 + T_3 = t_0 + T$$

Clearly, the final condition

$$v_{ref}^{(3)}(\tau_f) = v_{auto}(\tau_f)$$

is satisfied. Besides,

$$a_{ref}^{(3)}(t) = \begin{cases} \frac{\pi}{2T_3} v_{auto}(\tau_f) \cos\left(\frac{\pi(t-(t_0+T_1+T_2))}{2T_3} - \frac{\pi}{2}\right) \\ \quad \text{if } a_{auto}(\tau_f) > 0 \\ 0, \quad \text{if } a_{auto}(\tau_f) = 0 \\ -\frac{\pi}{2T_3} v_{auto}(\tau_f) \cos\left(\frac{\pi(t-(t_0+T_1+T_2))}{2T_3} - \frac{\pi}{2}\right) \\ \quad \text{if } a_{auto}(\tau_f) < 0 \end{cases}$$

$$a_{ref}^{(3)}(t_0 + T_1 + T_2) = \begin{cases} 0, \quad \text{if } a_{auto}(\tau_f) > 0 \\ 0, \quad \text{if } a_{auto}(\tau_f) = 0 \\ 0, \quad \text{if } a_{auto}(\tau_f) < 0 \end{cases}$$

and

$$a_{ref}^{(3)}(\tau_f) = \begin{cases} \frac{\pi}{2T_3} v_{auto}(\tau_f), \quad \text{if } a_{auto}(\tau_f) > 0 \\ 0, \quad \text{if } a_{auto}(\tau_f) = 0 \\ -\frac{\pi}{2T_3} v_{auto}(\tau_f), \quad \text{if } a_{auto}(\tau_f) < 0 \end{cases}$$

The continuous condition for acceleration requires that

$$a_{ref}^{(3)}(\tau_f) = a_{auto}(\tau_f)$$

which leads to

$$T_3 = \begin{cases} \frac{\pi v_{auto}(\tau_f)}{2a_{auto}(\tau_f)}, \quad \text{if } a_{auto}(\tau_f) > 0 \\ 0, \quad \text{if } a_{auto}(\tau_f) = 0 \\ -\frac{\pi v_{auto}(\tau_f)}{2a_{auto}(\tau_f)}, \quad \text{if } a_{auto}(\tau_f) < 0 \end{cases}$$

This determines  $T_3$ .

Besides,

$$v_{ref}^{(3)}(t_0 + T_1 + T_2) = \begin{cases} 0, \quad \text{if } a_{auto}(\tau_f) > 0 \\ v_{auto}(\tau_f), \quad \text{if } a_{auto}(\tau_f) = 0 \\ 2v_{auto}(\tau_f), \quad \text{if } a_{auto}(\tau_f) < 0 \end{cases}$$

which will be used in next step.

3. For  $t \in [t_0 + T_1, t_0 + T_1 + T_2]$ , suppose  $v_{ref}^{(2)}(t)$  is obtained by  $\mathcal{C}^1$ -interpolating the end point of  $v_{ref}^{(1)}(t)$  and the starting point of  $v_{ref}^{(3)}(t)$  as

$$v_{ref}^{(2)}(t) = (1 - \alpha(t)) v_{ref}^{(1)}(t_0 + T_1) + \alpha(t) v_{ref}^{(3)}(t_0 + T_1 + T_2) \quad (5.3.5)$$

Then

$$\begin{aligned} \dot{v}_{ref}^{(2)}(t) &= -\dot{\alpha}(t) v_{ref}^{(1)}(t_0 + T_1) + \dot{\alpha}(t) v_{auto}(t + T_1 + T_2) \\ t &\in [t_0 + T_1, t_0 + T_1 + T_2] \end{aligned} \quad (5.3.6)$$

The problem becomes to find a  $\mathcal{C}^1$  function  $\alpha(t)$  such that

$$\begin{aligned} \alpha(t_0) &= 0 \\ \alpha(t_0 + T) &= 1 \\ \text{sign}[\dot{\alpha}(t)] &= \text{const}, \quad t \in [t_0 + T_1, t_0 + T_1 + T_2] \end{aligned} \quad (5.3.7)$$

Let

$$\begin{aligned} \alpha(t) &= 0.5 - 0.5 \cos\left(\frac{\pi(t - (t_0 + T_1))}{T_2}\right) \\ t &\in [t_0 + T_1, t_0 + T_1 + T_2] \end{aligned}$$

$$\dot{\alpha}(t) = -\frac{\pi}{2T_2} \sin\left(\frac{\pi(t - (t_0 + T_1))}{T_2}\right)$$

It can be checked that all the conditions in (5.3.7) are satisfied. Furthermore,  $T_2$  is chosen such that

$$\begin{aligned} -d_{\max}(v_{ref}) &\leq \frac{\pi \sin\left(\frac{\pi(t - (t_0 + T_1))}{T_2}\right) (v_{ref}^{(1)}(t_0 + T_1) - v_{auto}(t_0 + T_1 + T_2))}{2T_2} \\ &\leq a_{\max}(v_{ref}) \end{aligned}$$

To satisfy this, it is sufficient that

$$\frac{\pi |v_{ref}^{(1)}(t_0 + T_1) - v_{auto}(t_0 + T_1 + T_2)|}{2T_2} \leq \min\{a_{\max}(v_{ref}), d_{\max}(v_{ref})\}$$

which is the only constraint for  $T_2$ . Note that this condition can be checked in real-time.

Combining all the three steps, the following result is obtained.

**Theorem 5.1** For temporary trajectory planning of vehicle control mode transition, a  $\mathcal{C}^1$  reference trajectory  $v_{ref}(t)$  always exists as

$$v_{ref}(t) = \begin{cases} v_{ref}^{(1)}(t), & t \in [t_0, t_0 + T_1) \\ v_{ref}^{(2)}(t), & t \in [t_0 + T_1, t_0 + T_1 + T_2) \\ v_{ref}^{(3)}(t), & t \in [t_0 + T_1 + T_2, t_0 + T) \\ v_{auto}(t - (t_0 + T) + \tau_f), & t > t_0 + T \end{cases}$$

which is tangent to both  $v_{man}(t)$  at  $t = t_0$  and to  $v_{auto}(t)$  at  $t = t_0 + T$ .

**Proof.** As the arguments above. ♦

The result is depicted as Figure 5.2.

**Remark 5.1** This approach is always effective because  $v_{auto}(t)$  is known. If  $v_{auto}(t)$  is unknown, it fails.

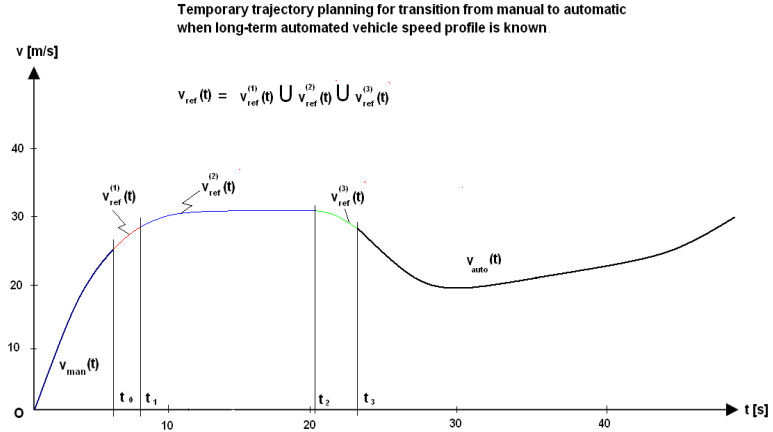


Figure 5.2: Trajectory planning for transition

## 5.4 An Alternative Approach

Suppose the transition is to be carried out within time interval  $t \in [t_0, t_0 + T]$ . It is interesting to consider the if it is possible for the transition trajectory to be composed of finite number of, say  $m$ , sections of parabolic curve

$$g_i(t) = a_i t^2 + b_i t + c_i$$

such that the following conditions hold:

(1) The overall curve is

$$v_{ref}(t) = \begin{cases} g_1(t), & t \in [t_0, t_1] \\ \dots \\ g_i(t), & t \in [t_{i-1}, t_i] \\ \dots \\ g_m(t), & t \in [t_{m-1}, t_m] \end{cases}$$

$$t_0 < t_1 < \dots < t_m = t_0 + T$$

(2)

$$\begin{aligned}
g_1(t_0) &= v_{man}(t_0) \\
\dot{g}_1(t_0) &= a_{man}(t_0) \\
g_i(t_{i-1}) &= g_{i-1}(t_{i-1}) \\
\dot{g}_i(t_{i-1}) &= \dot{g}_{i-1}(t_{i-1}) \\
i &= 2, \dots, m \\
g_m(t_0 + T) &= v_{auto}(t_0 + T) \\
\dot{g}_m(t_0 + T) &= a_{auto}(t_0 + T)
\end{aligned} \tag{5.4.1}$$

(3)

$$\begin{aligned}
-d_{\max}(v_{ref}) &\leq \dot{g}_i(t) \leq a_{\max}(v_{ref}) \\
i &= 1, \dots, m
\end{aligned}$$

Or equivalently

$$\begin{aligned}
-d_{\max}(v_{ref}) &\leq a_i t + b_i \leq a_{\max}(v_{ref}) \\
i &= 1, \dots, m
\end{aligned} \tag{5.4.2}$$

**Remark 5.2** Condition (1) states that  $v_{ref}(t)$  is composed of  $m$  sections of parabolic curves; (2) states that such a curve is  $\mathcal{C}^1$  and is tangent to manual driving speed curve and the pre-designed reference curve at time points  $t = t_0$  and  $t = t_0 + T$  respectively; (3) represents the bounded condition for acceleration.

The first question is: What is the minimum number  $m$  to achieve such a smooth connection?

If  $m = 1$ , there are 3 parameters  $(a_1, b_1, c_1)$  to be determined while (5.4.1) has 6 conditions. In general, it is impossible to choose those 3 parameters such that (5.4.1) is satisfied.

If  $m = 2$ , there are 6 parameters and 6 conditions in (5.4.1) which can be represented as

$$Ax = B$$

where

$$x = [a_1, b_1, c_1, a_2, b_2, c_2]^\top$$

$$A = \begin{bmatrix} t_0^2 & t_0 & 1 & 0 & 0 & 0 \\ 2t_0 & 1 & 0 & 0 & 0 & 0 \\ t_1^2 & t_1 & 1 & -t_1^2 & -t_1 & -1 \\ 2t_1 & 1 & 0 & -2t_1 & -1 & 0 \\ 0 & 0 & 0 & (t_0 + T)^2 & t_0 + T & 1 \\ 0 & 0 & 0 & 2(t_0 + T) & 1 & 0 \end{bmatrix}$$

$$B = [v_{man}(t_0), a_{man}(t_0), 0, 0, v_{auto}(t_0 + T), a_{auto}(t_0 + T)]^T$$

To have a solution, it is necessary and sufficient to choose  $t_1 \in [t_0, t_0 + T]$  such that  $A$  is non-singular. In this case,

$$x = A^{-1}B$$

which is a unique solution.

To satisfy condition (5.4.2), it is necessary to restrict the length of time interval  $[t_0, t_0 + T]$ . This is the disadvantage compared to the previous approach.

If  $m = 3$ , there are 9 parameters and 8 conditions. In this case, the solution is not unique. Again, it is necessary to restrict the length of time interval  $[t_0, t_0 + T]$  to satisfy condition (5.4.2). Besides, matrix  $A$  must satisfy some rank condition

$$rank[A, B] = rank[A]$$

Although this can be checked by symbolic computation, the approach is non-trivial.

## 5.5 Implementation

### 5.5.1 Hardware Requirements

For transition control, the following hardware requirements are minimal:

- (1) Human machine interfaces are available for activating braking and acceleration (control actuators) respectively;
- (2) Through the automated control state data base, the control actuator switch on/off should be acknowledged to the controller so that controller will be able to execute automatic control at the time instant of control mode switching;
- (3) All the longitudinal sensors can be activated and data readings are available during manual driving mode;
- (4) Ability to run the longitudinal controller continuously in the background without actually activating fuel/brake actuator during manual driving mode;

The algorithm for transition of a single agent has been tested by using a full size automated Buick Le Sabre. The longitudinal controller used is that reported in [25]. Test results for multiple transitions between manual and automatic control are shown in Figure 5.3. Manual and automatic control modes on/off are also shown.

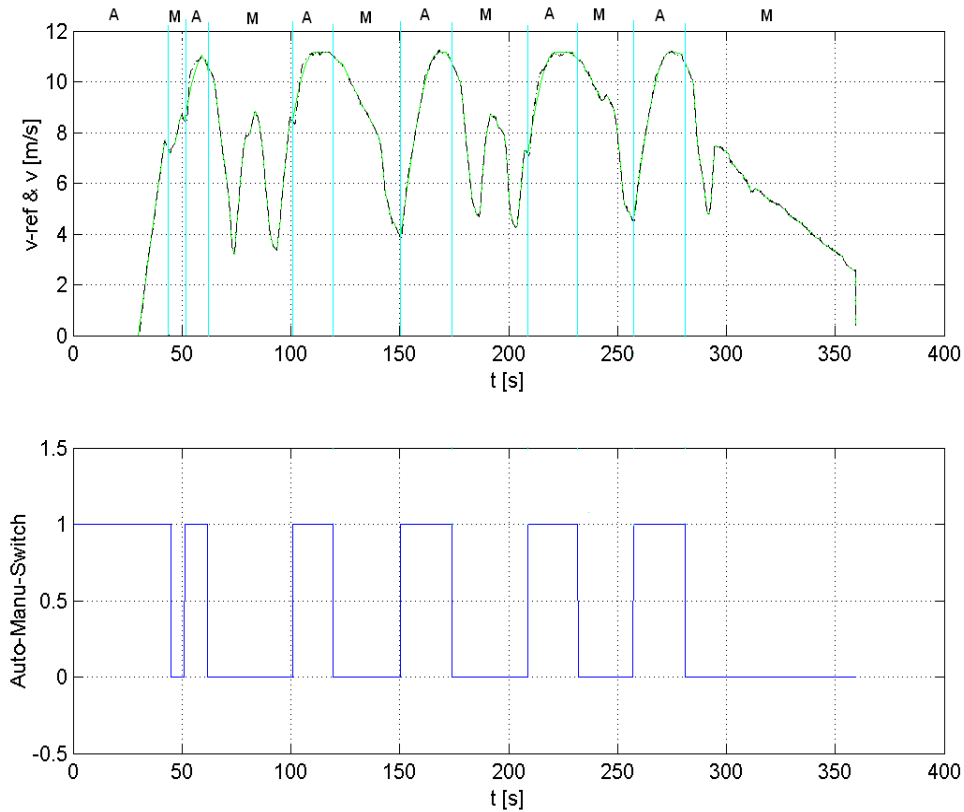


Figure 5.3: Multiple transition between manual and automatic control

In the first plot, solid line is the overall reference trajectory and the dash-dotted line is vehicle speed trajectory. Second plot is for manual and automatic control switch which is 1 if automatic is switched on and 0 otherwise. Some transitions started when vehicle is at acceleration mode and some at zero or deceleration mode. Dynamic trajectory planning and robustness of the controller guarantee the stability and smooth transitions between those modes. Proper logical control ensures the compatibility of all the modes.

Such implementation has been implemented and tuned for Trucks even for high speed. as mentioned before, HDT has very limited acceleration capability at high speed. To make the vehicle following desired speed profile at any speed range between  $5\sim 60[mph]$ , dynamical trajectory planning is critical so that the torque control command saturation can be effectively avoided. This means that, the dynamic trajectory planning for HDT transition must be subject to a severe constraints at time.

## 5.6 Concluding Remarks

Longitudinal transition control considered here is suitable for multiple transitions of a single vehicle between manual and automatic driving. For closed-loop control stability and passenger's comfort, smooth transitions are necessary between the two modes. To achieve this, three key steps are necessary in the control procedure beside hardware switching. (a) Vehicle state variables must be properly initialized; (b) A logical control needs to guarantee that the control algorithms are in one and only one mode as directed; (c) A continuously differentiable speed curve must be dynamically planned in real-time which is tangent to the manual driving speed curve at the end point and also to the long-term automated reference speed curve at some point. A general algorithm for such trajectory planning is provided. The result has been successfully implemented with Buick Le Sabre at PATH.



# Chapter 6

## Other Maneuver Development

As discussed in previous section, vehicle following is the fundamental maneuver. Besides, some other basic maneuvers are necessary to develop.

**Notations:**

$a_i^{(ref)}$  – desired reference acceleration/deceleration

$\bar{d}_i(v, \theta), \bar{a}_i(v, \theta)$  – maximum deceleration/acceleration capability

$v_i^{(ref)}$  – desired reference speed

$P_i, i = 1, 2, 3$  – vehicle ID

$v(t)$  – merging vehicle speed, measurable

$v_{md}(t)$  – desired speed of merging vehicle, to be determined

$v_p(t)$  – speed of the leader vehicle in the platoon on main lane, measurable

$x(t), x_{md}(t)$  – virtual distance between the leader vehicle and the merging vehicle

$t_{merg}$  – time instant for longitudinal merging control algorithm to start

$T_{merg}$  – time instant when merging is completed (real merge)

$T_{virt}$  – time instant when a virtual platoon is formed but merging is not completed

$Q_{start\_1}, Q_{start\_2}$  – vehicle positions on main lane and merging lane when  $t = t_{merg}$ , respectively

$Q_{virt\_1}, Q_{virt\_2}$  – virtual positions in main lane and merging lane at which virtual platoon is formed

$l_{des\_follow}$  – desired inter-vehicle distance after merging

$l_i$  – physical length of vehicle  $P_i, i = 1, 2, 3$ .

## 6.1 Splitting/Joining

Splitting maneuver is for the following vehicle decelerate to increase the inter-vehicle distance. Because truck/bus deceleration capability is comparable to that of passenger cars for low to medium deceleration. Thus the splitting algorithm used for automated passenger cars can also be used for truck/bus without much modification.

For joining maneuver, the situation will be quite different because, the following vehicle has to accelerate to reduce the inter-vehicle distance. On the other hand, truck/bus has very limited acceleration capability particularly at high speed. This constraint need to be taken into consideration in practice. The next is to show how to use the optimization procedure described in Chapter 2 to obtain a reference trajectory in real-time for truck/bus joining maneuver.

Due to the limitation of software, a simple example is considered. For multiple vehicle coordination, research is under going and will be presented next paper. As an example for the maneuver design strategy, consider the join maneuver between two vehicles. The goal of the control law in a join maneuver is to decrease the initial relative distance between the preceding platoon (or vehicle) and the following platoon (or vehicle) to a desired inter-platoon spacing  $L_{ref}$ . The relative speed should be zero at the end of the join maneuver. In this example, two vehicles are cruising with a prescribed velocity  $v_p(T_0) = 60[mph]$  initially and the following vehicle tries to reduce the inter-vehicle distance by  $3[m]$  while the leading vehicle moves with constant velocity  $v_p$ . Relation between acceleration and velocity in (??) was obtained from a driving test.

### Step 1. Initial Estimate Using Parameterized Trajectory

For the initial value estimate, we use the similar parameterization as Fig. 3-4. Then total maneuver time will be  $(p_1 + 4 \cdot p_3 + 2 \cdot p_4 + p_5)$  and the integration of the absolute value of acceleration be  $2 \cdot p_2 \cdot (p_3 + p_4)$ . The relevant cost function and constraints in (??) can thus be expressed using the parameters  $p_1 \sim p_5$ :

The performance index is:

$$J = \alpha_1 (p_1 + 4p_3 + 2p_4 + p_5) + \alpha_2 p_2 (p_3 + p_4)$$

The constraints are:

$$\begin{aligned} L_0 + p_2 (p_3 + p_4) (2p_3 + p_4 + 2p_5) &= L^{(ref)} \\ p_2 &\leq a_{\max} \\ v_0 - p_2 (p_3 + p_4) &\geq v_{\min} \end{aligned}$$

$$v_0 - p_2 (p_3 + p_4) \leq v_{\max}$$

$$\dot{a}_{des} \leq \dot{a}_{\max}$$

Figure 6.1 shows a numerical example of the initial estimate of reference acceleration profile and Figure 6.2 is the corresponding velocity profile for join maneuver assuming zero road grade.  $v_{max} = 65[mph]$ . Initially, the nominal maximum acceleration is assumed to be  $0.3m/s^2$  and the maximum jerk  $a_{\max} = 0.3m/s^3$ .

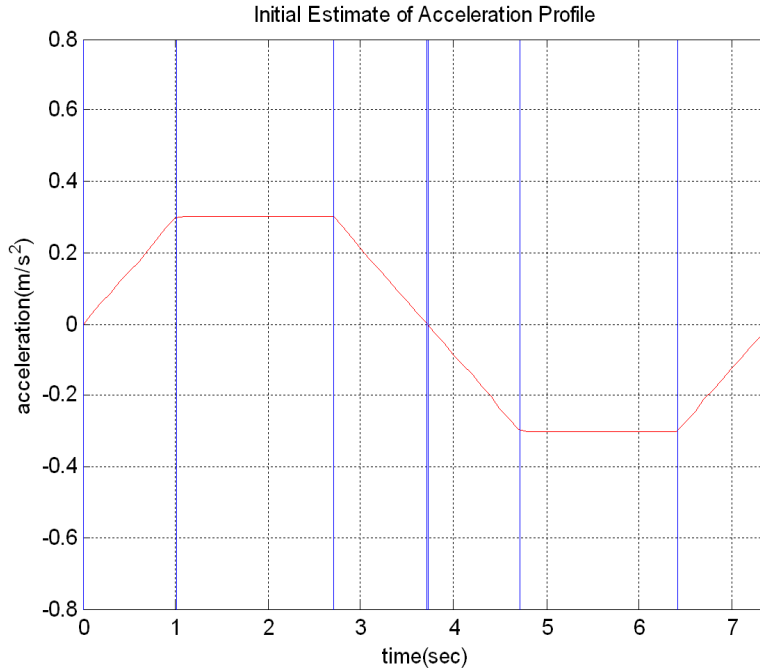


Figure 6.1: Acceleration profile: Initial Estimate

## Step 2. Iterative Computation with Constraints

Suppose that there is road grade as shown in Figure 6.3 Figure 6.4 represent initial velocity profile and velocity limit and  $v_{max}(\theta)$  is obtained using  $(?) \sim (?)$ . Initial estimate of velocity does not violate the constraints. However, in Figure 6.5, initial estimate of acceleration shows the possible actuator saturation in the position range  $50 - 100[m]$ . Figure 6.3  $\sim$  6.7 are new design values obtained from numerical iteration. Both velocity and acceleration satisfy the constraints on them.

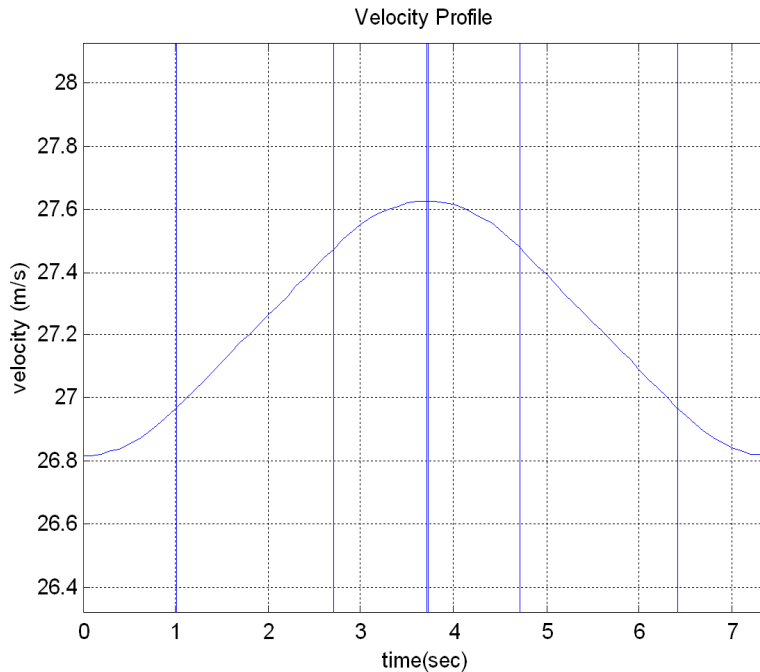


Figure 6.2: Velocity profile: Initial estimate

## 6.2 Automated Merging

As another example, consider the automated vehicle merging maneuver. Automated vehicle merging is defined as the entrance of merging vehicle from on-ramp into a platoon of vehicles in the main lane [14, 24]. A general road layout is depicted as in Figure 6.8.

### 6.2.1 Mathematical Modeling for Merging

The main problem for vehicle merging is to determine a desired synthetic acceleration for the merging vehicle from which throttle control command and brake control command can be determined. The desired synthetic acceleration is eventually determined by the desired speed  $v_{md}(t)$  for a controller. This  $v_{md}(t)$  should be determined by the speed  $v_p(t)$  of the leader vehicle in the platoon in the main lane as well as relative positions of the relevant vehicles at the time instant when merging maneuver starts. The original mathematical problem is a 2-point-boundary-value type which has no numerical solution suitable for real-

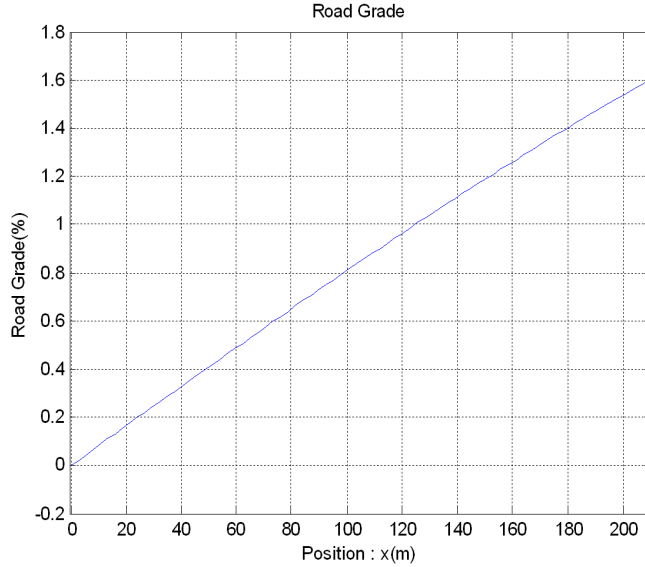


Figure 6.3: Road grade

time implementation. To avoid this difficulty, a concept of *virtual platooning* is introduced [14].

A virtual platoon means that at some time instant  $T_{virt}$

$$t_{merg} \leq T_{virt} \leq T_{merg}$$

$P_i$  arrives at  $Q_{virt\_i}$  as shown in Figure 3. At this point, the following conditions are satisfied:

$$\begin{aligned} v_{md}(T_{virt}) &= v_p(T_{virt}) \\ a_{md}(T_{virt}) &= a_p(T_{virt}) \\ |Q_{virt\_1}Q_0| + l_1 + l_{des\_follow} &= |Q_{virt\_2}Q_0| \end{aligned}$$

Then for  $t \in [T_{virt}, T_{merg}]$ , it is sufficient that

$$\begin{aligned} v_{md}(t) &= v_p(t) \\ a_{md}(t) &= a_p(t) \end{aligned}$$

for a real platoon to be formed at the time instant when  $P_2$  arrives at  $Q_0$ . The conditions can be stated as follows:

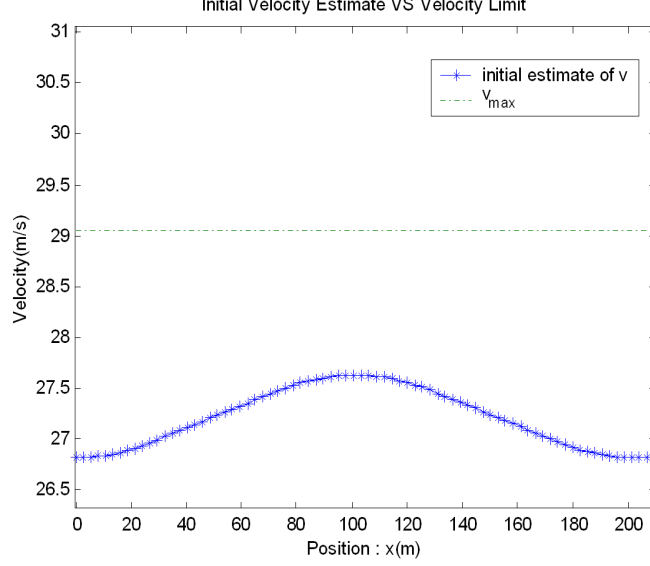


Figure 6.4: Initial velocity estimate

There exist time instant  $T_{virt}$  and point  $Q_{virt-1}$  between  $Q_{start-1}$  and  $Q_0$  and  $Q_{virt-2}$  between  $Q_{start-2}$  and  $Q_0$  such that

$$\begin{aligned}
 v_{md}(t_{merg}) &= v(t_{merg}) \\
 \int_{t_{merg}}^{T_{virt}} v_p(t) dt &= |Q_{start-1} Q_{virt}| \\
 \int_{t_{merg}}^{T_{virt}} v_{md}(t) dt &= |Q_{start-2} Q_{virt}| \\
 |Q_{virt-1} Q_0| + (l_1 + l_{des-follow}) &= |Q_{virt-2} Q_0| \\
 v_{md}(T_{virt}) &= v_p(T_{virt}) \\
 a_{md}(T_{virt}) &= a_p(T_{virt})
 \end{aligned} \tag{6.2.1}$$

## 6.2.2 Real-time Algorithm

The algorithm is stated in the following theorem which has been proved in [14] and primarily implemented in real-time [24].

**Theorem 6.1** Suppose that

(1) time response of the known longitudinal controller is fast enough and speed and distance tracking error is small enough, i.e.

$$a(t) \approx a_{md}(t)$$

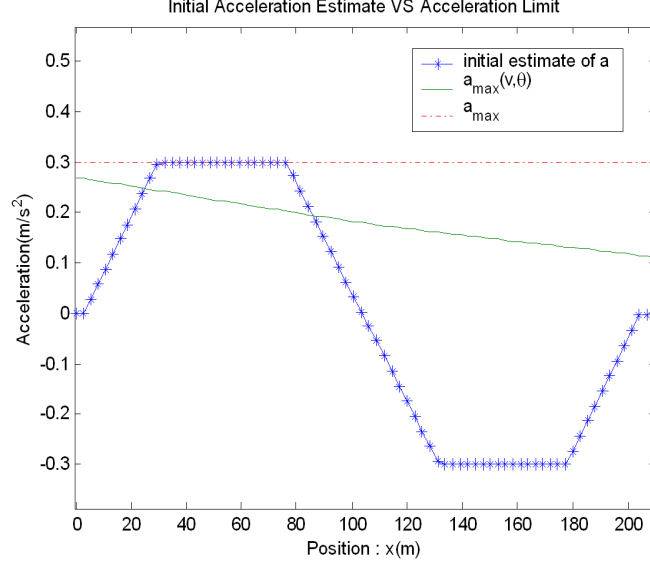


Figure 6.5: Initial acceleration estimate

$$v(t) \approx v_{md}(t) \quad (6.2.2)$$

$$x(t) \approx x_{md}(t)$$

for  $t \in [t_{merg}, T_{merg}]$ ;

(2)  $|Q_{start\_1}Q_0|$  and  $|Q_{start\_2}Q_0|$  are long enough, or equivalently, the time interval  $[t_{merg}, T_{merg}]$  is long enough to adjust the speed and distance of the merging vehicle;

(3) The positions of the specially coded magnets and vehicle length satisfy the following condition

$$dist\_para = |Q_{start\_1}Q_0| - |Q_{start\_2}Q_0| + l_1 + l_{des\_follow} > 0 \quad (6.2.3)$$

(4) There exists  $T \geq t_{merg}$  such that

$$\int_{t_{merg}}^t (v_p(s) - v(t_{merg})) ds \geq 2 dist\_para \quad (6.2.4)$$

hold for  $t \geq T$ .

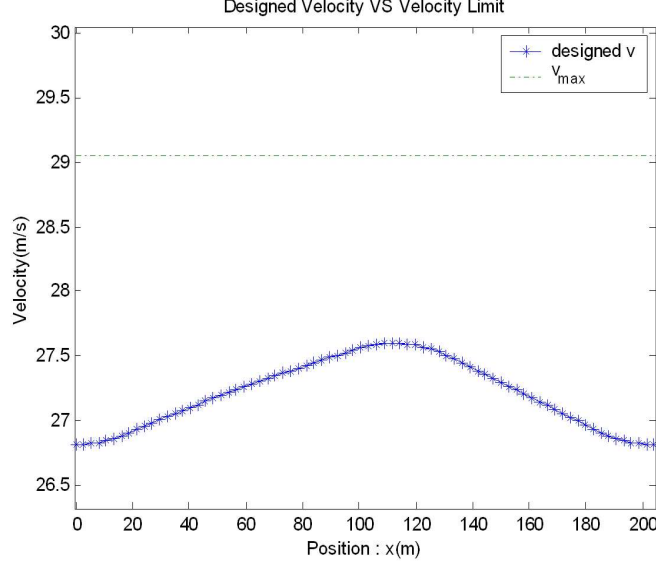


Figure 6.6: Desired velocity

(5) The following reference speed for  $P_2$  is fed into the longitudinal controller

$$v_{md}(t) = \begin{cases} (1 - \alpha(t)) v(t_{merg}) + \alpha(t) v_p(t), & t_{merg} \leq t \leq T_{virt} \\ v_p(t), & T_{virt} < t \leq T_{merg} \end{cases} \quad (6.2.5)$$

$$\alpha_0(t) = \frac{\int_{t_{merg}}^t v_p(s) ds}{\int_{t_{merg}}^t v(s) ds + dist\_para}$$

$$\alpha(t) = \alpha_0^\beta(t), \quad \beta > 0$$

Then virtual platoon is guaranteed to be formed for some  $\beta > 0$ . i.e. there exist a constant  $\beta > 0$ , a time instant  $T_{virt} \in [t_{merg}, T_{merg}]$  and points  $Q_{virt\_1}$  and  $Q_{virt\_2}$  such that

$$|Q_{virt\_i} Q_0| \leq |Q_{start\_i} Q_0|, \quad i = 1, 2$$

and all the conditions in (6.2.1) are satisfied. Besides,  $v_{md}(t)$  has the same smoothness property as  $v_p(t)$ .

### 6.2.3 Coordination Layer

Suppose that a vehicle approach a on-ramp and request a merging maneuver. It sends a message to establish a communication protocol with the nearest coordination layer manager.



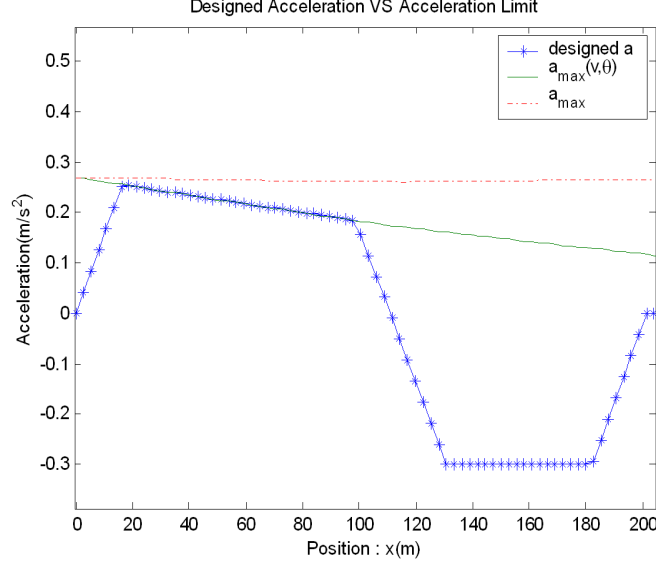


Figure 6.7: Desired acceleration

Upon receiving the request, based on the information from the vehicle and current state of the vehicles on the main lane (the first lane), it will decide: the merging start time, the platoon number into which the vehicle is to merge, the virtual position in that platoon. This decision should be optimized with respect to the following factors:

(1) The distance headway of main lane vehicles after merging:  $l_{des\_follows}$

(2) For safety, the desired splitting distance of main lane vehicles should be  $2l_{des\_follows} + l_2$  where  $l_2$  is merging vehicle distance.

(3) To guarantee stability of regulation layer control system, it is necessary to restrict the maximum acceleration/deceleration demanding for the merging vehicle.

(4) Maneuver time ( $T_{merg} - t_{merg}$ )

To simplify the problem, the following assumptions are made, which are reasonable in practice for most cases.

*Assumptions 1* Suppose that the merging point  $Q_0$  is known fixed (urban traffic) or within some known threshold (freeway).

*Assumptions 2* Main lane vehicle speed satisfies

$$\begin{aligned} |v_p(t) - V_m| &\leq \delta \\ |a_p(t)| &\leq \varepsilon \ll 1 \end{aligned}$$

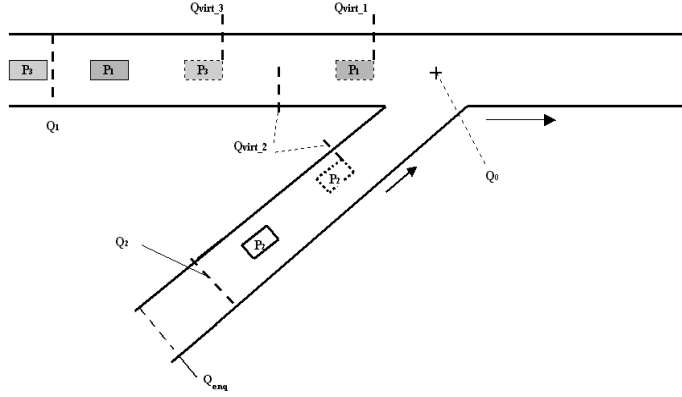


Figure 6.8: General road layout for automated vehicle merging

where  $V_m$  is a constant.

From (6.2.5),

$$\begin{aligned}\dot{v}_{md}(t) &= \dot{\alpha}(t)(v_p(t) - v(t_{merg})) + \alpha(t)a_p(t) \\ |\dot{v}_{md}(t)| &\leq |\dot{\alpha}(t)| |v_p(t) - v(t_{merg})| + \varepsilon\end{aligned}$$

To minimize  $|\dot{v}_{md}(t)|$ , a approximate solution is to choose the merging vehicle initial speed as

$$v(t_{merg}) = V_m$$

For such a choice,

$$|\dot{v}_{md}(t)| \leq |\dot{\alpha}(t)| \delta + \varepsilon$$

To minimize  $|\dot{v}_{md}(t)|$ , it is sufficient to minimize  $|\dot{\alpha}(t)|$  and  $\delta$ . The minimization of  $|\dot{\alpha}(t)|$  can be achieved in regulation layer at control design phase. To minimize  $\delta$ , it is sufficient to choose a proper platoon and virtual position for the merging vehicle to enter.

Suppose merging vehicle make an enquiry for merging at time instant  $t_{enq}$  with  $t_{enq} < t_{merg}$ . The distance  $|Q_{enq}Q_2|$  is known. Then

$$t_{merg} = t_{enq} + \frac{|Q_{enq}Q_2|}{a_{\max}}$$

The performance index is proposed as

$$J = b_1 (T_{merg} - t_{merg}) + \frac{b_2}{l_{des\_follow}} + b_3 |\dot{v}_{md}(t)|$$

which is to be minimized with respect to  $v(t_{merg})$  under the constraints (6.2.1) and the following

$$\int_{t_{merg}}^{T_{virt}} v(\tau) d\tau < |Q_2 Q_0|$$

which determines if a virtual platoon has been formed in a specified time threshold. The solution of the problem will be reported in future work.

*Decision of coordination layer:*

(a) Merging vehicle needs to adjust its speed before merging maneuver starts such that it is as close as possible to  $V_m$ .

(b) The virtual position of the vehicle which the merging vehicle should be inserted is  $|Q_1 Q_0| + (t_{merg} - t_{enq})$ . It determines which vehicle should be followed. Accordingly, the vehicle behind it should split to proper distance.

After the decision has been made, it passes the information to relevant vehicles and monitors the maneuver process based on information returned. It checks regularly for any fault and it is also responsible for emergency handling.

It is noted that this is just a simplified scenario. It can be considered in more detail which will be pursued in future work.

## 6.2.4 Regulation Layer

Once the maneuver is granted, it receives the above control maneuver parameters from the coordination layer. Then it also establishes a communication link with the two relevant vehicles in the main lane. The merging maneuver [24] starts at specified time instant. It also provides the coordination layer with necessary information, such as its speed and on-ramp position, on a regular basis. After the merging maneuver is successfully finished and all vehicles return to normal platooning control, a signal is returned to the coordination layer for ending the maneuver.

# Chapter 7

## Simulation Development

*Summary:* Two types of simulation have been carried out. One is in Matlab to emphasize on the real-time optimization in the coordination of maneuvers by the student Sungmoon Joo. A simple version of optimization package is used to achieve this. The objective to develop this simulation is to investigate coordination between rather general sets of maneuvers which can be partitioned into a finite number of fundamental maneuvers.

A real-time simulation is also developed for real-time implementation by Xiao-Yun Lu, the Principal Researcher of the project. The purpose of this version is to work out a C code in simulation which actually coordinate the specified maneuvers for Demo 2003, which are fixed in advance. This C code is expected to be used in the coordination of vehicle maneuvers under automatic control. In this sense, there is no overlap between those two version of maneuvers.

## 7.1 Introduction

For vehicle control system design, maneuver design, fault detect and management, it is necessary to have model based simulation tool which is faithfully represent the intrinsic vehicle dynamics. Although a Matlab Simulink vehicle model exist, which is pourparler used in classrooms, to implement the controller designed from those model is not practical yet. This is because the model there is very generic and ideal. Many internal/external disturbances and measurement noise representations are not very practical. Besides, before practical implementation of each maneuver, the algorithms developed need to be simulated in conjunction with the feedback controller designed. The most important point is that the coordination logics of those maneuvers must be made consistent before practical test. This requires to develop a simulation package which is close to practical implementation situation as possible.

## 7.2 Maneuver Simulator in Matlab

### 7.2.1 Objective

To verify and implement the proposed coordination layer design scheme, a simulator was developed. The simulation environment is Matlab and Simulink. Simulator development is not yet complete. As for verification purpose, 3 vehicles are simulated. We assume ideal sensor and communication without any loss of information. Regulation layer and physical layer control structure is shown in Figure 7.1. Regulation layer produces desired states (position, speed, acceleration) then lower level controller transforms this information into actuator control signal. However, the actuator is not implemented in this simulator and the desired acceleration becomes control input.

#### **Simulator Structure**

Scenario is prefixed and given by scenario file. The coordination layer reads the scenario file and coordinates the maneuvers according to the scenario. The architecture of the simulator is depicted in Figure 7.2.

Coordination layer and regulation layer communicate using `man_des` (desired maneuver), `man_para` (maneuver parameter) and `man_id` (current maneuver) signal.

Figure 7.3 shows a snap shot of simulator. Simulator displays all the relevant information about the maneuvers of three vehicles.

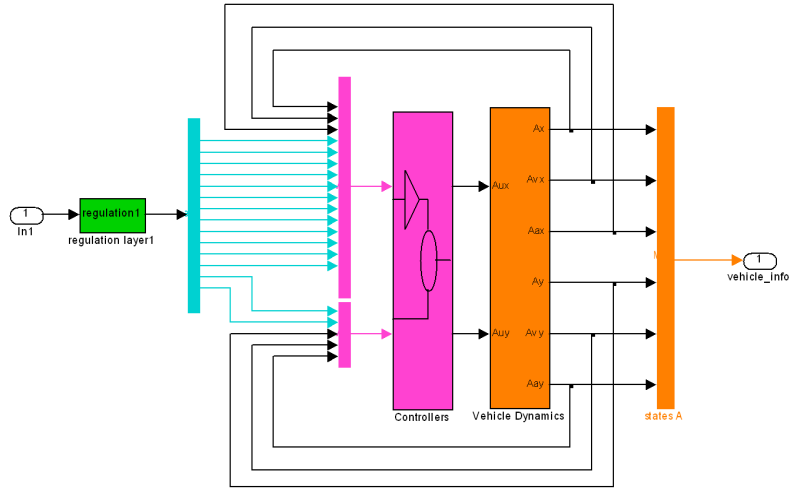


Figure 7.1: Regulation layer and physical layer

### 7.2.2 Some Remarks

In this report, new coordination layer model and design strategy are proposed. Using mathematical programming language and numerical solver, coordination layer design problem can be readily solved. To verify and implement the proposed design scheme, a maneuver simulator is developed. At current stage, simulator is still under development and coordination layer finite state machine is not yet completely implemented in simulation code.

For future work, we need to refine the mathematical programming model; especially the proper cost function for each maneuver is critical issue. On the other hand, fast and efficient numerical solver is necessary for real-time implementation of coordination layer.

## 7.3 Simulation in C for Real-time Code Construction

It is essential to coordinate all the vehicles in a system to make them run safely, compatibly and efficiently. Work in [10] described the theoretical and preliminary simulation results (using Matlab) for certain maneuvers of automated trucks/buses. This part describes the simulation using standard C code for real-time implementation purpose. In fact, the modules developed here can be directly used in real-time implementation. This is a critical approach

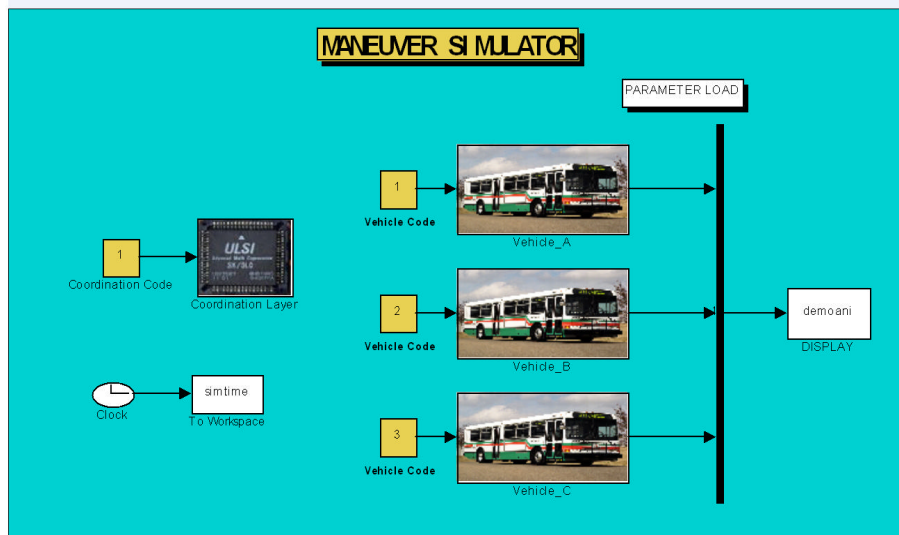


Figure 7.2: Simulator architecture diagram

in the sense that it will greatly reduce or avoid trial and error experimental work which can be very costly and dangerous for trucks and buses.

### 7.3.1 Software Structure of the Coordination of Maneuvers

There is a central coordination manager, which can be run on the leader vehicle in practical simulation. There are two possible way to implement the coordination. If there are two independent wireless communication systems or two independent channel of such a system such that one system connects all the nodes with each other, the coordination layer manager can be run independently. If there is only one communication systems (channel), the coordination information can be considered as part of the information broadcasted by the lead vehicle to all the vehicles.

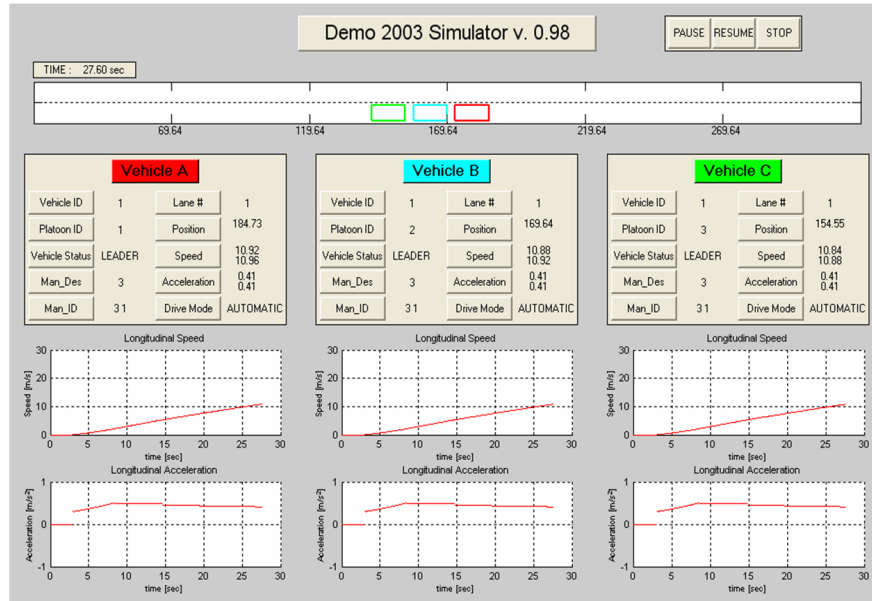


Figure 7.3: A simulation snap shot of Simulator

### 7.3.2 Definition of Parameters in Real-time Simulation

Several parameters are used to describe the maneuvers information:

(a) Each vehicle has a unique Vehicle ID, denoted as  $I$ ; (b) Each maneuver has a unique ID number, denoted as  $J$ ; (c) Desired maneuver of a specified vehicle, which is the command from the Coordination Manager to each vehicle involved; It can be realized as a 2-dimensional vector: as  $man\_des[2]$  in which  $man\_des[1]$  is the vehicle ID number and  $man\_des[2]$  is the number representing the desired maneuver; Once a vehicle received this ID number, it knows what maneuver it should perform subsequently; (d) Vehicle Maneuver Status ID: This is a 3-dimensional vector  $man\_id[3]$  which is to be passed from each vehicle to the coordination manager. It reports to the manager what is going on from each vehicle in the system.  $man\_id[1]$  is the subject vehicle ID,  $man\_id[2]$  is set to the number representing the desired maneuver received from the coordination manager;  $man\_id[3]$  is used to representing the current status of the maneuver, which describe different stages of the whole process of the maneuvering. It includes: maneuvering is till on, successfully accomplished or failed, etc.



Different maneuvers may have different set of numbers because some maneuvers are simple (like splitting) and some are complicated (like merging ).

The following are the definitions of man\_des and man\_id; Vehicle ID does not appear because these definition is generic to all vehicles. Some parameters are remained for future development.

Definition of man\_des:

- 0 : stay at rest with manual control
- 1 : stay at rest to get automatic control ready
- 2 : stay at rest with automatic lateral control ON
- 3 : automatic control following a self-generated reference trajectory (as a Single agent or a Leader)
- 4 : transition from manual to automatic control (as a single agent)
- 5 : platoon forming - following the previous speed but not the platoon desired distance (speed tracking)
- 6 : automatic joining within a platoon (speed and distance control to desired distance)
- 7 : vehicle following (at cruise speed - no other maneuver)
- 8 : splitting under automatic control to a specified distance w.r.t. preceding vehicle
- 9 : left-lane-changing to the end of a platoon 10 : right-lane-changing to the end of a platoon
- 11 : virtual splitting to specified distance from current distance on different lane
- 12 : virtual joining to specified distance from current distance on different lane
- 13 : double splitting (long distance splitting compared with 8)
- 14 : vehicle merging to a specified position from on-ramp
- 15 : free left-lane-changing to the middle of two vehicles (free lane changing)
- 16 : free right-lane-changing to the middle of two vehicles (free lane changing)
- 18 : collision avoidance by lane changing only
- 19 : collision avoidance by lane changing and speed reduction
- 20 : collision avoidance by emergency stop
- 24 : emergency splitting to longer inter-vehicle distance to stop (due to some incurable fault)
- 28 : lane departure - leaving AHS from off-ramp
- 29 : automatic closed-loop decelerating to stop using specified profile
- 30 : brake to stop in auto mode
- 31 : automatic open-loop decelerating to stop by applying specified deceleration command

- 32 : brake to stop in manual mode
  - 33 : gradually splitting to longer desired distance but carry on platooning (due to some fault)
  - 34 : gradually splitting and reducing speed to stop (due to some fault)
  - 35 : Cruise Control (as a single agent - radar miss target or no target)
  - 40 : Adaptive Cruise Control (in a platoon with at least one radar but no communication )
  - 41 : Cooperative Adaptive Cruise Control (with at least one radar and communication )
  - 45 : manual control (including all the maneuvers)
- Definition of man\_id (The first entry is in agreement with man\_des):
- (0,0) : stay at rest with manual control ready
  - (0,1) : stay at rest with manual lateral control ready
  - (0,2) : stay at rest with manual longitudinal control ready
  
  - (1,0) : stay at rest to get automatic control ready
  - (1,1) : stay at rest automatic air braking ON
  
  - (2,0) : stay at rest with automatic lateral control on
  - (2,1) : stay at rest but automatic lateral control fail to activate
  
  - (3,0) : automatic control to follow a self-generated reference trajectory (as a Single agent or a Leader)
  - (3,1) : automatic control following a self-generated reference complete (as a Single agent or a Leader)
  - (3,2) : automatic control following a self-generated reference trajectory fail (as a Single agent or a Leader)
  - (3,3) : automatic control following a self-generated reference trajectory- accelerating (as a Single agent or a Leader)
  - (3,4) : automatic control following a self-generated reference trajectory- constant speed (as a Single agent or a Leader)
  - (3,5) : automatic control following a self-generated reference trajectory- decelerating (as a Single agent or a Leader)
  
  - (4,0) : transition from manual to automatic control (as a single agent)
  - (4,1) : transition from manual to automatic control complete (as a single agent)
  - (4,2) : transition from manual to automatic control fail

- (5,0) : platoon forming - following the previous speed but not the platoon desired distance (speed tracking)
- (5,1) : platoon forming complete
- (5,2) : platoon forming fail
- (5,3) : platoon forming - speed tracking only, no distance control
- (5,4) : platoon forming - joining or splitting, according current distance and desired distance (distance control)
  
- (6,0) : automatic joining within a platoon (speed and distance control to desired distance)
- (6,1) : automatic joining within a platoon complete (return to vehicle following control)
- (6,2) : automatic joining within a platoon fail
  
- (7,0) : automatic vehicle following (at cruise speed - no other maneuver)
- (7,1) : automatic vehicle following complete
- (7,2) : automatic vehicle following fail
  
- (8,0) : splitting under automatic control to a specified distance w.r.t. preceding vehicle
- (8,1) : splitting under automatic control complete (return to vehicle following control)
- (8,2) : splitting under automatic control fail
  
- (9,0) : left-lane-changing to the end of a platoon
- (9,1) : left-lane-changing to the end of a platoon complete
- (9,2) : left-lane changing
- (9,3) : to drop back to match the distance and speed
- (9,4) : virtual platooning complete
- (9,5) : left-lane shifting to the end of a platoon (left steering)
- (9,6) : left-lane shifting to the end of a platoon complete
  
- (10,0) : right-lane-changing to the end of a platoon
- (10,1) : right-lane-changing to the end of a platoon complete
- (10,2) : right-lane-changing to the end of a platoon fail
- (10,3) : to drop back to match the distance and speed
- (10,4) : virtual platooning complete
- (10,5) : right-lane shifting to the end of a platoon (right steering)
- (10,6) : right-lane shifting to the end of a platoon complete (right steering)
  
- (11,0) : virtual splitting to specified distance from current distance on different lane
- (11,1) : virtual splitting successful

(11,2) : virtual splitting fail

(12,0) : virtual joining to specified distance from current distance on different lane

(12,1) : virtual joining successful

(12,2) : virtual joining fail

(14,0) : vehicle merging to a specified position from on-ramp

(14,1) : real platooning complete (transition to platooning control)

(14,2) : merging fails (either virtual platoon not formed or real merging fail)

(14,3) : merging vehicle in auto-mode as a single agent

(14,4) : merging maneuver start (merging maneuver begin to use merging algorithm)

(14,5) : virtual platooning control

(14,6) : virtual platooning complete

(15,0) : free left-lane-changing to the middle of two vehicles (free lane changing)

(15,1) : free left-lane-changing complete

(15,2) : free left-lane-changing fail

(15,3) : free left-lane-changing vehicle adjusting speed, acceleration

(16,0) : free right-lane-changing to the middle of two vehicles (free lane changing)

(16,1) : free right-lane-changing complete

(16,2) : free right-lane-changing fail

(16,3) : free right-lane-changing vehicle adjusting speed, acceleration

(18,0) : collision avoidance by lane changing only

(19,0) : collision avoidance by lane changing and speed reduction

(20,0) : collision avoidance by emergency stop

(24,0) : emergency splitting to longer inter-vehicle distance to stop (due to some incurable fault)

(24,0) : emergency splitting to longer inter-vehicle distance to stop (due to some incurable fault) complete

(24,0) : emergency splitting to longer inter-vehicle distance to stop (due to some incurable fault) fail

(28,0) : lane departure - leaving AHS from off-ramp

(28,1) : lane departure - leaving AHS from off-ramp complete

(28,2) : lane departure - leaving AHS from off-ramp fail

- (29,0) : automatic closed-loop decelerating to stop using specified profile
- (29,1) : automatic closed-loop decelerating to stop complete
- (29,2) : automatic closed-loop decelerating to stop fail
  
- (30,0) : brake to stop in auto mode
- (30,1) : brake to stop in auto mode complete
- (30,2) : brake to stop in auto made fail
  
- (31,0) : automatic open-loop decelerating to stop by applying specified deceleration command
- (31,1) : automatic open-loop decelerating complete
- (31,2) : automatic open-loop decelerating fail
  
- (32,0) : brake to stop in manual mode
- (32,1) : brake to stop in manual mode complete
- (32,2) : brake to stop in manual mode fail
  
- (33,0) : gradually splitting to longer desired distance but carry on platooning (due to some fault)
- (33,1) : gradually splitting to longer desired distance but carry on platooning (due to some fault) complete
- (33,2) : gradually splitting to longer desired distance but carry on platooning (due to some fault) fail
  
- (34,0) : gradually splitting and reducing speed to stop (due to some fault)
- (34,1) : gradually splitting and reducing speed to stop (due to some fault) complete
- (34,2) : gradually splitting and reducing speed to stop (due to some fault) fail
  
- (35,0) : Cruise Control (as a single agent - radar miss target or no target)
  
- (40,0) : Adaptive Cruise Control (in a platoon with at least one radar but no communication )
- (41,0) : Cooperative Adaptive Cruise Control (in a platoon with at least one radar and communication )
  
- (45,0) : manual control (including all the maneuvers)
- (45,1) : manual control (including all the maneuvers) complete (return to auto mode)

*Simulation Scenario description in simulated maneuver:*

The total track length for simulation is 5000[m]. Three trucks are involved in the maneuver simulation.

In the first (right) lane, the vehicle with  $ID = 3$  (magenta) stopped at about 500[m] away from the initial point.

Two trucks (with  $ID = 1, 2$ ) with initial speed on lane two with each driven manually at certain speed below 20[*mph*].

Truck 1 and 2 performing transition maneuver from manual to automatic driving;

Truck 1 and 2 performing platoon forming maneuver under automatic control;

Truck 3 in lane 1 starting to move from initial speed 0 and speeding up;

Truck 3 performing merging maneuver to the end of the platoon by pull up the speed to that of truck 1 and 3;

Truck 3 to form a virtual platoon with truck 1 and 2;

Truck 3 performing left lane changing maneuver;

Upon finishing lane changing, three trucks forming a platoon;

Three trucks decelerating to stop in the end.

### 7.3.3 Simulation Operation and Display

The executable code, *man\_sim.exe*, can be run with Microsoft Windows (*Windows 98, Me, 2000, and Windows XP*). Another file *dos4gw.exe* must be in the same directory to support the execution. All the vehicle speed, inter-vehicle distance displayed are true simulation parameters. Once it to run, the WIN-DOS will prompt for input of the maximum speed, which can be any speed below 60[*mph*], which is high enough for a fully loaded truck/bus. All the simulation messages and the parameters for each of the three vehicles will be displayed in sub-windows. Figure 7.4 is a snap shot of the simulation display.

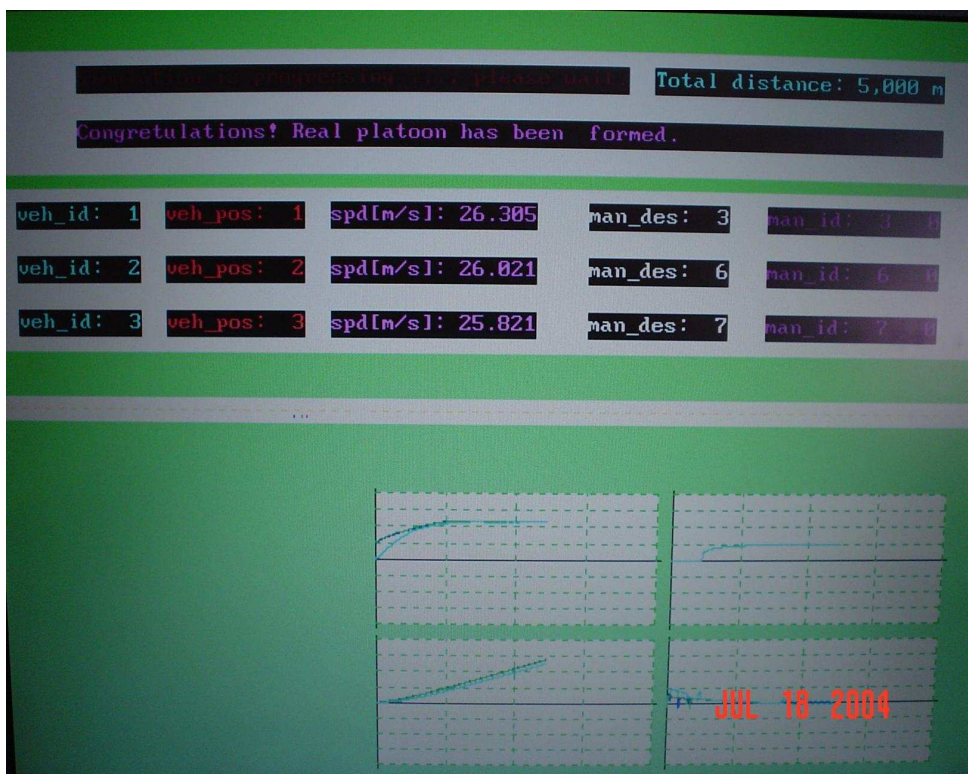


Figure 7.4: A simulation snap shot of Simulator

# Chapter 8

## Future Work

This project is a preliminary research for HDT/Bus maneuver design/coordination of those maneuvers based on simulation development with some possible implementation. Due to the limit of the project scope, only static coupling between vehicles are considered. In simulation, the maneuvers are pre-fixed. Besides, only some maneuvers are practically implemented. Future work will at least includes the following aspects:

- (1) Further investigation on vehicle dynamical coupling criteria which reflect real automated vehicle driving situation;
- (2) Systematic maneuver design with dynamically changing coupling criteria;
- (3) Systematic coordination design with dynamically changing coupling criteria;
- (4) Simultaneously multiple maneuvering handling;
- (5) Real-time algorithm development; Both 1 – *dim* and 2 – *dim* motions with varying road grade should be involved;
- (6) Maneuver and coordination design for mixed road vehicles from a passenger car to a HDT with road grade involved.



# Bibliography

- [1] A. Burns and A. Wellings, 1997, *Real-time Systems and Programming Languages*, 2nd Ed., Addison-Wesley Longman
- [2] S. B. Choi and P. Devlin, 1995, Throttle and brake combined control for intelligent vehicle highway systems, *SAE chapter*, (951897)
- [3] Chui, C. K. and Chen, G, 1999, *Kalman Filtering, with Real-Time Applications*, Third Edition, Springer, Berlin
- [4] Fitch, J. M., 1994, *Motor Truck Engineering Handbook*, 4th Ed., SAE, USA
- [5] Fritz, H., Longitudinal and lateral control of heavy-duty trucks for automated vehicle following in mixed traffic: experimental results from the CHAUFFEUR project, *Proc. of IEEE Int. Conf. on Contr. Applications*, Kohala Coast-Island of Hawai'i, U. S. A., Aug. 22-17, 1999
- [6] J. K. Hedrick, Nonlinear controller design for automated vehicle applications, *Proc. UKACC Int. Conf. on Contr. '98, 1-4 Sept. 1998, Swansea, U. K.*, p23-31
- [7] R. Hermann and A. Krener, 1977, Nonlinear controllability and observability, *IEEE Trans. Auot. Contr.*, **Vol. AC-22, No. 5**, p728-740
- [8] Isidori, A., 1995, *Nonlinear Control Systems*, Springer-Verlag, 3rd Edition
- [9] A. Isidori, 1994,  $H_\infty$  Control via measurement feedback for affine nonlinear systems, *Int. J. of Robust and Nonlinear Control*, **Vol. 4**, p553-574
- [10] S. Joo, X. Y. Lu and J. K Hedrick, Longitudinal maneuver design for coordination layer for automated highway system, *Proc. of American Control Conference*, Denver, Colorado, p42-47

- [11] Khalil, H. K. , Nonlinear Systems, 2nd Ed., Prentice Hall, New Jersey, 1996
- [12] Kiencke, U. and L. Nielsen, 2000, *Automotive Control Systems, For Engine, Driveline, and Vehicle*, Springer, Berlin,
- [13] D. Lee, R. Attias, A. Puri, R. Sengupta, S. Tripakis and P. Varaiya, A wireless token ring protocol for intelligent transportation systems, *Proc. of the 4th IEEE Int. Conf. on Intelligent Transportation Systems*, August 2001
- [14] X. Y. Lu and J. K. Hedrick, 2000, Longitudinal control algorithm for automated vehicle merging, *Proc. 39th IEEE CDC*, Dec. 12-15, Sydney, Australia, p450-455
- [15] E. H. M. Lim and J. Karl Hedrick, 1999, Lateral and longitudinal vehicle control coupling for automated vehicle operation, *Proc. of American Control Conference*, San Diego, California, June, p3676-3680
- [16] Liu, X., Goldsmith, A., Mahal S. S. and Hedrick, J. K., Effects of communication delay on string stability in vehicle platoons, *Proc. of IEEE Conf. on Int. Trans. Syst.- Oakland (CA), USA-August 25-29*, p. 627-632, 2001
- [17] Lu, X. Y. and Spurgeon, S. K., Robust sliding mode control of uncertain nonlinear systems, *Systems & Control Letters*, Vol. 32, no. 2, p75-90, 1997
- [18] Lu, X. Y., Hedrick, J. K. and Drew, M, 2002, ACC/CACC - Control design, stability and robust performance, *Proc. of American Control Conference*, May 8-10, Anchorage, Alaska, p.4327-4332
- [19] X. Y. Lu, 2002, Coordination layer control and decision making for automated ground vehicles, *Proc. of American Control Conference*, May 8-10, Anchorage, Alaska, p.3034-3039
- [20] X. Y. Lu and J. K. Hedrick, Modeling of heavy-duty vehicles for longitudinal control, *Proc. of The 6th Int. Symposium on Advanced Vehicle Control*, Hiroshima, Japan, Sept. 9-13, 2002, **Paper No. 109**
- [21] Lu, X. Y. and Hedrick, J. K., A panoramic view of fault management for longitudinal control of automated vehicle platooning, *Proc. of 2002 ASME IMECE, Dynamic Systems and Control Division, Advanced Automotive Technologies Symposium, IMECE2002-32106*, Nov. 17-22, New Orleans, 2002

- [22] X. Y. Lu and J. K. Hedrick, 2003, Longitudinal control design and experiment for Heavy-Duty Trucks, *Proc. of 2003 American Control Conference*, June 4-6, Denver, Colorado, p36-41
- [23] X. Y. Lu and J. K. Hedrick, Practical string stability, *Proc. of 18<sup>th</sup> IAVSD Symposium on Dynamics of Vehicles on roads and Tracks (Int. Association of Vehicle System Dynamics)*, August 25-29, 2003, Atsugi, Kanagawa, Japan
- [24] X. Y. Lu, H. S. Tan, S. E. Shladover, J. K. Hedrick, 2000, Implementation of longitudinal control algorithm for vehicle merging, *Proc. of 5th Int. Symposium on Advanced Vehicle Control*, Aug. 22-24, Ann Arbor, Michigan, chapter no. 52
- [25] Lu, X. Y., Tan, H.-S., Shladover, S. E. and Hedrick, J. K., 2001, Nonlinear longitudinal controller implementation and comparison for automated cars, *Trans. of ASME, Journal of Dynamic Systems, Measurement and Control*, Vol. 123, p161-167
- [26] X. Y. Lu and J. K. Hedrick, 2003, Longitudinal control algorithm for automated vehicle merging, *Int. Journal of Control*, **Vol. 76, No. 3**, p193-202
- [27] X. Y. Lu and J. K. Hedrick, New Approach for asymptotic stability analysis in the case of discontinuous Lyapunov function derivative, *Proc. of 42nd IEEE CDC*, Dec. 9-12, 2003, Hawaii, USA, p5083-5084
- [28] P. A. Lynn & W. Fuerst, 1994, *Digital Signal Processing with Computer Applications*, John Willey & sons, Chichester
- [29] O'Neil, P. V., *Advanced Engineering Mathematics*, Wadsworth Publish Company, Belmont, California, 1983
- [30] Peng, H., 1992, A theoretical and experimental study on vehicle lateral control, *Proc. of American Control Conference*
- [31] R. Rajamani, S. B. Choi, J. K. Hedrick and B. Law, 1998, Design and experimental implementation for a platoon of automated vehicles, *Proc. of the ASME Dynamic Systems and Control Division*
- [32] R. Rajamani and A. Howell and J. K. Hedrick, A complete fault diagnostic system for longitudinal control of automated vehicles, *Symposium on Advanced Technologies, 1997 ASME International Congress*

- [33] R. Rajamani, H.-S. Tan, B. Law and Zhang, 2000, Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons, *IEEE Trans. on Control Systems Technology*, Vol. 8, No. 4, p. 695-708
- [34] S. E. Shladover, 1995, Review of the state of development of advanced vehicle control systems, *Vehicle Systems Dynamics*, Vol. 24, p551-595
- [35] Swaroop, D. and Hedrick, J. K., String stability of interconnected systems, *IEEE Trans. Auto. Contr.*, 40, no.3, p349-357, 1996
- [36] Swaroop, D., String stability of interconnected systems: An application to platooning in Automated Highway Systems, Ph. D. Thesis, Univ. of California, Berkeley, 1994
- [37] Tan, H.-S., J. Guldner, Patwardhan, S., Chen, C. and Bougler, B., 1999, Development of an Automated Steering Vehicle Based on Roadway Magnets - A Case Study of Mechatronic System Design, *IEEE/ASME Transactions on Mechatronics*, **vol. 4, no. 3**, pp. 258-272.
- [38] Varaiya, P., 1993, Smart cars on smart roads: problems of control, *IEEE Trans. AC-38, no. 2*, p195-207
- [39] E. J., Yanakiev, J. Eyre, D. and Kanellakopoulos, 1998, of AVCS for Analysis, Design and Evaluation for Heavy-Duty Vehicles with actuator delays, **California PATH Research Report**, UCB-ITS-PRR-98-18
- [40] L. Yang, J. H. Yang, E. Feron and V. Kulkarni, Development of a performance based approach for a rear-end collision warning and avoidance system for automobiles, *Proc. IEEE Intelligent Vehicle Symposium*, Columbus, Ohio, June 9-11, 2003

## Appendix

Maneuver Simulator (MAN-SIM) Manual for Matlab

### A.1 Overview

This appendix describes the steps you need to run MAN-SIM.

### A.2 System Requirement:

In order to install and run MAN-SIM, your computer must have:

Microsoft Windows 95 or later version(Windows 98, Me, 2000, XP)

Matlab version 6.0 Release 12 or later version

A hard disk drive with at least 1.5 megabytes of free space

### **A.3 Installation**

Installing MAN-SIM is very simple-just copy the following files into your directory

-demosim.mdl

-coordination.m

-regulation.m

-gen\_ref.m

-controllers.m

-demopara.m

-demoani.m

-join.m

-split.m

-merge.m

-acceleration.m

-deceleration.m

-laneshift.m

-scenario1.dat

-scenario2.dat

-BUS.mat

-ULSI.mat

### **A.4 Running Simulation**

Once MAN-SIM is installed, below is shown a six-step procedure for running a simulation.

Step 1. design your maneuver scenario and write scenario2.dat

Step 2. according to scenario2.dat, write scenario1.dat

Step 3. according to your scenario, change demopara.m

Step 4. start Matlab and open demosim.mdl

Step 5. double click PARAMETER LOAD button

Step 6. double click SIMULATION START button

Details on step 1 3 are described in the following chapters.

#### **Step 1 : Scenario2.dat**

##### **file format**

Scenario2.dat file has 19 columns:

Column	Meaning	Format
1	Vehicle code(vehicle identifier)	integer
2	Scenario index	integer
3	Old(current) desired maneuver	integer
4	Old(current) vehicle status	integer
5	Old(current) vehicle id(relative id in a platoon)	integer
6	Old(current) platoon id	integer
7	New desired maneuver	integer
8	New vehicle status	integer
9	New vehicle id(relative id in a platoon)	integer
10	New platoon id	integer
11	Maneuver trigger flag	integer
12	Trigger parameter 1	integer / real
13	Trigger parameter 2	integer / real
14	Trigger parameter 3	integer / real
15	Maneuver parameter 1	integer / real
16	Maneuver parameter 2	integer / real
17	Maneuver parameter 3	integer / real
18	Maneuver parameter 4	integer / real
19	Maneuver parameter 5	integer / real

### Maneuver

Current version of MAN-SIM can simulate the following atomic maneuvers.

Table A-2

Maneuver	Number	Meaning
STAY_AT_REST_MAN	0	To stay at rest in manual drive mode
MANUAL_DRIVE	45	Manual drive(same algorithm as AUTO_SELF_GEN_TRA)
MAN_TO_AUTO	4	Transition from manual to automatic
STAY_AT_REST_AUTO	2	Stay at rest in automatic drive mode
AUTO_SELF_GEN_TRA	3	Follow self generated trajectory
JOIN	6	Decrease inter vehicle distance
SPLIT	8	Increase inter vehicle distance
L_LANE_CHANGE	51	Lane change to the left lane
R_LANE_CHANGE	52	Lane change to the right lane
MERGE	60	Merging maneuver (using the algorithm in [19])
ACCELERATE	100	Accelerate
DECELERATE	191	Decelerate

### Maneuver parameters

Maneuver \ Maneuver Parameters	Table A-3				
	P1	P2	P3	P4	P5
STAY_AT_REST_MAN	0	0	0	0	0
MANUAL_DRIVE	1	Desired speed	0	0	0
MAN_TO_AUTO	0	0	0	0	0
STAY_AT_REST_AUTO	0	0	0	0	0
AUTO_SELF_GEN_TRA	1	Desired speed	0	0	0
JOIN(Figure 8.1)	a	b	c	d	0
SPLIT(Figure 8.1)	a	-b	c	d	0
L_LANE_CHANGE	0	0	0	0	0
R_LANE_CHANGE	0	0	0	0	0
MERGE	Target vehicle	Merge position	Desired intervehicle distance	Target vehicle length	0
DECELERATE (Figure 8.1)	a	b	c	0	0
DECELERATE (Figure 8.1)	a	-b	c	0	0

### Status

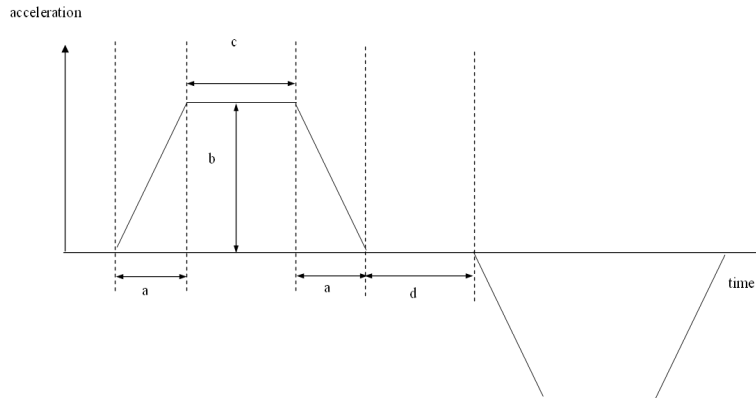


Figure 8.1: A simulation snap shot of Simulator

Table A-4

Status	Number
LEADER	0
FOLLOWER	1

Note that current version of MAN-SIM assumes following initial setting:

- a. initial status : LEADER
- b. initial maneuver : STAY\_AT\_REST\_MAN

**Maneuver trigger flag**

Table A-5

Trigger flag	Meaning
0	Automatic trigger
1	Position
2	Time
3	Position & time



## Trigger parameters

Trigger flag\Trigger parameters	TP1	TP1
0	0	0
1	Position	0
2	0	Time
3	Position	Time

## Step 2 : Scenario1.dat

Scenario2.dat file has 6 columns:

Column	Meaning
1	Vehicle code 1
2	Number of scenarios
3	Vehicle code 2
4	Number of scenarios
5	Vehicle code 3
6	Number of scenarios

## Step 3 : Demopara.m

Variables and parameters are defined in this file. Initial position of vehicles(XP, YP) and simulation

time should be changed according to each scenario.

(Example)

A. Initial position

vehicle 1 : (50m, lane 1), vehicle 2 : (36, lane 1), vehicle 3 : (500m, lane 2)

$XP = [50 \ 36 \ 500];$

$YP = ([1 \ 1 \ 2]-[1 \ 1 \ 1])*LANE\_WIDTH+LANE\_WIDTH*0.5*[1 \ 1 \ 1];$

B. Simulation time = 270 sec

`set_param('demosim','stoptime','270');`

## A.5 Simulation Step

Default setting is 0.1[s] for continuous time variable. For discrete step, default setting is 0.2[s].

To change the discrete step value, change the value of dperiod variable in coordination.m  
and  
regulation.m