Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Entry/Exit Implementation

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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

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and Development

NOTICE

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Acknowledgments

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1 Summary

An Automated Highway System (AHS) is the most advanced and highest risk element of the overall program on Intelligent Transportation Systems.

The objectives of this study are: to identify the issues that the implementation of AHS entry and exit must address, to arrive at firm or tentative conclusions about those issues, and to indicate the uncertainties that remain in the absence of firm conclusions. Issues in entry/exit are of direct concern to several other areas: check-in (b) and check-out (c), safety (n), roadway deployment (h) and impact on non-AHS roadway (i). One must ensure that these inter-connected issues are not overlooked. Our study pays special attention to safety, check-in and check-out, and has been coordinated with the related PATH studies on roadway deployment.

The following is a summary of our findings presented as a sequence of assertions, grouped under three headings: roadway configuration, strategies for entry and exit maneuvers, effect of entry and exit on AHS traffic. The assertions are supported to varying degrees by the argument in the report: some qualify to being called "conclusions," others are "issues" that need resolution, the rest are "concerns" that need to be addressed.

Roadway configuration

This concerns the different ways by which vehicles can enter the automated lane and the need for barriers.

- The transition lane (between automated and manual lane) may be divided into segments, one per entry and exit. There is no need for a continuous transition lane;
- Automated lane entry/exit via dedicated ramps simplifies coordination;
- Permitting manual vehicle to merge with automated vehicles is dangerous;
- Suitably designed barriers that allow emergency vehicles to go through can avoid the need for a continuous breakdown lane.

Strategies for entry/exit

Entry and exit of vehicles into and from the automated lane must be carefully choreographed, both because of safety and capacity. A major outcome of our work is a control design that seems to achieve high levels of safety and capacity.

- Platooning leads to better capacity and safety than AACC (Advanced Adaptive Cruise Control), but it requires inter-vehicle communication for coordination;
- Vehicle leaving automated lane and entering transition lane must be coordinated with vehicles on transition lane, if any;

- Provision must be made for removing vehicle from transition lane if its driver is unable to resume control;
- Large spacing between vehicle entering automated lane and the vehicle in front of it can be hazardous if the latter decelerates rapidly;
- AACC vehicles on dedicated lane may lead to instability or inefficiency.

Effect of entry/exit on other traffic

Since automated lane have a much higher capacity than manual lanes, feeding and discharging such a lane can disrupt traffic. The disruption can be reduced by proper coordination. An outcome of our work is an analytical model that can be used to evaluate the extent of the disruption in terms of excess travel time and reduced flow.

- Merging of vehicle with mainstream traffic on automated lane must be coordinated to prevent disruptive "shock wave";
- If vehicles are allowed to enter automated lane without controlled stop, the flow on the automated lane can be seriously disrupted.

2 Introduction

This section is in four parts. We begin with a brief description of entry and exit in the AHS. We then summarize the focus of our study and reasons for that focus. The issues concerning entry and exit that we have addressed are described next. The section concludes with a description of our approach.

2.1 Entry and exit

An Automated Highway System (AHS) is the most advanced and highest risk element of the overall program on Intelligent Transportation Systems (ITS). It is the most advanced element, not only because it embodies the most sophisticated form of computer-based "intelligence," but also because it must show dramatic gains in highway capacity and safety. AHS involves the highest risk, not only because it requires the introduction of information technology that will significantly replace driver control, but also because its implementation will require a radical change in the *system* of highway traffic. The objectives of this and other studies in the Precursor Systems Analyses (PSA) of AHS are: to identify the issues that an AHS design must address, to arrive at firm or tentative conclusions about those issues, and to indicate the uncertainties that remain in the absence of firm conclusions.

The PSA studies are grouped into 16 activity areas, labeled (a)–(p). This study is concerned with area (j), "AHS Entry/Exit Implementation." Issues in entry/exit are of direct concern to several other areas: check-in (b) and check-out (c), safety (n), roadway deployment (h) and impact on non-AHS roadway (i). One must ensure that these inter-connected issues are not overlooked. Our study pays special attention to safety, check-in and check-out, and has been coordinated with the related PATH studies on roadway deployment.

AHS entrances are the narrow veins that feed the wide arteries of the automated lanes. If those veins get constricted or if they are too few in number, the arteries will be starved, and the AHS capacity will remain underutilized. The stream of vehicles leaving the automated lanes debouch into narrow AHS exits. If those exits are blocked or if they are unable to cope with a heavy stream, traffic can spill back into the automated lanes, creating massive traffic jams. The design of AHS entry and exit, the management of the processes by which vehicles negotiate their passage through them, and the coordination of that passage with the stream on the automated lanes thus have a determining effect on the achievable traffic flows of the AHS.

At some point during entry, control over the vehicle passes from the driver to the automated system. And at some point during exit the driver takes over responsibility for the vehicle from the system. These transfers of authority between system and individual driver last a few seconds, but they are nevertheless periods of potential danger. The transfer must be smooth, the agent taking over control must be ready and prepared, and agreed-upon procedures must be invoked if the transfer falters.

The movement of a vehicle from entry to mainstream of the automated lane has to be choreographed. The movement cannot be left to chance. At the moment when the AHS takes control of the vehicle, its speed is likely to be lower than the speed on the automated lane. The AHS control system (distributed between vehicle and roadway infrastructure) must accelerate the vehicle to the mainstream speed at the point when it merges into the automated lane. At that point, vehicles on the automated lane must be disposed in such a way as to accept the entering vehicle. If for any reason the introduction of the vehicle into the automated stream fails to follow the prepared script, agreed-upon procedures must be invoked to recover from the failure.

These considerations show that the study of "entry/exit" shares important concerns with the studies of "safety," "check-in" and "check-out." In order to achieve adequate capacity and safety, the physical layout of entry/exit may need to be arranged in ways that can not be accommodated in existing highways at locations where it would be most desirable to place an entry/exit due to the pattern of demand. In this respect "entry/exit" may affect how and where the AHS can most profitably be deployed.

In its expanded description, the Broad Agency Announcement properly finds that the basic objective of the entry/exit studies is to "develop relationships between AHS parameters, including: check-in and check-out time, number of instrumented AHS roadway lanes, speed and density of traffic on the AHS roadway lanes at peak hours, land use requirements." Even from our very preliminary remarks above, it should become clear that these relationships will depend on fairly detailed specification of the physical design of entry/exit, the processes that govern a vehicle's entry and exit and its coordination with mainstream traffic on the automated lanes. Further, this specification must meet stringent safety criteria. These observations should help anticipate the special focus of the present study.

2.2 Special focus

Three features distinguish this study from the parallel studies of entry/exit:

- Two alternative arrangements of entry and exit are specified in some detail: one assumes that entry and exit occur through a "transition lane" separating manual from automated lanes, the other assumes that entry and exit occur through dedicated "ramps";
- Entry and exit of a vehicle are choreographed with the movement of vehicles on the automated lanes. The coordination is achieved through
  - the exchange of a structured set of messages, called a *protocol*, between relevant vehicles and roadway infrastructure, and
  - longitudinal and lateral control laws that safely navigate the vehicle through entry and exit;
- Vehicles on the automated lanes are organized in *platoons* in order to improve AHS safety and capacity. (A platoon is a string of closely spaced vehicles that move as a unit. Spacing between platoons is large.)

As will be seen below, the issues our study addresses are, with small differences, the same as those of the parallel entry/exit studies. But these three features channel this study in a direction different from these parallel studies and therefore our conclusions contain a different emphasis.

We now summarize the major arguments that underlie the choice of these three features. The arguments are based on considerations of safety and capacity. A detailed discussion is presented in section 6.1.

Because the AHS must have fewer serious casualties than current highway traffic, manually controlled and automated vehicles must be segregated from each other. Traffic on automated lanes will have a larger flow, hence greater speed and density, than traffic on manual lanes. If the two types of traffic are mixed, the frequency of unpredictable and inappropriate maneuvers of manually controlled vehicles will be at least as large as that on today's highways, but because of the greater speed and density on automated lanes, an accident resulting from those maneuvers would lead to more serious casualties. Thus mixing both traffic types will lead to a higher casualty rate than today, which is unacceptable. Segregation of the two traffic types can only be achieved either by a transition lane or by special ramps, where the supervised transfer of control between driver and AHS takes place. In either case, no portion of the highway will legitimately permit the intermingling of the two traffic types.[1] This is the argument for the first feature.

At some point during entry, in the transition lane or in the on-ramp, control of the vehicle will be taken over by the AHS. The control system must now initiate an entry maneuver at the successful completion of which the vehicle has merged into the mainstream on the

[1] Of course, the intentional or unforeseen intrusion of one traffic type into a portion of highway reserved for the other may occur. To reduce such intrusions is the objective of other studies.

automated lane. The time available for this maneuver and the space dedicated to it on the transition lane or on the ramp are both limited. Successful completion of the maneuver in this limited space-time interval will require that the movement of the entering vehicle and the disposition of the nearby vehicles on the automated lanes be closely coordinated. Achieving this coordination will, in our view, place significant demands on the layout of entry/exit and the placement and capabilities of sensors and communication infrastructure in the roadway and on vehicles. This accounts for the separate emphasis on the second feature.

Based on earlier successful designs [1, 2] we have partitioned the coordination task into two functions: a logical function implemented by a communication protocol, and the actual longitudinal and lateral control implemented in feedback laws. This partition, of course, is not mandatory, and there are plausible alternatives. A detailed discussion appears in section 6.3.

The third distinguishing feature of our study is the assumption that traffic on automated lanes is organized in platoons. This is not a necessary feature of the study, and, with appropriate modification, much of our analysis remains valid without it, as will become clear.[2] However, as argued in section 6.1, in order to achieve high capacity and safety, inter-vehicle spacing must either be large or small, and this implies a platoon organization.

2.3 Issues addressed

The specific issues investigated in this study are also the concern of the parallel studies. The issues are organized in the following list:

- Strategies for entry and exit maneuvers;
- Integration with a roadway deployment study undertaken by PATH;
- Alternative ramp configurations, as well as entry/exit via a transition lane;
- Queue lengths at several critical transition regions;
- Transfer of control;
- Effect of entry and exit on mainstream AHS traffic;
- Length of transition lane and ramps.

Because this list is almost self-explanatory, only a brief elaboration is provided.

Strategies for entry/exit maneuvers include the communication protocols, the feedback laws governing longitudinal and lateral control, and provisions for aborting a maneuver if it is not practicable or safe to continue the maneuver. We have attempted to determine how to place an AHS with appropriate entries and exits within a section of US 101—one of several highway corridors investigated in the PSA roadway deployment study undertaken

[2] The essential modification is to insist that the maximum permitted platoon size is one.

by PATH. In addition to entry/exit via a transition lane, we study alternatives based on special ramps.

Queues can develop at several places where vehicles move from one control regime to another as, for example, between transition lane and automated lane. The queues account for the temporary mismatch of flows between the two regimes. If entry or exit is improperly coordinated, or if too many vehicles attempt entry or exit, the mainstream flow on the automated lane can be disrupted. Finally, the length of the transition lane and ramps determines the time available for the entry/exit maneuver. The time available is also determined once the speed and acceleration involved are specified.

2.4 Approach

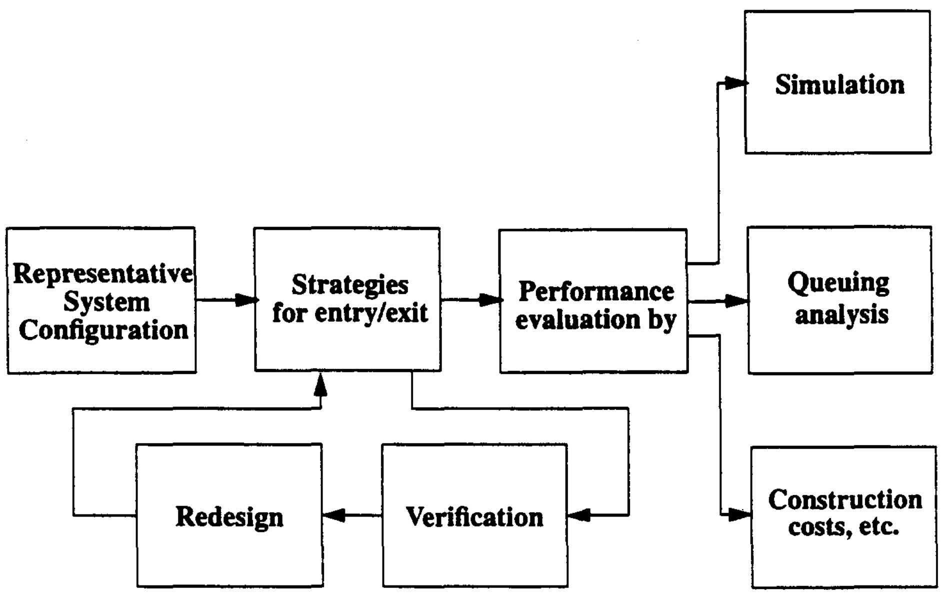


Figure 1: The approach

The logic of our approach follows the three steps depicted in Figure 1. Step 1 provides a specification of "Representative System Configurations (RSC)." An RSC is a group of four distinguishing design characteristics that sets the boundaries within which the study investigates the variation of more detailed AHS design choices. An individual study, like ours, confines itself to one RSC or a small set of RSCs. Parallel studies explore alternative RSCs. The four characteristics of an RSC are:

- Infrastructure impact—the amount of construction required to implement the AHS. In this study this is the construction of the transition lane and special ramps;
- Traffic synchronization—the degree to which the movement of vehicles is coordinated. This refers to the strategies of entry/exit and to the organization of vehicles in platoons;
- Instrument distribution—how information technology is distributed between vehicles and roadway;

- Operating speed—the range of speeds that the automated lanes will accommodate. Only light duty vehicles at 100 km/hour (30 m/sec) are considered here. However, the analysis is readily modified to permit higher speeds.

Step 2 gives the detailed design of strategies for entry/exit. As noted before, a strategy has two parts: communication protocols that ensure that the sequence of logical steps required for successful entry/exit maneuvers is followed, and the implementation of those steps in feedback laws for lateral and longitudinal control. Figure 1 indicates that the design process is iterative: each version of the design is tested to check whether it meets the requirements for successful maneuvers, followed by a redesign if those requirements are not met, until a satisfactory design is invented. In this report, of course, only the final design is presented.

Step 3 evaluates the performance of a satisfactory design. Three methods are employed. One method depends on the construction and analysis of models that explain the formation of queues. The second relies on simulations of the AHS that highlight the processes of entry/exit. The third method evaluates other dimensions, including construction costs and ease of deployment on existing highways.

The remainder of this report is organized as follows. Section 3 presents the RSCs that frame this study. Section 4 summarizes the technical discussion of the Steps 2 and 3 outlined above. Section 5 presents our conclusions. The analyses that follow the approach outlined here are more fully presented in the Appendices, Section 6.

3 Representative system configurations

This section specifies the Representative System Configurations or RSCs that frame our study. An RSC comprises four design characteristics: infrastructure arrangement, traffic synchronization, instrument distribution, and operating speed. Table 1 summarizes the defining characteristics. We consider each characteristic in turn.

3.1 Infrastructure arrangement

Our five assumptions narrow down the range of possible infrastructure arrangements.

Assumption 1: AHS deployed on existing highway

The AHS is deployed on part of an existing highway, containing four lanes (in each direction). One or two of those lanes are converted for AHS use. The AHS occupies the inner lanes, the outer lanes continue to be used for manual traffic as before. As a consequence of this assumption, manual lanes (MLs) and automated lanes (ALs) will exist side by side, and entrance into (and exit from) ALs must occur either through the MLs or by means of special ramps elevated above the MLs. We refer to the arrangement of entry and exit through the ML as the *manual lane option* or MO and the arrangement using special ramps as the *ramp option* or RO. (These two arrangements constitute the first feature of the special focus of this study.)

Assumption 2: Manually controlled and automated vehicles segregated

Table 1: Summary of RSC defining characteristics.

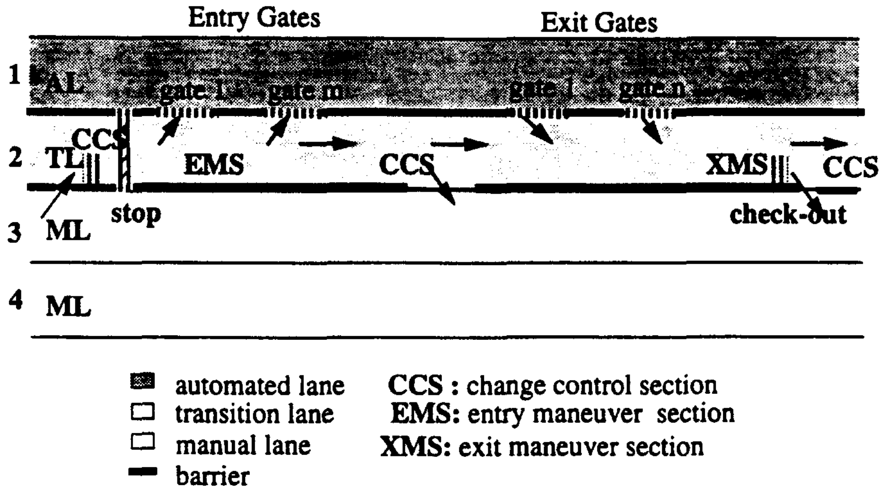
Characteristics	Assumptions	Comments
Infrastructure arrangement	1. AHS deployed on existing highway 2. Manually and automatically controlled vehicles are segregated 3. Vehicles undergo check-in at entry 4. Vehicles undergo check-out at exit 5. Barriers between TL and AL, ML	Four infrastructure arrangements 1,2,3,4a,b illustrated in Figures 2-6
Traffic synchronization	1. Platoon organization on AL 2. Strategies for coordination, control use communication protocols, sensor-based feedback control laws	Improves capacity and safety, Figures 7, 8 Architecture in Figure 9
Instrument distribution	Sensors, communication and control calculation	Distributed between roadside and vehicle
Operating speed	30 m/s on AL, 30 m/s on TL; maximum permissible accel/decel/jerk	These determine capacity and geometry

Manually controlled and automated vehicles do not co-exist on any stretch of roadway. This assumption is made to satisfy certain safety constraints. A consequence of this assumption is that ALs and MLs are segregated.[3] Another consequence is that the process of entry is in two phases. In the first phase, a vehicle is manually controlled. At the end of that phase it is automatically controlled. Thus the roadway occupied during the entry process must correspondingly be divided into two segments. In the first segment vehicles are manually controlled, in the second segment they are automatically controlled. The roadway where this transfer of control occurs is called the *transition lane* or TL. In the MO, one of the MLs is taken over by the TL, and the TL lies between the ALs and MLs. In the RO, the TL occupies part of the length of the ramp. The exit process is symmetric. There is a TL comprising two segments: in the first segment vehicles are automatically controlled, in the second they are manually controlled.

Figure 2 is a schematic of the MO arrangement, Arrangement 1. It shows two inner lanes of a four-lane highway taken over by the AHS. Lane 1 is automated, lane 2 is devoted to the TL, lanes 3 and 4 are MLs. Entry into the TL takes place from the "fast" ML. Similarly, manually controlled vehicles enter the fast ML from the TL. The other details in Figure 2 are discussed later.

Figures 3-6 illustrate four different RO arrangements. Arrangement 2, Figure 3, also occupies two MLs. The innermost lane, lane 1, is automated, with no entry or exit. Lane 2 is divided into segments at least 5 km long. Each segment terminates at one end in an entrance ramp and at the other end in an exit ramp. The ramps are elevated structures.

[3]It is possible, indeed likely, that an inner lane may be restricted to automated vehicles for part of the day, and revert to manually controlled vehicles during the rest of the day, as is the case today with HOV lanes.



Note: Transition Lane of 2 km is needed per entry/exit

Figure 2: Entry/exit arrangement 1

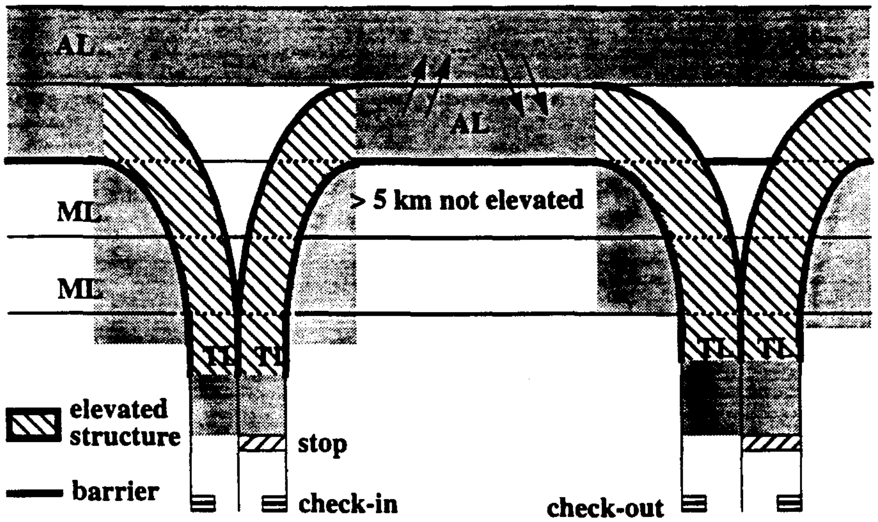
We imagine that these widely separated ramps would be linked with entrances and exits from the MLs (not shown in the figure), although the latter would have additional entrances and exits. The AHS ramps constitute the TL. As will be seen later, arrangement 2 offers the simplest coordination and control strategies.

Arrangement 3, Figure 4, converts both lanes 1 and 2 into ALs. An entrance ramp feeds directly into an AL. Vehicles from that AL exit directly into an exit ramp. The entry and exit ramps need to be at least 5 km apart. As in Arrangement 2, they may be linked with entrances and exits from the MLs. Arrangement 3 has a greater capacity than Arrangement 2, but requires significantly greater coordination and control.

Arrangements 4a and 4b, Figures 5 and 6, combine attractive features of Arrangements 1 and 3. They require a degree of coordination that is almost as simple as Arrangement 1, and achieve a capacity close to that of Arrangement 3. However, these arrangements will require more complex construction because a 2 km-long section of the ALs that lies between entrance and exit ramps must be elevated.

Table 2 summarizes the differences between these arrangements for several characteristics.

In Table 2 the row corresponding to capacity is based on the following calculation. Manually controlled lanes have a capacity of 2,000 vehicles/hour, so that the original four-lane highway has a capacity of 8,000. An AL has a capacity of 6,000 vehicles/hour. Under arrangement 1, there are two MLs, one AL, and one transition lane, carrying no additional sustained flow, leading to a total capacity of $2 \times 2,000 + 6,000 = 10,000$ vehicles/hour. In arrangements 2, the ramp segment can accommodate an additional sustained flow of 2,000, leading to a total capacity of 12,000 vehicles/hour. In arrangements 3 and 4b there are two ALs and two MLs giving a capacity of $2 \times 2,000 + 2 \times 6,000 = 16,000$ vehicles/hour. Arrangement 4a has one AL and three MLs that can support a total capacity of $6,000 + 3 \times 2,000 = 12,000$



Note: Entry/exit to AL and ML may be connected

Figure 3: Entry/exit arrangement 2

vehicles/hour. The argument supporting the capacity estimates for the ALs are presented later.

Assumption 3: Vehicles undergo check-in

A vehicle seeking to travel on the AHS will undergo a *check-in* process.[4] "Check-in" refers both to a location on the TL and to the time it takes for the process to complete. The time per vehicle is assumed to be so small that vehicles queued up for check-in can be accommodated on the TL, under both MO and RO.

This assumption limits the amount of space-time available on the TL for check-in. If the

[4] There are PSA studies devoted to "check-in." Our assumption concerns the way check-in affects the infrastructure arrangements, especially the TL.

Table 2: Comparison of different infrastructure arrangements.

Characteristic	Manual	Arr. 1	Arr. 2	Arr. 3	Arr. 4a	Arr. 4b
Capacity (veh/hour)	8,000	10,000	12,000	16,000	12,000	16,000
Construction	—	—	Low	Medium	High	High
Control complexity	—	Medium	Low	High	Medium	Medium
Exit to fast manual lane	—	Yes	—	—	—	—
Min distance bet entry	—	3 km	5 km	5 km	5 km	5 km

Notes: (1) Construction High, Medium, Low refers to the complexity of the construction, presumably correlated with cost. (2) Control complexity High, Medium, Low refers to "tightness" of control specification and the need for special sensors and communication.

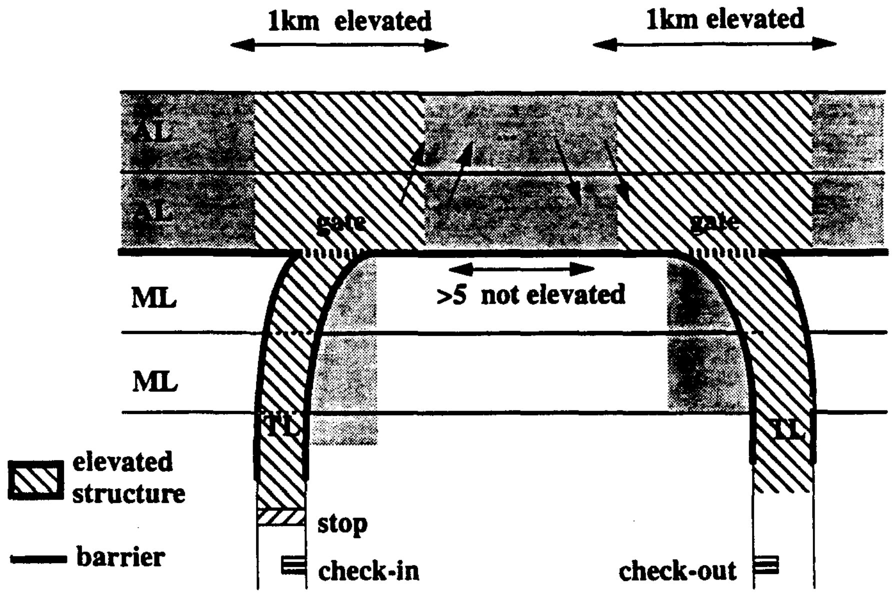


Figure 4: Entry/exit arrangement 3

check-in process cannot be conducted in that space-time, the process could be divided into two phases: the first phase, requiring more space-time, is conducted outside the TL; the second phase, within the TL, serves only to verify that the first phase was successfully completed. Figures 2-6 indicate where check-in is located on the TL.

Under manual control, a vehicle enters the TL at some point before the beginning of the check-in process. In Figure 2 this point is indicated by the leftmost arrow leading from the ML into the TL. In Figures 3-6, this point is on the entrance ramp somewhere before "check-in" but it is not explicitly indicated. At the end of a successful check-in, the vehicle is under automatic control. If a vehicle fails the check-in tests, it should be unable to proceed to the ALs.[5] Provisions must be made for these failed vehicles to leave the AHS under manual control and will require modifications in the infrastructure arrangements shown in the Figures. In arrangement 1, Figure 2, there must be a path to return to the ML for these vehicles. In Figures 3-6, there must be a similar path. In the latter case, this path could be linked to the outermost ML. These modifications will not be considered any further.

Some time after a vehicle passes check-in, it starts an *entry maneuver* which takes the vehicle from the TL to an AL. Provisions, akin to those needed to handle vehicles that fail check-in tests, must also be made for vehicles that fail to enter the AL. This is a failure of the control system, discussed under traffic synchronization, section 3.2, and should be rare.

Assumption 4: Vehicles undergo check-out

This is an assumption about the *check-out* process, somewhat symmetric with that of check-in. When a vehicle leaves the AL, it enters the TL.[6] At some point the check-out process

[5] Procedures, presumably investigated by the "check-in" studies, prevent failed vehicles from entering the AHS, inadvertently or deliberately.

[6] Other PSA studies deal with check-out, so we limit ourselves to aspects with a bearing on infrastructure

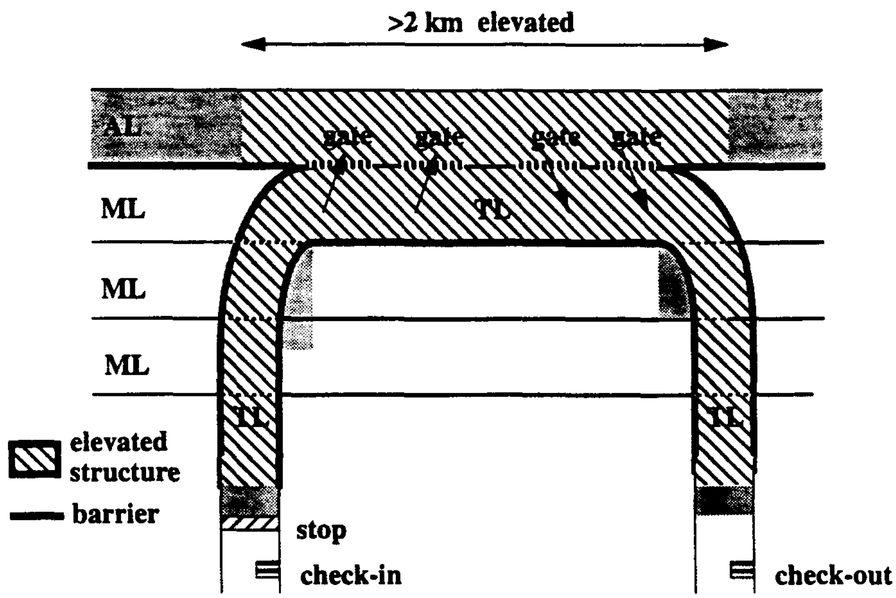


Figure 5: Entry/exit arrangement 4a

starts. Thus check-out is both a location in the TL (as indicated in Figures 2-6) and an amount of time. The check-out process tests that the driver is able to take over control. If the process terminates successfully, the vehicle is placed under manual control. Provisions must be made to ensure safety in case tests determine that the driver is unable to take control.

These provisions will require modifications in the arrangements shown in the Figures. In arrangement 1, Figure 2, it is possible for vehicles that fail check-out, to continue along the TL under automatic control and bring the vehicle to rest, before it reaches the entrance from the ML to the TL. In Figures 3-6, vehicles that fail check-out are brought to rest under automatic control at some point after the locations marked "check-out."

It is possible that vehicles wishing to leave the AL are unable to do so because queued vehicles have blocked exits. This, too, is a control system failure. It is discussed in section 3.2.

Assumption 5: Barriers between TL and AL, ML

Entry into and exit from the TL is restricted to specific locations, by means of barriers between the TL and AL and the TL and ML. There are several reasons for doing this. First, barriers prevent automated vehicles in the AL from entering those portions of the TL reserved for manually driven vehicles, automated vehicles in the TL from entering the ML, etc. (This merely reinforces segregation of automated and manually controlled vehicles, Assumption 2.) Second, it will reduce the likelihood of a collision in the TL from "spilling over" into the AL or ML, and vice versa. Third, the barriers are breached by "gaps" or "gates" of sufficient length (specified later) to permit movement of vehicles between the TL and AL or ML. The barriers thus confine the location of these gates, permitting tight

arrangements.

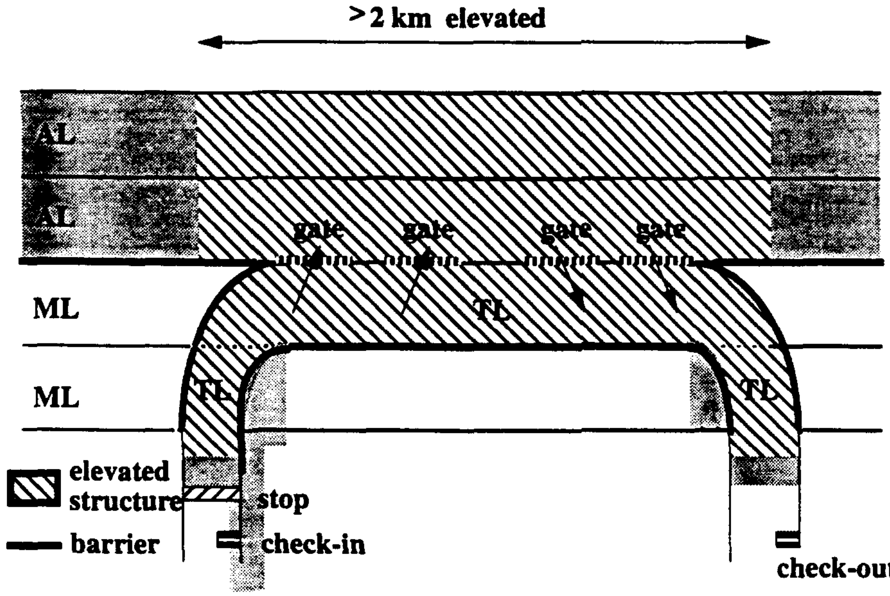


Figure 6: Entry/exit arrangement 4b

coordination between vehicles on the AL and TL. The barriers are indicated in Figure 2, Arrangement 1. The gates between TL and AL are also indicated there, as are the gaps between TL and ML. The gates between TL and AL are also indicated in Figures 4-6, Arrangements 3,4a,4b. There is no need for gates in Arrangement 2, Figure 3.

Barriers are discussed in greater detail in section 6.1.

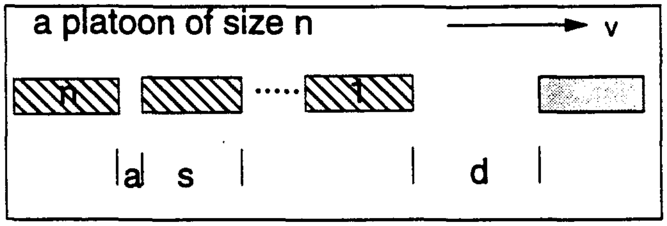
3.2 Traffic synchronization

Traffic synchronization refers both to the overall organization of traffic as well as to the specific strategies used to coordinate the processes of entry and exit with traffic on the ALs and to control vehicle motion. We have made two assumptions about traffic synchronization. (The two assumptions account for the two other features of the focus of this study.) We state those below, together with arguments in support of those assumptions. The arguments concern capacity and safety.

Assumption 1: Platoon organization on ALs

Traffic on the ALs is organized in "platoons" of closely spaced vehicles with large spacing between platoons. Figure 7 shows by a simple calculation that a capacity of 8,250 vehicles/hour can be achieved with intra-platoon spacing of 2 m, inter-platoon spacing of 60 m, average platoon size of 15, and a vehicle speed of 25 m/s (90 km/h), assuming a 5 m vehicle length. This capacity estimate must be interpreted with caution, for two reasons.

In the first place, the estimate rests on the assumption that traffic on the ALs can be synchronized or controlled so as to maintain indefinitely a two-meter intra-platoon spacing and a 60-meter inter-platoon spacing, at 25 m/s. In section 6.1 we summarize the evidence supporting the claim that this level of performance is possible.[7]



Capacity = C = v . n / [ns + a(n - 1) + d] veh / lane / hour

Assume v = 90 k/h, s = 5m. Then

n	a	d	C
1	-	40	2,000
5	2	60	4,800
15	2	60	8,250

Notes

n=15 yields nearly 4 times today's capacity

capacity proportional to speed

Figure 7: Platoon organization and capacity

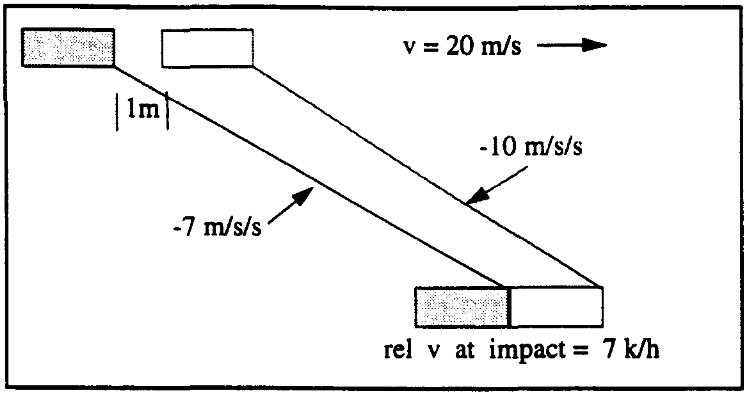
In the second place, the capacity estimate is for "steady state" flow conditions, ignoring disruptions to the flow from entry and exit of vehicles. (In other words, this is the maximum "longitudinal" capacity.) It is obvious that if there is a significant "lateral" flow caused by entry and exit, this capacity will be reduced. The extent of the lateral flow will depend on the capacity of entrances as well as on trip lengths, and on the manner in which entry and exit are coordinated with traffic on the AL. We argue in section 6.5 that with the form of coordination described below, entry and exit capacity of 1,800 vehicles/hour, and with average trip length of 10 km, the longitudinal capacity will be reduced at most by 10 percent, i.e., from 8,250 to 7,400 vehicles/hour. Thus, a large capacity is afforded by the platoon organization, with suitable coordination and control.

The platoon organization also favors safety. A detailed comparison with other forms of traffic organization is presented in section 6.1. The essence of the argument, first presented in [3], can be understood with the help of Figure 8. If two vehicles traveling at 20 m/s are initially separated by a distance d, and the first one decelerates at 10 m/s/s while the second decelerates at 7 m/s/s, they may collide. The relative speed at collision, Δv, as a function of d, has an inverted U shape: Δv is small for large and small values of d, and large for intermediate values of d. The platoon organization provides vehicle spacings that are either small (intra-platoon spacing) or large (inter-platoon spacing).

Assumption 2: Strategies for coordination and control

The entry of vehicles from the TL is coordinated with relevant vehicles on the AL by means of communication protocols that ensure safety and cause minimum disruption of flow on

[7] For an overview of analytical, simulation and experimental evidence see [2] and the references cited therein.



Relative speed on impact is small if inter-vehicle spacing is either small or large. This is achieved by organizing traffic in platoons.

Figure 8: Platoon organization and safety

the ALs. Once the communication protocol reaches agreement that a vehicle can properly carry out the entry maneuver, that maneuver is executed by feedback laws that determine the vehicle's throttle, braking and steering actuator signals. The feedback laws are based on sensor readings that provide information about the disposition of vehicles relative to the entering vehicle.

The exit of vehicles from the AL into the TL is also coordinated using communication protocols. And the exit maneuver is executed by sensor-based feedback laws that guide the exiting vehicle.

An entry or exit maneuver is aborted if at any time it is determined that continuation of the maneuver leads to a hazardous situation. This unexpected situation may be caused by a system failure, and should occur rarely.

As we noted in section 2.1, the coordination of the movement of vehicles on the TL and AL, and the automatic guidance of vehicles through entry and exit, have a determining influence on AHS capacity and safety. The better the design of coordination and control strategies, the more predictable is the movement of vehicles, the less is the disruption caused by entry and exit, and the safer are these maneuvers. For these reasons, much effort in this study has gone in the design, verification, and performance evaluation of these strategies.

A detailed discussion of coordination and control may be found in sections 6.2, 6.3. We only give an outline here. Traffic on the AL is organized in *platoons.* The lead vehicle in a platoon is called the *leader*, the others are *followers.* A one-vehicle platoon is a *free agent.* At any moment of time, an automated vehicle is a leader, follower or free agent.

The platoon is the basic unit of automation. Only a leader or free agent can initiate a maneuver. (However, a follower may request its leader to initiate a maneuver.) A follower's control task is only to stay in its platoon at the specified intra-platoon spacing. There are five possible maneuvers: in *join* a leader of a platoon joins the platoon in front of it to form a larger platoon; in *split* a leader splits its platoon into two platoons at a designated position; in *change lane* a free agent changes lane;[8] in *entry* a free agent or a *pre-platoon*[9] enters the AL from the TL; in *exit* one vehicle at a time leaves the AL platoon from an exit into the TL.

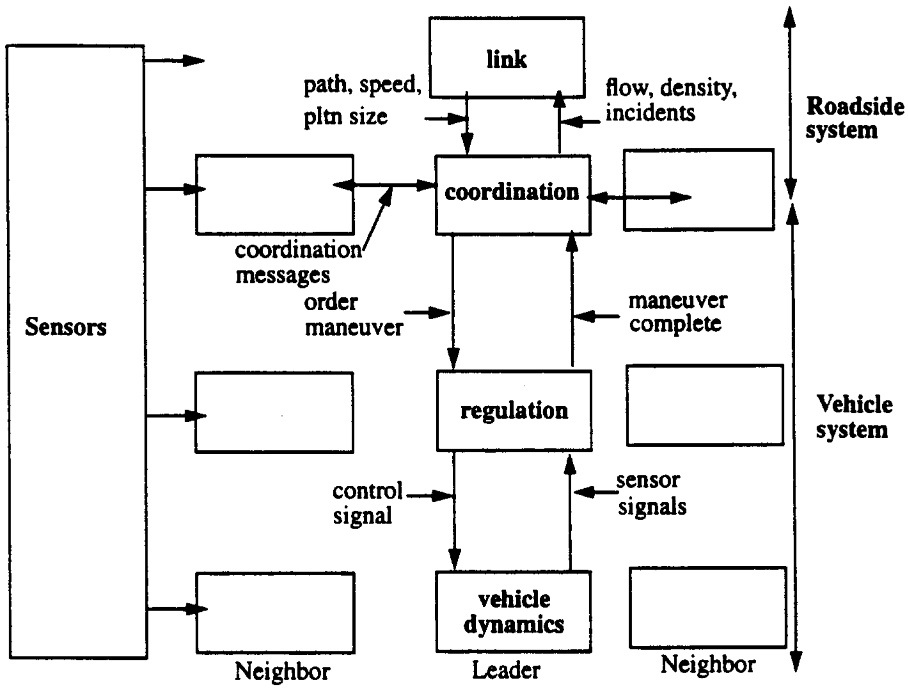


Figure 9: Coordination and control architecture

Figure 9 gives a block diagram of the coordination and control architecture, organized as a three-layer hierarchy. Coordination is shared by the roadside-based link layer and the vehicle-based coordination layer. The link layer assigns target speed and platoon size, and informs a vehicle when it should exit. It also informs vehicles if there is an incident, and suggests remedial action, if necessary.[10] A vehicle's coordination layer determines which of the five maneuvers is to be conducted. (For example, if the vehicle learns from the link layer that it is close to its exit, the coordination layer will attempt the exit maneuver.) Having determined the maneuver to be attempted, the coordination layer exchanges messages with the coordination layers of its relevant neighboring vehicles requesting their cooperation. If such cooperation is not forthcoming, which may happen for a variety of reasons, including the most likely reason that one of those neighbors is itself engaged in some other maneuver, the maneuver is aborted and the request is repeated at a later time. If cooperation is

[8] If there is only one AL, change lane is unnecessary.

[9] A pre-platoon is a platoon in the TL. Usually entry is carried out one vehicle (free agent) at a time; however, the flow from a TL entrance into the AL can be increased if a small number of vehicles can enter together as a pre-platoon.

[10] Examples of remedial actions are: "exit if later exit is blocked," "slow down (or stop) if lane is blocked." One link layer design, together with simulation-based performance results, is presented in [4]. Link layer design is beyond the scope of this study and is not discussed further.

secured, the leader's coordination layer commands its regulation layer to invoke the (pre-programmed) feedback control law that executes the maneuver.

The regulation layer comprises seven feedback laws, five of which correspond to the five maneuvers. The remaining two laws, described first, are used when a platoon is not engaged in a maneuver. The *cruise* law keeps the leader in its lane at the target speed suggested by the link layer, while maintaining a safe distance from the platoon in front.[11] A follower vehicles always implements the *follower* law which maintains its position within the platoon at the desired spacing from the vehicle in front of it.

The *join* law accelerates the leader and then decelerates it so that it joins the platoon in front. The *split* law decelerates the leader until it is at a safe distance from the platoon in front. The *change lane* law steers a free agent from one lane to an empty space in an adjacent lane.

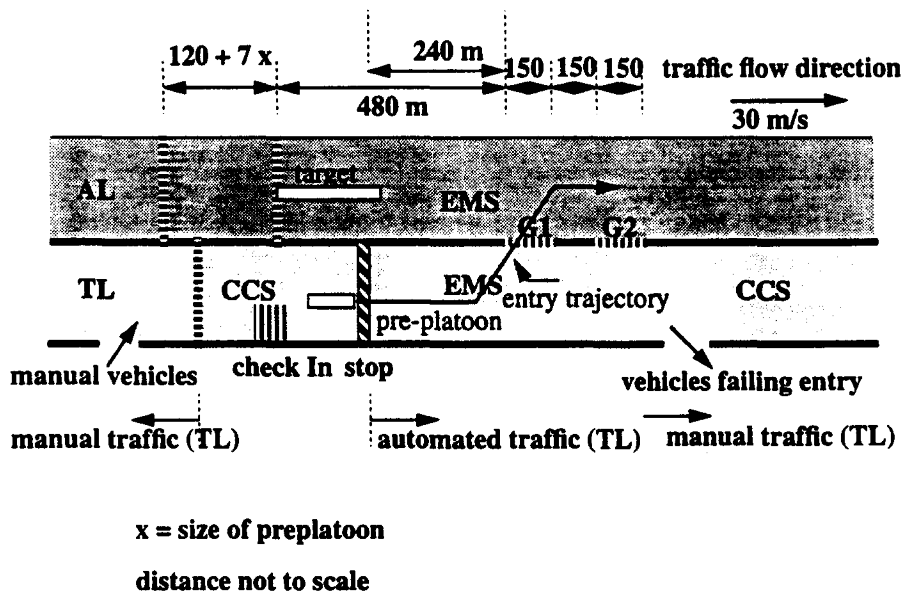


Figure 10: Regulation layer for entry: Arrangements 1,3,4

We now describe the *entry* law. Under this law, a pre-platoon in the TL is accelerated to the speed on the AL, then enters the AL through a gate, and finally joins up with the rear of a platoon—the *target*—in the AL. At the end of the maneuver the pre-platoon is part of the target platoon. (This is illustrated in Figure 10.) At the beginning of the maneuver, the pre-platoon is at rest in the TL, at the "stop sign" indicated in Figures 2-6. It is assumed that the maximum speed in the AL is 30 m/s, and that for comfort, the maximum values for jerk and acceleration are 2 m/s^3 and 2 m/s^2, respectively. Since the pre-platoon is at rest at the beginning of the entry maneuver while the target may be traveling as fast as 30 m/s, a simple calculation shows that a 240 meter-long section in the TL is sufficient for the entry maneuver. In Figures 2 and 10 this section is labeled EMS. The TL contains similar sections in the arrangements of Figures 3-6, but they are not indicated. The entry law determines

[11]The cruise law is identical with the so-called AICC (autonomous intelligent cruise control) law [5, 6, 7], combined with a lateral control law that keeps the vehicle in its lane.

the throttle, braking and steering actuator control signals of the pre-platoon, assuming that it knows the relative position of the target. Thus sensors providing this information must be available. The lateral motion from TL into AL should take about 5 sec. Assuming a maximum speed of 30 m/s gives a gate length of 150 m, as indicated in Figure 10.

In order for the entry law to be executed safely, the movement of the entering pre-platoon and the target must be coordinated. In particular, the latter must not itself be engaged in a maneuver, nor must its size be so large that the combined size exceeds the size recommended by the link layer. These logical conditions are checked by the communication protocol exchanged by the pre-platoon and the leader of the target platoon. That *entry protocol* is presented in section 6.2 and will not be discussed further here.

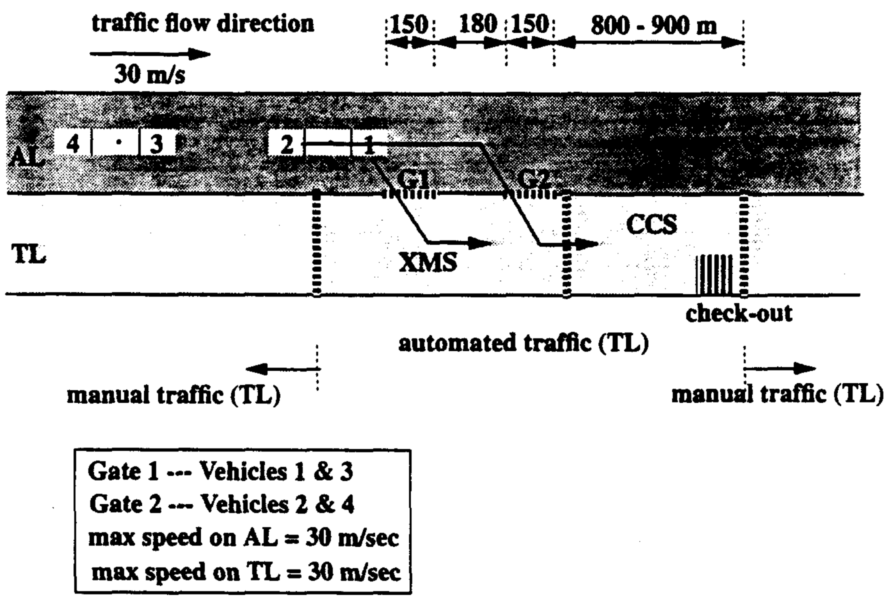


Figure 11: Regulation layer for exit: Arrangements 1,3,4

We now describe the *exit* law. A vehicle exiting from the AL may be part of a platoon, and more than one vehicle may exit from the same platoon. For safety reason (see Section 6.1), we do not allow different vehicles from the same platoon to exit through the same gate. This requires many gates per exit. Figure 11 illustrates the exit maneuver, assuming up to two vehicles can exit from the same platoon. This requires two gates. Under the exit law, the platoon must create a short space for each exiting vehicle, which must then enter the TL through an exit gate. We also require that the vehicle forward in the platoon must exit from the *rear* gate. The platoon on AL will then close up the gap created by the exiting vehicle, whereas, the vehicle on TL will longitudinally align itself so that the next vehicle in the same AL platoon that will exit from the next gate can do so at a small distance (intra-platoon spacing) behind it. Thus the vehicles exiting from the same AL platoon from a platoon on TL. This is called as a post_platoon. Assuming the same maximum jerk and deceleration values for comfortable driving as for entry, we can calculate the length of the exit maneuver section or XMS, as shown in Figure 11. An exit gate must be 150 m long, again assuming it takes 5 sec to move from AL to TL at a speed of 30 m/s. At the end of the XMS, the post_platoon is broken down into single vehicles so that the human drivers can take over the control of the vehicles.

In order for the exit law to be executed safely, at most two vehicles per platoon can exit (assuming there are only two gates), and they should exit from the proper gate. If more than two vehicles wish to exit, the platoon should be split up upstream from the exit gates. This coordination is achieved through another communication protocol, the *exit protocol*, also presented in section 6.2 and not further discussed here.

We now argue why it may be necessary to abort a maneuver after it has started, with the help of Figure 10. Suppose the pre-platoon has secured the agreement of the target. The regulation layer implements the entry law, and the pre-platoon begins to accelerate, expecting to rendez-vous with the target at the entrance gate. If for some unanticipated reason the target platoon is forced to decelerate (perhaps because the platoon in front of the target slowed down or because of a fault), the spacing between the target and the platoon behind it may became too short to accommodate the pre-platoon entry. In this case, avoiding a hazardous situation may require aborting the entry maneuver. Thus the coordination and control strategies must include a "safety check" and provision to abort the maneuver in case the safety check is violated at any time during the maneuver. Furthermore, as discussed above under Assumptions 3 and 4 of section 3.1, the TL must include provisions to accommodate any vehicle that has failed to enter. Similar procedures must be incorporated in the coordination and control strategies for exit. Aborting a maneuver is not dangerous. It may, however, cause some local disruption in traffic on TL and it may prevent a vehicle from entry. It should occur rarely.

We have assumed that the pre-platoon starts the entry from rest (at the stop sign). It will take some time for it to accelerate to the AL speed. It is easy to modify the entry maneuver so that entering vehicles, following check-in (which itself may not bring vehicles to halt), initiate the entry maneuver without coming to a stop. This will reduce slightly the maneuver time, but create two disadvantages which seem overwhelming. First, because the vehicle is moving, its position will not be closely coordinated with that of the target, so that the vehicle may have to stay in the TL for a longer time. If the AL is crowded, this time may be significant. As a result, the EMS section will have to be longer than the 240 m indicated in Figure 10. Second, the less tight coordination between the positions of the target on the AL and the pre-platoon in the TL implies that the location where the latter enters the AL will be uncertain, and so the "gate" will have to be longer than the 150 m gap indicated in Figure 10. The larger gap, in turn, increases the possibility that an accident in the TL or AL spills over into the other lane, reducing safety.

Entry and exit under Arrangement 2 are much simpler than under Arrangement 1. In the former, as seen in Figure 3, entering vehicles leave the TL and automatically end up in an AL in a portion dedicated to entering vehicles. Once on the AL, they merely need to execute a change lane maneuver into the inner AL. Similarly, an exiting vehicle only needs to execute a change lane maneuver into the outer AL. Thus in Arrangement 2 there is no need for a special entry or exit maneuver. This simplicity of coordination and control is achieved at a cost, however. If the inner AL is crowded or if many vehicles are seeking

Table 3: Features of TL in arrangements 1,3,4.

Feature	Stop on EMS	No stop on EMS
Length of EMS on TL	240 m	332 m
Length of EMS on AL	480 m	678 m
Space to form pre-platoon	100 m	150 m
Time needed for entry	31-36 sec	30-37 sec
Instrumented space on AL	660 m	858 m
Pollution	Higher	no effect
Driver comfort	discomfort due to stop	no effect

Notes: (1) Instrumented space refers to the coverage of the sensors and communications needed for the entry maneuver, see section 3.3. (2) The time and space needed when there is no stop on EMS may be longer than indicated. (3) Pollution is higher because of greater acceleration due to the stop.

entry, the entering vehicle will take a longer time to coordinate a lane change.[12] As a result the outer AL section between entry and exit has to be considerably longer—at least 5 km—compared with at most 2 km needed for Arrangement 1.

Arrangements 4a and 4b offer the possibility of using coordinated entry and exit as under Arrangement 1, requiring special maneuvers, or of using only the change lane maneuver of Arrangement 2. However, under the latter arrangement, the 2 km-long elevated section (figures 5,6), would have to be at least 5 km long, possibly increasing the construction complexity and cost.

Table 3 summarizes some of the features of the TL in Arrangements 1,3 and 4.

3.3 Instrumentation distribution

Instrumentation refers to the sensors, communications, and computational equipment needed to support the coordination and control strategies described in section 3.2, and distribution refers to how these are distributed between vehicles and roadway infrastructure. Table 4 summarizes the instrumentation distribution. We discuss each item in Table 4 in turn starting from the top. The coordination protocol of the entry layer, illustrated in Figure 10, determines (among other logical checks) whether there is sufficient space behind the target platoon to accommodate the pre-platoon. We envision that this is done using sensors on the AL. As seen in Figure 10 those sensors must cover a range of 190 meters in the portion of the AL called EMS, where the entry maneuver occurs. The accuracy of 1 % may be more than required. Similarly, as indicated in Figure 11, a vehicle exiting from the AL and entering the ML must be aware of the presence of any vehicles on the XMS portion of the ML, devoted to the exit maneuver.

The platoon organization demands that the lead vehicle have a longitudinal sensor that

[12] See [8] for a study that relates the time needed for entry via a change lane as a function of the flow on the inner AL and the flow of vehicles attempting entry. Also see section 6.5 for a queuing analysis.

Table 4: Instrument distribution.

Equipment	Function	Location
Road occupancy sensor	Determines if there is sufficient space behind target to accommodate entering pre-platoon. Sensor covers 190 m, accuracy $\pm 1\%$ One at gate & one 480m upstream of the gate	On EMS in AL, for Arrangements 1,3,4
	Determines if there are vehicles on XMS in TL. Sensor covers 150 m, accuracy $\pm 1\%$ One sensor required for each gate	On XMS in TL, for Arrangements 1,3,4
Longitudinal range, speed sensor	Leader detects 80 m ahead, including 60 m inter-platoon distance, accuracy $\pm 1\%$	On vehicles in AL
	Follower detects 5 m ahead, accuracy $\pm 1\%$	On vehicles in AL
Lateral range, speed sensor	Entering vehicles on TL detect target on AL. Range of 30 m, accuracy $\pm 1\%$	On vehicles in TL
	Vehicles in AL changing lane detects veh. in adjacent lanes up to 30 m, accuracy $\pm 1\%$, Arrangement 2	On vehicles in AL,
Communic-ation	Between road occupancy sensors, pre-platoon	Roadside, vehicles
	Between vehicles for coordination protocols	Vehicles
	Within platoon for follower law	Vehicles
Coordination and control computation	Link layer coordination	Roadside
	Entry, exit coordination	Roadside, vehicles
	Other five maneuvers coordination	Vehicles
	Seven feedback laws	Vehicles

Table 5: Assumptions about vehicle capabilities.

Capability	Value
Speed on AL	30 m/s
Speed on ML	20 m/s
Max comfortable accel/decel	2 m/s^2
Max comfortable jerk	2 m/s^3
Emergency braking	7 m/s^2
Vehicle type	Private auto/light truck

measures the distance and speed of the vehicle in front of it up to some range, which is larger than the inter-platoon distance. The range of 80 m, and 1 % accuracy, seems adequate.[13] The longitudinal sensor range required for followers is much shorter.

During the execution of the entry feedback law, the pre-platoon first accelerates, then enters the AL through a gate, and then joins the target platoon. Proper steering through the gate and making a rendez-vous with the target requires lateral sensors which measure distance and speed. A range of 30 m is sufficient. In Arrangement 2 where the entry maneuver is replaced by the simpler change lane maneuver, a similar lateral sensor is needed.

Coordination of maneuvers requires communication services between roadside and vehicle and between neighboring vehicles. There is also a need for communication among vehicles in a platoon, for control and coordination.

The computations involved in the coordination and control tasks may, in principle, be carried out anywhere. Elementary considerations of robustness and reliability, together with the technological trends towards lower cost and higher computational power in microprocessors, suggest that these tasks should be decentralized, and that computational resources should be located as close as possible to where the necessary information is available. These considerations lead to the locations suggested in the last item of Table 4.

3.4 Operating speed

Under the heading of "operating speed" we include several items pertaining to the assumed capabilities of automated vehicles: nominal speeds on AL and TL, nominal values of acceleration, deceleration and jerk, and vehicle type. These are listed in Table 5.

The assumptions about vehicles speed and acceleration underlie the calculations of the lengths of the various segments in the TL of Figures 10, 11. They also figure in the calculation of the minimum (safe) inter-platoon distance of 60 m that enters the capacity calculation of Figure 7. Finally, it is assumed that heavy vehicles are not allowed in the ALs (or that they have a separate dedicated lane). This permits us to assume that vehicles traveling in a platoon have a comparable performance.

[13]PATH's longitudinal control experiments uses a radar with a range of 30 m and an accuracy of 5 %.

It should be noted that all of the analyses presented in sections 4-6 can be modified in obvious ways to accommodate larger operating speeds. Thus the nominal speed of 30 m/s should be treated simply as a parameter. It turns out that for reasonable ranges of speed, the "longitudinal" capacity will increase slightly almost in proportion to the nominal speed. This is a major advantage of highway automation.

4 Technical discussion

As depicted in Figure 1, our approach involves three steps: (1) specification of the RSCs, (2) design of entry/exit strategies, and (3) performance evaluation of the resulting system. Step 1 was discussed in detail in section 3. This section is in two parts. The first part is devoted to entry/exit strategies, and the second to performance evaluation.

4.1 Entry/exit strategies

Six features of the assumed RSCs frame the design of these strategies:

- Manually controlled and automated vehicles are segregated;
- ALs and MLs are separated by a TL;
- There are barriers separating the TL from ALs and MLs; These barriers have "gates" or gaps for vehicles moving into and out of the TL;
- Vehicles undergo check-in and check-out at specific locations in the TL;
- Vehicles in the AL are organized in platoons;
- Vehicle capabilities on the ALs are given by Table 5.

The first four features are embodied in the entry/exit arrangements 1,2,3,4a,4b.

Strategies for entry

We first discuss the entry strategy for arrangement 1 of Figure 2. The strategies for Arrangements 3 and 4 are virtually identical. The strategy for arrangement 2 is discussed later.

Consider Figure 2. Manually controlled vehicles enter from the ML at the leftmost portion of the TL via a gate or exit lane. They enter the section labeled CCS (change control section). After successfully passing through the check in, the control of the vehicle will be transferred from the driver to AHS. The sequence of events that will take this automated vehicle from TL onto AL can be represented by a flow chart of Figures 12, 13. The vehicle under automatic control will come to a stop behind the stop sign. Thus, a small queue of vehicles that want to enter the AHS will form behind the stop sign. Physically, the stop sign is a roadside controller with communication capabilities. The stop sign communicates with the road occupancy sensor on AL which determines available space behind an AL platoon, called the target platoon. The available space in turn determines the maximum size of preplatoon that can join behind the target platoon on AL without creating disturbance for the upstream AL traffic. In case space is available on AL, the first vehicle at the stop sign communicates with the leader of the target platoon requesting cooperation in the entry maneuver. The permission to proceed is granted if the target platoon is not already busy with some other maneuver and the combined size of the target and the preplatoon does not exceed the maximum allowable platoon size on this section of the AHS.

Once an agreement is reached, the first vehicle at the stop sign forms a preplatoon of appropriate size and becomes its leader. Preplatoon formation is similar to 'join' maneuver of [1] but it does not involve any control action by the regulation layer as the vehicles in the queue have the same velocity (zero m/sec) and required intra-platoon separation between them. The preplatoon accelerates to catch up with the target platoon while the vehicles stopped behind the preplatoon move forward up to the stop sign and wait for the next available gap on AL. Given the passenger comfort bounds on acceleration and jerk, a simple calculation shows that it takes 16 seconds and 240 meters for a stopped vehicle to reach the AL operating speed of 30 m/sec. During that time, the target platoon travels 480m at 30m/sec. This determines the location of AL road occupancy sensor to be 480m upstream of the entrance gate.

At the end of the acceleration phase, the preplatoon should be aligned with target platoon and traveling at the same speed. This requires velocity of the target platoon to be relayed to the leader of the preplatoon so that its feedback controller can adjust to the changes in speed of target in response to the traffic on AL. The feedback control law used by the leader of the accelerating preplatoon ensures that when the preplatoon reaches the gate, it is properly aligned with the target platoon moving at the same speed so that lane change can safely take place. The preplatoon changes lane at a short distance behind the target platoon and completes the entry maneuver by joining the target platoon.

In rare situations, such as accidents on AL, two things can go wrong. The changes in speed of the target platoon could be drastic so as to create substantial error in the alignment of two platoons; or the gap behind the target platoon may shrink because of congestion on AL. Whereas the former condition can be detected by the lateral sensors of the preplatoon leader, the latter requires an additional road occupancy sensor to monitor the gap behind the target platoon. This sensor is placed at the entrance gate. In either case, the entry maneuver is aborted (before the lane change is started), the preplatoon is broken up in CCS (figure 10) and the control of the vehicle is returned to the driver who then drives the vehicle onto ML. A slight variation of this scheme used in arrangements 4a and 4b is as follows: After aborting the entry maneuver, the preplatoon continues its journey through the exit gates on TL coordinating its movement with the exiting vehicles. At the end of XMS, it is broken up and control is turned over to the driver.

The entry maneuver can be carried out even if the target platoon on AL does not exist which might be the case if the traffic density on AL is low. In this case, the preplatoon on TL will enter onto AL as an independent platoon. To do this without disturbing the AL traffic will require available space to be at least $2 \times 60m$ (inter-platoon separation in the

front and back of preplatoon) + size of preplatoon on AL.
Thus, for a maximum preplatoon size of 10, the road occupancy sensor should have a range of 190m. The average speed on AL obtained from the link layer of AHS, is used in the feedback law for the accelerating preplatoon.

The entry maneuver for arrangements 2, 4a and 4b is similar except that the vehicles join TL directly from the arterial streets, rather than from the ML.

Strategies for exit

We now describe exit strategy for arrangements 1, 3 and 4. The exiting vehicle, which may be part of a platoon on AL, executes a lane change maneuver to enter the XMS section of the TL at an exit gate. More than one vehicle may exit from the same platoon. Design of an exit strategy must follow the safety principle of Section 6.1 which requires the safe longitudinal vehicle following distance to be either very small (such as the intra-platoon separation of 2m on AL) or sufficiently large (such as inter-platoon separation on AL). It is also shown in [9] that high relative velocity collisions can occur if the preceding vehicle applies maximum braking and the trailing vehicle is following it with an intermediate spacing greater than 2 car lengths but less than the safe inter-platoon separation. This rules out the possibility of two vehicles from the same AL platoon exiting from the same gate as they won't have safe separation between them on TL. Another potential danger with allowing more than one vehicle from a platoon to exit through one gate is that the platoon on AL will be left with several gaps or larger ones violating the safety principle. Thus different vehicles from the same platoon exit using different gates.

It is natural to consider the following strategy to ensure safety on TL when its operating speed is lower than the operating speed on AL. Once on TL, the exiting vehicle decelerates to TL speed. The distance between successive exit gates[14] should be such that the vehicle that exits through first gate can create a large (safe) spacing between itself and the next vehicle exiting from the parent platoon at the next gate. This guarantees safety for vehicles exiting from the same platoon on AL. However, because of the speed differential between TL and AL, it is possible that a vehicle from the trailing AL platoon may catch up with the slow moving vehicle on TL and might collide with it after exiting at a later gate. Because of this, to attain collision-free operation, we adopt the following slightly more complicated strategy for exit.

Under this strategy, all vehicles that exit from same AL platoon form a platoon on TL. We call this a *post-platoon.* The forward-most exiting vehicle in AL platoon exits through the rear-most gate. The AL platoon closes the gap (by executing a "join" maneuver) between two gates. The exited vehicle longitudinally aligns itself (by decelerating first and then accelerating) such that the next vehicle can change lane at the intra-platoon separation of 2m behind it. The second vehicle exits as a follower of the post-platoon. The post-platoon leader receives the location of the next exiting vehicle from its parent AL platoon and then uses its lateral sensors to align itself with this vehicle. Under extremely rare conditions such

[14]The inter-gate distance should be sufficient to allow AL platoon to close up the gap created by the exiting vehicle.

as control system failures, this alignment is not properly achieved, in which case the second vehicle aborts its lane change onto TL and attempts the exit maneuver at a later gate. Road occupancy sensors are also needed to check for available space behind the post_platoon on TL. The leader of the platoon on AL has to keep track of the aborted exit maneuvers and assign new exit gates to these vehicles. The protocol used for this coordination is presented in Section 6.3.

The post-platoon always travels parallel to the parent platoon on AL thereby avoiding being hit by vehicles exiting from other AL platoons. At the end of XMS, the post-platoon is broken in to free agents. The free agents slow down and create larger inter-vehicle separation such that human drivers can take over the control of the vehicles. If for some reason, the driver is unable to take over control, a special turnout, called dormitory (not shown in the figure), is provided where the vehicle comes to rest. Figure 14 contains the flow chart description of the logical steps involved in exit under this strategy.

Entry/exit strategies under arrangement 2

The coordination and control strategies for entry/exit under Arrangement 2 are much simple than other arrangements. Similar to other arrangements, all vehicles are operating as free agents under automatic control after they pass check-in station on entrance ramp (See figure 3). In this arrangement, instead of stopping at the stop sign and waiting for a suitable gap on AL, the vehicles accelerate up to the average speed of automated lane. The average speed on AL can be obtained from the link layer controller on AHS. In this case, vehicles on TL will not form platoons. Once on the surface section of TL, the vehicles find themselves adjacent to an automated lane. At this point, they will execute 'lane change' maneuver according to [1, 7, 10] to change lane to AL. The automated vehicles on AL that want to exit, will similarly change lane (after becoming a free agent) onto TL. The TL section ends into an exit ramp. Vehicles on exit ramp will slow down and increase their separation (similar to 'break up' maneuver described earlier) so that human drivers can take over the control of the vehicle.

This shows that, we do not need any special hardware (such as road occupancy sensors, stop light, communication devices) as well as any special control laws for entry/exit under this Arrangement. At the beginning of the entrance ramp, the vehicles need to know the average speed on AL, which can be relayed from the link layer on AHS. Depending on the density of traffic on AL, conventional ramp metering can be used to control the flow of cars entering the transition lane.

4.2 Performance evaluation

When a vehicle (or pre-platoon) enters the AL from the TL, the AL platoon immediately behind the entering vehicle may have to slow down in order to maintain a safe distance. In turn, this may cause the platoon behind it to slow down as well. This slow down will propagate upstream on the AL in a "shock wave." The shock wave is finally arrested when it encounters an inter-platoon gap that is larger than the safe distance.

The slow down of AL platoons causes a degradation in performance that can be evaluated in two equivalent forms: the delay induced by the shock wave measured as platoon $\times$ distance[15], and the additional time measured as platoon $\times$ time (platoon-hours)[16]. The degradation depends on several factors:

- The strategy used to coordinate the entrance of vehicles from TL into AL with AL vehicles;
- The probability distribution of AL inter-platoon distances;
- The average speed and flow on AL.

Suppose that an entering vehicle needs a space of S m on the AL. (S depends on speed, size of entering vehicle or pre-platoon and the control law used by the vehicle.) Suppose that the inter-platoon distances are independent, Poisson distributed random variables with a mean value $D > \Delta$ where Δ is the safe distance. In section 6.6 we show that the average delay is

$$E\delta = \frac{S^2}{2(D-\Delta)} \text{ platoon-meters.}$$

If the nominal speed on AL is v m/s, this delay leads to an additional travel time of $E\delta/v$ platoon-sec.

If we assume an average trip length of L meters, an average platoon size of N vehicles, then the trip time is increased on average by a factor γ,

$$\gamma = \frac{N}{L} \times \frac{S^2}{2(D-\Delta)}.$$

Consider the following case: AL flow = 6,000 v/hour, $N = 10$, speed of 30 m/s, vehicle length of 5 m and intra-platoon distance of 2 m. (These assumptions give $D = 110$ m.) Suppose the safe distance is $\Delta = 60$. Suppose, lastly, an average trip length over the AL of 10 km. Then

$$\gamma = \frac{S^2}{10^5}.$$

If we assume $S = 100$ m, this gives $\gamma = 10$ %, i.e., the average trip time is increased by 10 %. The maximum flow is correspondingly reduced from 6,000 to 5,400 v/hour. If the speed can be increased from 30 to 33 m/s, the flow of 6,000 v/hour would be restored. The assumed deviation of $S = 100$ m seems rather high if entry into AL is coordinated in the manner that is suggested in this report. γ is also reduced if pre-platoons of more than one vehicle enter the AL.

5 Conclusions

An Automated Highway System (AHS) is the most advanced and highest risk element of the overall program on Intelligent Transportation Systems. Entry/exit is arguably the most

[15] This is the additional distance platoons would have travelled on the AL had they not been slowed down.
[16] This is obtained by dividing the previous measure by the average AL speed.

complex function that must be implemented in the AHS. Since it involves the transfer of control between driver and system and the transfer of the vehicle between AL and TL, both safety and capacity are critically affected by the way in which entry/exit is implemented.

This study has proposed a fairly detailed design and evaluation for implementing entry/exit. The major features of the design include:

- Coordination of the movement of a vehicles on TL and AL using communication protocols that have been verified;
- Lateral and longitudinal control laws that guide vehicle movement to and from the AL, based on a nonlinear system-level model of the vehicle. These laws have been subject to a limited validation based on simulation;
- Performance analysis of degradation of speed and flow on the AL due to disruption of the AL traffic caused by vehicle entry.

The second major product of this study is the design of four different types of entry/exit roadway configurations. In attempting to deploy an AL on an existing highway, the designer can select one of these configurations depending on the availability of space and structural cost. The parallel PATH study on roadway deployment has been focussed on a challenging segment of US Route 101 in Southern California. That study found the four configurations proposed here to provide a sufficiently flexible range of designs to meet the difficult requirements imposed by that segment of highway.

The objectives of this study are: to identify the issues that the implementation of AHS entry and exit must address, to arrive at firm or tentative conclusions about those issues, and to indicate the uncertainties that remain in the absence of firm conclusions. Issues in entry/exit are of direct concern to several other PSA study areas: check-in (b) and check-out (c), safety (n), roadway deployment (h) and impact on non-AHS roadway (i).

The following is a summary of our findings presented as a sequence of assertions, grouped under three headings: roadway configuration, strategies for entry and exit maneuvers, effect of entry and exit on AHS traffic. The assertions are supported to varying degrees by the argument in the report: some qualify to being called "conclusions," others are "issues" that need resolution, the rest are "concerns" that need to be addressed.

Roadway configuration

This concerns the different ways by which vehicles can enter the automated lane and the need for barriers.

- The transition lane (between automated and manual lane) may be divided into segments, one per entry and exit. There is no need for a continuous transition lane;
- Automated lane entry/exit via dedicated ramps simplifies coordination and control;
- Permitting manual vehicle to merge with automated vehicles is dangerous;

- Suitably designed barriers that allow emergency vehicles to go through can avoid the need for a continuous breakdown lane.

Strategies for entry/exit

Entry and exit of vehicles into and from the automated lane must be carefully choreographed, both because of safety and capacity. An importatnt product of our study is a control design that seems to achieve high levels of safety and capacity.

- Platooning leads to better capacity and safety than AACC (Advanced Adaptive Cruise Control), but it requires inter-vehicle communication for coordination and control;
- Vehicle leaving automated lane and entering transition lane must be coordinated with vehicles on transition lane, if any;
- Provision must be made for removing vehicle from transition lane if its driver is unable to resume control;
- Large spacing between vehicle entering automated lane and the vehicle in front of it can be hazardous if the latter decelerates rapidly;
- AACC vehicles on dedicated lane may lead to instability or inefficiency.

Effect of entry/exit on other traffic

Since automated lane have a much higher capacity than manual lanes, feeding and discharging such a lane can disrupt traffic. The disruption can be reduced by proper coordination. We have developed an analytical model that can be used to evaluate the extent of the disruption in terms of excess travel time and reduced flow.

- Merging of vehicle with mainstream traffic on automated lane must be coordinated to prevent disruptive "shock wave";
- If vehicles are allowed to enter automated lane without controlled stop, the flow on the automated lane can be seriously disrupted.

6 Appendices

6.1 Safety and capacity

Modes of operation on an AHS

An Automated Highway System (AHS) is designed to reduce congestion, partly by increasing the flow of vehicles on an automated lane (AL) by a factor of three or more. Spacings at which human drivers are too liable to run into the vehicle ahead can, it is suggested, be made safe by the use of automatic controls, not subject to human error. Thus congestion is relieved. Nevertheless, it is recognized that mechanical failures of both vehicles and control systems are possible, though hopefully rare. With a greatly increased lane flow, such failures can credibly lead on to accidents in which many people are hurt.

Shladover [3] pointed out that if a vehicle is following another which decelerates abruptly the resulting collision occurs at low relative speed if the vehicles are either well-separated or very close together. Large separations between all pairs is inconsistent with the desired capacity. He was led on to propose motion in closely-spaced platoons containing 3-20 vehicles. The different platoons are so far apart that the follower can stop without colliding if the leader suffers a mishap. The vehicles within a platoon use sensors and communication with the leader for their longitudinal control action. This concept lies at the basis of the AHS design adopted here.

Others, notably Autonomous Adaptive Cruise Control (AACC), Cooperative Adaptive Cruise Control (CACC) and Point Follower Control (PFC) use other configurations. In AACC, autonomous controls are used by each vehicle to keep a desired distance behind its predecessor, which we take to be constant for all vehicles at any one speed. The vehicles use only sensor readings with no communication. In CACC, the same result is achieved with communication between vehicles. AACC and CACC, unlike the other configurations, can operate in the presence of manually-controlled vehicles. In PFC a vehicle stays in a slot defined by the infrastructure, which moves along the AL. These slots 10–20 m long are moving along the highway. Each slot may or may not contain a vehicle.

Safety

Hitchcock [11] compares these competing strategies from the point of view of safety from mechanical failures. In the accidents he discusses, strings of vehicles respond to the initial incident by braking. Nevertheless collisions occur. One of the factors affecting the severity of injuries is the variability between vehicles. In any of the longitudinal control schemes, if vehicles were all identical there would be few or no collisions. In fact, however, the maximum deceleration that a vehicle can achieve depends on the condition of its brakes, and, in wet weather, on the condition of its tires. In well maintained vehicles these do vary, but not very much.

The only failures of longitudinal control which can generate accidents are ones in which a vehicle's acceleration changes abruptly, or will not change when this is necessary. It is argued that the fail-safe mode of the longitudinal control system will be to have a "brakes-on" failure. In this case, the brakes are fully applied by a vehicle without warning to the following vehicles. The following assumptions about the communication capabilities are used.

- In the platooned condition, and also in CACC, a message is passed back from vehicle to vehicle in the platoon. This is modeled by a communication delay of 0.01 s. There is then a delay before brakes are applied (0.09 s is used);
- With AACC, each vehicle can only detect the vehicle ahead of it. We take mechanical

delay before application of brake to be 0.09 s. This is optimistic with present day brake technology, but it can become possible in the future. Thus the generally negative conclusions we reach about AACC later are not due to pessimism here;.

- PFC systems are controlled from the infrastructure. We therefore consider a delay of 0.09 s.

Given these assumptions, a detailed study is conducted in [11] of effects of sudden braking by a vehicle on its followers. The distribution of vehicle masses and of friction coefficient values is taken to be random. The calculation is based on a "Monte Carlo" simulation, that is, values of the random parameters are given fixed values determined by an unbiased process for each run, and the runs are repeated many times, till the probabilities or expected rates of death and injury in a given situation can be determined statistically.

It is shown that at high capacities the performance of closely spaced platoons is superior to that of competing configurations in terms of casualty rate per failure. The PFC systems are second. Close-spaced platoons are certainly superior to high-density AACC-only configurations by at least an order of magnitude. One very desirable feature of platoons is the fact that all collisions occur below the threshold at which deaths can occur[17], and another is the lack of sensitivity to road surface conditions and system speed.

Whether or not all this is important depends on the frequency of the brakes-on failure. If the reliability of the longitudinal control system leads to the brakes-on failure at a rate of 1% per year, then the injury rate for the non-platooned systems due to this cause alone exceeds that due to all causes at present, while that for platooned systems is around 10% of the present rate. If the failure rate is reduced to 0.1% per year, the platooned system will still have a worth-while advantage, in reducing injuries to about 10% of the present rate. If the failure rate is reduced to 0.01% per year—a mean time between failures of about 106 hours operating time—the advantage becomes insignificant.

The position of AACC, mixed with ordinary manual traffic, is interesting. At low fractions of the total traffic, it gives rise to no great safety problems, but as the possibility rises that one AACC vehicle will follow another, the risk of casualties rises sharply, and by the time that there are five AACC vehicles for every manual one, it may come to be thought necessary to prescribe stringent conditions on the mean time between failures of the automatic braking system.

Thus, platooning strategy is the clear favorite from the safety point of view. Even allowing for the TL, which bears little through traffic, the capacity per unit width can be made high—twice or three times that for manual lanes. The system can thus be economic. If an AACC system has to be designed for such a high safety standard, the inter-vehicle distance will be so large that the main objective of increasing the capacity will be lost.

[17] From accident records and hospitalization data, 3 m/s is used as a threshold relative velocity for a collision before hospitalization is needed.

Capacity

Let us consider the effect of automation on capacity. In platooning environment, the vehicles will be following each other at a very small distance. These tightly packed platoons will be traveling at a large separation between them. Taking intra-platoon spacing as d, interplatoon spacing as D, vehicle length as s and a steady state speed of v m/s, gives a capacity of

$$C = v \times \frac{n}{ns + (n-1)d + D} \times 60 \text{ vehicles/lane/hr}$$

if traffic is organized in n car platoons. If we analyze this equation for $s = 5$ m and $v = 72$ km/hr, it can be seen that the capacity of 7200 veh/hr can be achieved, with $d = 2$ m, $D = 60$ m and platoon size of 20, which is almost four times the maximum capacity of manual traffic. Another advantage of platooning is that the capacity increases in proportion to the operating speed as can be seen from the above equation.[18] Furthermore it is shown in [8] that the capacity reduction due to lateral flow required for entry/exit is less than 10%.

Thus amongst the various competing solutions for AHS, we choose platooning to be the preferred configuration.

Segregation of automated and manual traffic

The casualty rates that are acceptable are not currently defined. But it is clear that AHS must appear to be less dangerous to car occupants than the manual traffic (on freeway) that it replaces. In fact such accidents as do occur are likely to make newsworthy photographs: many will involve many vehicles, and when, as will be true in most cases, the injury rate is low, the public is more likely to ascribe this to luck than to sound engineering. When fatal accidents do occur, they are likely to be multi-fatality ones. Thus an AHS will appear more dangerous than it is. We suggest here that safety criteria, if they are to be publicly, politically and legally acceptable will require that the injury rate due to any one kind of accident should be less than 10% of the present rate on freeway. Ultimately the decision about what is acceptable in such cases is for legislatures.

The requirement above that safety be increased by a considerable factor over the present situation implies that there be no manual traffic on the high-density AL. Otherwise human errors will occur at the same rate as at present, and produce accident rates which are likely to be significantly larger than at present, since speeds and densities will be increased on ALs. This means, incidentally, that full economic advantage may be taken of automation, and lane widths of ALs can be narrowed. For some designs of the TL and in fault conditions manual and automated traffic may co-exist on parts of the TL, but this is at low density and reduced speed. It has sometimes been suggested that, for example, platoon leaders might operate with manual control of interplatoon spacing. Under such conditions freedom from interplatoon collision would be lost in many fault conditions—each such event could be a multi-fatality accident.

[18]This is not strictly true because D should increase with v.

Dividers between lanes

Even though the manual and automated traffic are segregated, an AHS may well consist of automated lanes (ALs) with traffic in platoons and manual lanes on the same freeway. With such a configuration there are arguments for and against the provision of a physical barrier (called a divider) between the automated lanes and the rest. On the one hand, a divider is unattractive to drivers. It is likely to make them feel "fenced in" and could generate claustrophobic reactions. While changing lanes through a gate, drivers may become alarmed or fearful. ("Gates" are the gaps that have to be left in the divider to permit vehicles to enter or leave the AL.) Changing lanes between such gates could reduce capacity. The end of a divider would itself be an obstacle which a vehicle can strike, come to rest and be struck by other vehicles. Thus, it is argued, dividers create more casualties than they prevent.

On the other hand, Hitchcock [11] asserts that a divider is necessary to prevent the casualties which would otherwise occur in secondary accidents when a collision on the manual lanes intrudes on the ALs. With high-speed vehicles, such an occurrence would lead to multiple casualties. Further, the divider will not generate serious casualties. Its end need be only a foot or so high. If a car hits the divider's end while changing lane, the passenger compartment would not be penetrated, and deceleration would not be very great. Because a vehicle would join a platoon only by entering at the rear, the following platoon could stop without running into a vehicle stranded on the barrier. Such an accident would interrupt traffic on the AL, but would generate no serious casualties. The secondary accidents prevented by the divider, however, would generate serious casualties.

Hitchcock [11] analyzes the enumerated data about "relevant accidents" on a section of the Santa Monica freeway. These are accidents on the manual lanes as a result of which a vehicle is projected on to the leftmost lane, where the ALs would be. Hitchcock calculated the death rate in automated vehicles on an AL on this freeway due to secondary collisions after a relevant accident in the absence of a divider. With platooned operation the death rate would be around 0.4 times the present rate due to *all* causes. It is also shown that with other control modes, the effect is even worse. With gates between AL and ML, the death rate drops by a factor of 10 for platooning.

Since the death rate without AL/TL dividers is unacceptable, any system meeting safety criteria must have them. It is not immediately apparent, however, that barriers can be made safe. It is clearly possible for a barrier to be struck end-on by a vehicle which is changing lane through a gate. If the barrier is a Jersey beam, or the familiar corrugated-metal barriers seen on freeways, this is known to be extremely dangerous. The barrier must be designed in such a way that it will resist penetration by a vehicle striking its side, but will yield, giving a moderate deceleration when struck end-on. Another possibility applies between ALs, or at the entry-gate, where the barrier has only to contain vehicles to a narrow lane. Here a low barrier, which will pass under the vehicle and slow it by causing it to plow through sand may perhaps be acceptable. Refer to [11] for different possible designs of barriers.

6.2 Infrastructure arrangement

In this section, we present four different highway arrangements to arrange entry/exit from arterial streets (city/local streets) to AHS via either a transition lane or dedicated ramps.

Arrangement 1

Figure 2 is a schematic of Arrangement 1. It shows two inner lanes of a four-lane highway taken over by the AHS. Lane 1 is automated, lane 2 is devoted to the TL, lanes 3 and 4 are ML. Entry into the TL takes place from the "fast" ML. Similarly, at the end of exit maneuver, manually controlled vehicles enter the fast ML from the TL.

The advantage of this scheme is that it does not require construction of separate entrance/exit ramps. The disadvantage is that the entry/exit onto the AL is through the leftmost (fast) ML. Thus the congestion on AL will affect the traffic on MLs and vice versa. Note that about 2-3 km of transition lane is needed per entry/exit. Parts of TL can potentially be used for manual traffic between two entrances.[19] But in an urban area (mostly where AHS will be deployed), as the entrances and exits are close to each other, this will create lot of disturbance to manual traffic. Therefore, we assume that one lane of the original four lane highway is converted into transition lane over the entire length of highway. This lane does not contribute to the capacity of the highway. For this arrangement, increase in capacity is moderate: from 8,000 vehicles/hour for the existing manual highway to 10,000 vehicles/hour (6,000 vehicles/hour for the AL, 2,000 vehicles/hour for each ML and 0 for TL).[20]

subsubsection*Arrangement 2 This arrangement (Figure 3) also occupies two ML. The innermost lane, lane 1, is automated, with no entry or exit. Lane 2 is divided into segments at least 5 Km long. Each segment terminates at one end in an entrance ramp and at the other end in an exit ramp. The ramps are elevated structures that connect lane 2 to the arterial streets. We imagine that these widely separated ramps would be linked with entrances and exits from the MLs (not shown in the figure), although the latter would have additional entrances and exits. The AHS ramps constitute the TL. According to Section 4.1, arrangement 2 offers the simplest coordination and control strategies.

The advantage of this scheme is the provision of separate entry/exit from arterial traffic to AL and manual lanes. The congestion on AL does not directly affect the traffic on MLs and vice versa. This scheme does not need dedicated hardware (sensors, communication devices etc.) in the infrastructure for entry/exit maneuver as explained in Section 4.1. These advantages are obtained at the cost of construction of elevated TL. As the transition lane segments are at least 5 Km long, the TL can carry up to 2,000 vehicles/hour that can

[19] Another way to see this is to note that each entry/exit requires a segment of TL. There is no need for a continuous TL. Thus in Figure 2, the TL would consist of one segment for entry, and another segment for exit.

[20] This is a conservative estimate. As noted above, there is no need for a continuous TL. Moreover, the capacity calculation presented here do not take into account the relative widths of manual and automated lanes. As the automated lanes could be narrower than the manual lanes, conversion of a manual lane to automated lane can create some more space which might be utilized to increase capacity by adding another lane. Typically, converting a ML to an AL can free up to one fourth of the previous ML width.

exclusively travel on TL. Therefore, this arrangement results in a maximum capacity of 12,000 vehicles/hour; 6,000 vehicles/hour for the AL, 2,000 vehicles/hour for each ML and 2,000 vehicles/hour for the TL.[21]

Arrangement 3

The third arrangement considered is shown in Figure 4. Two manual lanes, 1 and 2, are converted into AL. An entrance ramp feeds directly into an AL. Vehicles from that AL exit directly into an exit ramp. The automated lanes themselves have to be elevated at the entry and exit ramps. This arrangement has greater capacity than Arrangement 2, as two automated lanes and two manual lanes result in the maximum capacity of 16,000 vehicles/hour. Similar to Arrangement 2, the AL and ML traffic do not affect each other. This arrangement results in highest capacity with additional construction cost comparable to arrangement 2. But, it also requires significantly more complex coordination and control than Arrangement 2. One of the drawbacks of this arrangement as drawn in figure 4 is that the entry and exit side of the TL are not connected thereby not providing any path for the vehicle that has aborted its entry maneuver. One needs to construct special turnouts for this purpose from the entrance ramp to the MLs or the arterial streets increasing construction cost and complexity. This also means that the entry maneuver should be executed at a very high precision increasing the communication and control complexity.

Arrangement 4

The schematic diagram of arrangement 4 is shown in Figure 5. This arrangement combines attractive features of arrangements 1 and 3. This requires a degree of coordination that is as simple as arrangement 1 and achieves a maximum capacity of 12,000 vehicles/hour, same as arrangement 2 but with a different proportion of manual to automatic traffic. In this case, the highway can carry 6,000 vehicles/hour of manual as well as automatic traffic. However, this arrangement will require complex construction because a two km-long section of the AL that lies between entrance and exit ramps must be elevated along with the TL that has to pass over 2 km of the left-most ML.

In this arrangement, we can convert either one or two MLs into automated lanes. The scheme of figure 5, where one lane is automated, is called arrangement 4a. Arrangement 4b (figure 6) will have two automated lanes and two manual lanes resulting in maximum capacity of 16,000 vehicles/hour. This increases construction cost even further as both the automated lanes should be elevated for the entire length of the TL.

6.3 Protocol design and verification

Recall Figure 9. It gives a block diagram of the coordination and control architecture, organized as a three-layer hierarchy. Coordination is shared by the roadside-based link

[21] All capacity calculations are based on the assumption that the distribution of trip origin/destination patterns, the location of entry and exits, and the non-AHS urban arterials are able to support the capacity flows on the AHS.

layer and the vehicle-based coordination layer. The design and verification of coordination layer protocols for entry and exit maneuver under arrangements 1, 3 and 4 are presented in this section. In this and the next section, we present a controller design which can implement the entry/exit strategies discussed in Section 4.1. The first step is to break up the strategies into two parts: a logical part consisting of a sequence of discrete steps and continuous time sensor-based feedback control laws that are used to implement each of these logical steps. This has many advantages, in particular, the logical steps break down the feedback control design problem into simple and manageable tasks, and it can be verified that the sequence of logical steps itself possesses certain desirable properties. The logical tasks are organized into the coordination layer and the feedback control laws are included in the regulation layer. We present the design of coordination layer for entry and exit maneuvers in this section. The regulation layer control laws are described in the next section.

The logical steps in the entry/exit maneuver are modeled by interacting finite state machines, similar to a communication protocol. Thus, in case of entry, we have finite state machines to capture the discrete decisions taken by the vehicle that is entering the AHS. The vehicle state transitions through discrete steps such as passing the check in, stopping at the stop sign, accelerating to catch up to the target, changing lanes, etc. To capture the dependence of some of these decisions on factors such as availability of the gap on AL, we also model all the relevant parts of the environment. Thus in our model, we will have finite state machines representing the state of the stop sign, road occupancy sensor, longitudinal sensors as well as target platoon leader (figure 15). In most cases these will be simple two state machines and will indicate, for example if a gap exists on the AL or not.

The protocols monitor the current state of the vehicle and the environment as well as the interactions between vehicles on TL and AL. Each state of the FSM has outputs associated with it. The state transitions of the finite state machine of the vehicle depend on its state and the outputs of other machines. Thus the design of the protocol also models communication among different "agents" such as the vehicle, stop light, road occupancy sensor etc, via the interacting FSMs. In each state, the FSM of the vehicle in turn, invokes a (precomputed) continuous time feedback control law. Finite state machines for the exit maneuver were also designed in a similar fashion.

The protocols so designed were verified automatically using COSPAN [12]. COSPAN is a verification tool that works by symbolically analyzing a given set of FSM to make sure that their performance satisfies certain requirements specified by the user. It should be noted that symbolic testing is different from simulation or execution of the system; it is an automated mathematical proof that the system fulfills the requirements.

The machines for the entering vehicles as well as the environment were translated to code in the Selection/Resolution (S/R) FSM model used by COSPAN. The transitions of the environment machines that determine what the vehicle will do next are "selected" by the verification algorithm to take on all possible values, thus recreating all the runs that the FSM may produce. If the design passes the specification, then the verification tool return "yes", otherwise it produces a counterexample, i.e., a trace of events that failed the requirement. The design is then changed so that the failed trace cannot occur in the new design. This procedure constitutes the first loop of design-verification-redesign of figure 1.

It was verified that the entry maneuver satisfies the following properties with respect to the system behavior:

- Every vehicle that requests entry into the AHS, eventually succeeds;
- No entering vehicle collides with vehicles on AL.

The first property is proved under a so-called "fairness" assumption: a gap will eventually appear on the AL. The second property is proved under the assumption that the regulation layer control laws are properly designed and work perfectly along with the sensors.

Similarly for the exit maneuver, it was verified that

- Every vehicle that requests exit from AHS, eventually succeeds;
- No exiting vehicle collides with vehicles on TL.

6.4 Feedback control laws

The design of the feedback control laws is based on the dynamic model of a vehicle which is described in the next section. Since we are considering only autos/light trucks on AHS, the lateral and longitudinal dynamics of the vehicle are assumed to be decoupled. We design the lateral and longitudinal control laws separately based on this decoupled vehicle model of the vehicle.

Longitudinal Dynamics

We use a simplified nonlinear, third order, ordinary differential equation model for the longitudinal control design:

$$\begin{aligned} \dddot{x}_i &= b_i(\dot{x}_i, \ddot{x}_i) + a_i(\dot{x}_i)u_i && (1) \\ a_i(\dot{x}_i) &= \frac{1}{m_i \tau_i(\dot{x}_i)} && (2) \\ b_i(\dot{x}_i, \ddot{x}_i) &= -\frac{2K_{di}}{m_i}\,\dot{x}_i\,\ddot{x}_i - \frac{1}{\tau_i(\dot{x}_i)}[\ddot{x}_i + \frac{K_{di}}{m_i}\dot{x}_i^2 + \frac{d_{mi}}{m_i}] && (3) \end{aligned}$$

where the subscript i indicates the i^{th} vehicle. x_i is the position of this vehicle with respect to a fixed roadside reference (therefore $\dot{x}_i, \ddot{x}_i$ are its velocity and acceleration, respectively), m_i is its mass, τ_i is the time constant of its engine, u_i is the engine input, K_{di} is the aerodynamic drag coefficient and d_{mi} is the mechanical drag.

Although vehicle powertrain models describing engine, transmission, tire forces and brake dynamics in more detail exist in the literature, we believe that the above model is adequate for control design. For the design of the longitudinal controller for the leader of a platoon the following simplifying assumptions were made about the state of the vehicle and the parameters of the model:

- The whole state (x_i, $\dot{x}_i$, $\ddot{x}_i$) can be measured directly, so that full state feedback is possible without the use of an observer;
- m_i, τ_i, K_{di}, d_{mi} are known. This is quite a strong assumption as these quantities are usually known only approximately and might change with time, even for the same car. However it allows us to linearize the model by state feedback as discussed in the next section (see [7]). An adaptive version of the controller may be designed at a later stage to relax this assumption.

The controller design was carried out in two stages, as outlined in Figure 16. In the first stage (inner loop), nonlinear feedback was used to make the intermediate closed loop system input-output (from v to y) linear. In the second stage (outer loop), controllers for the linear system were designed.

Linearizing control

For a particular class of nonlinear systems it is possible to find a state feedback control law such that the resulting closed loop system is linear from the input-output point of view. The conditions that characterize this class of systems can be found in the nonlinear systems literature (see [7] for references). The system (1)-(3), however, is simple enough to allow us to obtain the linearizing state feedback law by inspection, without having to go into the details of nonlinear control theory. The requisite control law is:

$$u = \frac{1}{a(\dot{x}_i)} \left[-b(\dot{x}_i, \ddot{x}_i) + \mathrm{v}\right]$$

The resulting linear system is in a controllable canonical form:

$$\frac{d}{dt}\begin{bmatrix} x_i \\ \dot{x}_i \\ \ddot{x}_i \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_i \\ \dot{x}_i \\ \ddot{x}_i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \mathrm{v} \tag{4}$$

The objective now is to choose a suitable v to achieve the desired performance. The control laws for the longitudinal motion of the cars on AL, namely cruise control and control laws for join, split and change lane maneuvers, are also developed by using this model. For details, refer to [7].

Lateral Dynamics

A detailed model describing lateral dynamics of a vehicle is obtained in [13]. We use a simplified version of that model used in [13] for designing the "lane following" control law and in [10] for designing the "lane change" control law.

The simplified model for lateral motion is given by:

$$\begin{aligned} \ddot{y} &= \frac{A_1}{V}\dot{y} - A_1\epsilon + \frac{A_2}{V}\dot{\epsilon} + B_1\delta - \frac{K_y}{m}(V_{wy} - V\epsilon + \dot{y})^2 \,\mathrm{sign}\,(V_{wy} - V\epsilon + \dot{y}) \\ \ddot{\epsilon} &= \frac{A_3}{V}\dot{y} - A_3\epsilon + \frac{A_4}{V}\dot{\epsilon} + B_2\delta \end{aligned}$$

where

$$
\begin{aligned}
A_1 &= \frac{-4C_s}{m},\ A_2 = \frac{-2C_s(l_1 - l_2)}{m},\ A_3 = \frac{-2C_s(l_1 - l_2)}{I_z}, \\
A_4 &= \frac{-2C_s(l_1^2 - l_2^2)}{I_z},\ B_1 = \frac{2C_s}{m},\ B_2 = \frac{2C_s l_1}{m}.
\end{aligned}
$$

The parameters are given by:

$$
\begin{aligned}
\delta &= \text{Steering wheel angle (Control Input)} \\
y, \epsilon &= \text{Lateral position and yaw angle of a vehicle} \\
V &= \text{Longitudinal speed of the vehicle} \\
V_{wy}, K_y &= \text{Lateral wind speed and lateral air drag coeff.} \\
C_s &= \text{Cornering stiffness} \\
m, I_z &= \text{Mass and moment of inertia about the yaw axis of the vehicle} \\
l_1, l_2 &= \text{Distances from center of gravity to front and rear axle}
\end{aligned}
$$

Entry and exit under arrangement 2 can be carried out by the control laws developed in [7, 10, 13].
We now present control laws used for entry/exit under Arrangements 1, 3 and 4.

Entrance onto AL

1. Stop sign regulation Law:
   This longitudinal control law is used on TL before the stop sign, along with the 'lane keep' lateral control law of [13]. In this section of the TL, all vehicles are operating as 'free agents' under automatic control. The goal of this controller is to 'safely' follow the preceding vehicle and eventually stop at the stop sign. Similar to the cruise control law of [7], we define safe following distance on TL to be:

   $$d_{safe} = \lambda_v\, \dot{x}_i + \lambda_p, \quad \text{where } \lambda_v = 1\text{s},\ \lambda_p = 2\text{m}.$$

   The free agents[22] will follow each other with a constant time separation of one second. Distance between two stopped vehicles will be 2 m. We have two distinct cases in this region.

   - If the vehicle ahead is closer than the stop sign, we use the following control law

     $$
     \begin{aligned}
     u = \dddot{x}_i &= k_1\ \ddot{x}_i + k_2\ (\dot{x}_i - \dot{x}_{i-1}) - k_3\ e_i &(5)\\
     e_i &= (x_{i-1} - x_i - L_{i-1}) - (\lambda_v\, \dot{x}_i + \lambda_p) &(6)
     \end{aligned}
     $$

     where e_i represents the error in maintaining safe following distance for vehicle i. L_{i-1} is the length of the vehicle $i-1$. We assume that all vehicles are 5 m long;

[22] A free agent is a single vehicle platoon.

- If the vehicle ahead is farther away than the stop sign (e.g., there is no vehicle ahead), we use the following control law:

$$u = \dddot{x}_i = k_1 \ \ddot{x}_i + k_2 \ \dot{x}_i - k_3 \ d_{stop} \tag{7}$$

  where d_{stop} is the relative distance between front bumper of vehicle i and the stop sign where d_{stop} is provided by longitudinal sensor.

In both cases, we use $k_1 = -2.1$, $k_2 = -1.47$, $k_3 = -0.343$ to place the closed loop poles at -0.7. The choice of control gains ensures that the acceleration and jerk bounds for passenger comfort are not violated.

2. Accelerate to Enter Law:
The objective is to accelerate the stopped pre-platoon up to the speed of AL target platoon, so that the two platoons are longitudinally aligned. First, the controller calculates a desired trajectory similar to the one shown in figure 17. We use the following bounds on acceleration ($|a_{max}| < 2m/s^2$) and jerk ($|\dot{a}_{max}| < 2m/s^3$) for trajectory calculation.[23] The distance between stop sign and gate depends on the maximum speed on AL, which we assume to be 30 m/sec. If the target platoon on AL is going at 30 m/sec, then the desired trajectory is calculated such that the target platoon and the preplatoon will be aligned exactly at the beginning of the gate. If the speed of target platoon on AL is slower, then the alignment takes place before the gate. The acceleration trajectory is parametrized by time and symmetric. The initial velocity of the target platoon v_0 and the distance between stop sign and gate result in a quadratic equation whose solution determines the time parameters specifying the desired trajectory.

Figure 17 contains a plot of the desired trajectory where the speed of target platoon on AL is 25 m/sec and the distance between stop sign and the entrance gate is 240 m.

This trajectory calculation assumes that while the preplatoon is accelerating, the speed of AL target platoon is constant. This assumption may not hold as the target platoon has to respond to the state of traffic in front of it on AL. Therefore, we use the following feedback law to guarantee asymptotic trajectory tracking:

$$\begin{aligned}
u &= \dddot{x}_d + k_1(\ddot{x}_i - \ddot{x}_d) + k_2(\dot{x}_i - \dot{x}_d + v_0 - \dot{x}_{tgt}) + k_3(x_i - x_d + x_{tgt} - xd_{tgt}) \quad (8)\\
x_{tgt} &= \text{Distance of the target platoon from gate}\\
xd_{tgt} &= \text{Desired } x_{tgt}\\
&= v_0 \ t_{accel}, \text{ Using the constant speed assumption about target platoon}\\
t_{accel} &= \text{Time elapsed since the beginning of acceleration.}
\end{aligned}$$

In this equation, x_d denotes the desired trajectory that is calculated at the beginning of the maneuver. The values of the gains ($k_1 = -3, k_2 = -3, k_3 = -1$) are chosen so that the system is stable (closed loop poles at -1) and the resulting acceleration and jerk are within bounds. This longitudinal control law along with "lane keep" lateral

[23]These bounds guarantee passenger comfort.

control law [13] is used on TL by the accelerating preplatoon leader. The followers of the preplatoon use "follower" control law of [14, 15].

Ideally, at the end of the desired trajectory, the two platoons are aligned (rear bumper of the last vehicle of target platoon is 2 m in front of front bumper of the preplatoon) and they are traveling at the same speed. However, it is possible that the preplatoon reaches the target platoon, before it reaches the gate. In this case, it has to keep following the target platoon until it reaches the entry gate and gets a command to change lane. The following control law is used to track the speed of target platoon:

$$u = k_1\ddot{x}_i + k_2(\dot{x}_i - \dot{x}_{tgt}) + k_3\,(e_{lat} + 2) \tag{9}$$

$$e_{lat} = \text{Distance from last vehicle of target platoon to first vehicle of preplatoon,} \tag{10}$$

The lateral sensor of the first vehicle of preplatoon can provide the value of e_{lat}.

The feedback law of equation (9) needs information about speed and relative position of target platoon from the gate. The lateral sensors on-board the vehicle cannot be used as the two platoons can be as far as 240 m at the beginning of the maneuver. We assume that the target platoon leader uses its radio transmitter to send its velocity and distance information to the preplatoon leader, at regular intervals.

3. Lane Change onto AL:
   We use control law presented in [10] to execute the lane change maneuver. The design of [10] is similar to the design of "accelerate to enter" control law presented above. In particular, a desired trajectory for the lateral position of the car is calculated and then feedback is used to asymptotically track this trajectory. The desired trajectory in this case is sinusoidal. The following bounds on lateral acceleration and jerk are imposed in calculating the trajectory: $a_{max} = 0.05m/s^2$ and $j_{max} = 0.1m/s^3$.

   In this case we want the entire preplatoon to change lane onto AL. We use the control law of [10] individually for each vehicle of the preplatoon to get the desired result. Note that the followers of the preplatoon cannot start executing the lane change control law until they have reached the gate.

   The "accelerate to enter" control law is used for longitudinal dynamics for the preplatoon leader during this time.

4. Close Up on AL:
   The goal of this control law is to close up the gap in front of the vehicle to 1 m while following the speed of the platoon ahead. By now both vehicles are in the same lane. We use the control law of equation (5) with $\lambda_p = 2m$ and $\lambda_v = 0$.

5. Lane Following and Longitudinal Vehicle Following:
   The lateral control law for lane following developed in [13] is used by every vehicle of the preplatoon whenever it is not changing lane onto AL. Similarly all the followers in the preplatoon use the longitudinal control law of [14] to follow the preceding vehicle at a fixed intra-platoon spacing of 2 m. These control laws have already been developed for platooning operation on AHS and will not be discussed any further.

Exit from AL

1. Lane Change onto TL:
   We use the control law of [10] to execute a lane change of a vehicle from AL onto TL. As only one vehicle changes lane through a gate at a given time, we can use the control law of [10] without any modifications.

2. Close Up on AL:
   This is the same control law as in the entry maneuver discussed above.

3. Catch Up on TL:

   This control law is used by the leader of the post-platoon on TL, when it has to join with another vehicle exiting from its parent platoon on AL. The objective is to longitudinally align with the vehicle, which is going to exit at the next gate. The goal is to start with a zero velocity mismatch and a distance mismatch of d_0 and end the maneuver with a zero velocity mismatch and 2 m gap between the exiting vehicle and the end of the post-platoon. The strategy is similar to the one used for 'accelerate to enter'. Given the value of d_0, a desired trajectory is generated based on the assumption that the parent platoon in AL travels at constant velocity. Then a feedback controller (similar to the one in equation (8)) is used to asymptotically track this trajectory. Figure 18 shows the desired trajectory, when the platoons are traveling at 25 m/s and the post-platoon has to catch up with a vehicle that is three vehicles behind it, resulting in $d_0 = 18$ m. Note that while calculating the distance d_0, one has to take into account the fact that the parent platoon is undergoing a "close up" maneuver at the same time.

4. Cruise Control law on TL:
   This control law is the default for the leader of the post-platoon. The aim of this controller is to follow the preceding vehicle with a safe inter-platoon separation. We use the cruise control law of [7] for this purpose. As the platoon leaders on AL are also following the same control law, the post-platoons on TL always remains longitudinally aligned with part of the parent platoon on AL, always remaining in its "shadow."

5. Platoon Break Up:
   At the end of the last gate of XMS, the transition lane contains post-platoons of automated vehicles that have exited from AL. The next step is to hand over the control to the human drivers. But humans are unable to drive in platoons. Therefore, the aim of this control law is to convert every vehicle of the post-platoon into a free agent with an interplatoon gap suitable for human drivers to take over. (We use 2 seconds as a suitable inter-platoon gap).

   We make use of the lead control of [7]. Recall that the lead controller of [7] can be used for "split" maneuver as well (although it would take much longer than the "split" control law used in [7]). This maneuver is initiated for all vehicles of the post-platoon at the same time. This causes all vehicles in the post-platoon to follow the lead control of [7] with $\lambda_p = 0$ m and $\lambda_v = 2$ s. The followers of the post-platoon find themselves 2 m behind the vehicle in front but traveling at the same speed. The controller decelerates the vehicle to slightly lower velocity than the vehicle in front and holds it constant until the desired separation is achieved. It takes about 30 seconds to reach a separation of 50m at 25 m/s. This requires a "break up section" of at least 900m at the end of TL. Figure 19 shows simulation plot of a three vehicle post_platoon breaking up in 30 seconds. The two followers slow down to 23 m/sec and 21.5 m/sec respectively in order to create the required gap.

6.5 Simulations

The modeling of the entry-exit maneuvers was implemented in the *SmartPath* simulation environment.

SmartPath is a highway system simulator. It provides a framework for simulation and evaluation of Intelligent Transportation System (ITS) alternatives. *SmartPath* can simulate automated, manual, or mixed mode traffic; it also accommodates different control, communication, and computing architectures.

SmartPath is a micro-simulator, i.e., the functional elements and the behavior of each vehicle and highway component with respect to normal and degraded mode of operations are individually modeled.

SmartPath consists of two separate modules: simulation and animation. The *SmartPath* animator is a tool to view and examine the simulated data of the AHS in the most natural way. The effect is akin to what might be seen from a traffic helicopter moving over the AHS. The user can control the motion of the helicopter, rewind the animation, and adjust its speed; the motion of the helicopter can be restricted to the highway or forced to follow a specific car.

The simulation data provides information about the position, speed, and maneuvers of each vehicle in the AHS at every unit of simulation time. With the animation interface, the user can select a vehicle and view the interaction between the vehicle and its neighboring vehicles.

In *SmartPath* a vehicle can have different behaviors depending on the type of lane on which it is traveling. For example, when a vehicle is in a manual lane, it has a manual behavior, and as soon as it enters a transition lane or an automated lane, it switches from the manual behavior to the transition or automated behavior, respectively. For a complete report on *SmartPath* see [16].

To simulate the entry and exit maneuvers, we modeled the "check-in" station, stop-light and its related sensors in the automated lane, and gates and their sensors individually. The simulation scenario we developed is as follows:

A vehicle (we call it our-vehicle) enters the highway system from an entrance. It is initialized as an automated vehicle with the manual behavior, since it is in an entrance lane (which leads to the TL). Its on-board computer, then, transmits its destination to the link layer control of that section, which inquires about a routing from the network layer controller. The network layer controller provides a route. (The network layer will route our-vehicle through the AL because of its shorter travel times.) The link layer controller of the section, in turn, broadcasts its recommendations (Turn-Right, Turn-Left, Stay-in-own-lane) for every possible destinations to the vehicles traveling on that section. Our-vehicle follows the recommendations until it enters TL, which causes the switch from manual to the transition behavior.

The transition behavior is modeled after the protocol described in section 6.3: our-vehicle first waits until it gets a message from the check-in station, it then activates its stop-sign regulation law, and so on.

After the completion of the maneuver, the vehicle again will switch from transition lane to the automated behavior, which is completely described in [1].

Figure 20 shows the first stage of entry maneuver. The light has been turned green, and a car has received an acknowledgement to its entry-request and has formed the pre-platoon.

Figure 21 shows a frame of the animation while a platoon of three cars is entering the automated lane.

The simulation of exit maneuver follows the exit protocol described in Section 6.3. Figure 22 shows a frame of an animation when a vehicle is in the process of changing lane through a gate. At the end of the exit maneuver, the vehicle is in the transition lane and enters the manual lanes as soon as it sees no barriers and it is safe to change lane.

6.6 Performance analysis

When a vehicle (or pre-platoon) from the TL enters the AL, the AL platoon immediately behind the entering vehicle may have to slow down in order to create a safe distance between itself and the entering vehicle. This may force the platoon behind it to slow down also, and so on, creating a "shock wave" that travels upstream on the AL. The shock wave will be arrested when it encounters an inter-platoon gap that exceeds the safe distance.

We present an analytical stochastic model to calculate how far the shock wave will travel, the resulting decrease in the average AL speed, and the capacity loss due to the decreased speed.

Model

Suppose that inter-platoon distances are iid (independent, identically distributed) random variables, denoted d. Let Δ be the safe distance. Assume that $d \geq \Delta$, with probability 1, and assume that $x := d - \Delta$ is an exponentially distributed random variable with mean μ^{-1}, i.e., x has the probability density

$$p(x) = \mu e^{-\mu x}, \ x \geq 0.$$

For convenience also denote $p_1(x) \equiv p(x)$.

Now consider the sum of n inter-platoon distances, $\sum_1^n d_i$, all the d_i being iid as mentioned above. Then, with $x_i := d_i - \Delta$,

$$\begin{aligned}
p(\sum_1^n d_i - n\Delta = x) &= p(\sum_1^n x_i = x) \\
&= p_n(x) = \mu^n \frac{x^{n-1}}{(n-1)!} e^{-\mu x}, \; x \geq 0. \qquad (11)
\end{aligned}$$

Now suppose we are given a fixed number $S > 0$. (S will be the "gap" on the AL needed by the entering vehicle.) Define the non-negative random integer M by

$$M = m \Leftrightarrow \{\sum_1^m x_i \leq S < \sum_1^{m+1} x_i\}.$$

So the probability that $M = m$ is given by $P_S(m) = \text{Prob}\{\sum_1^m x_i \leq S < \sum_1^{m+1} x_i\}$. One can calculate the probabilities $P_S(m)$ from the p_n by observing that

$$P_S(m) = \int_0^S p_1(x_1 \geq S - y) \times p_m(y) dy.$$

A little calculus then gives the following formula:

$$P_S(m) = e^{-\mu S} \frac{(\mu S)^m}{m!} = P_S(m-1) \times \frac{\mu S}{m}, \; m = 0, 1, ... \qquad (12)$$

Equation (12) is the formula for a Poisson distribution. Thus the number M of platoons disturbed by the deviation S, has a Poisson distribution. (M is the number of platoons that are affected by the shock wave.) In particular the mean number of disturbed (or delayed) platoons is $EM = \mu S$. If we write the mean inter-platoon distance as $D := Ed$, and recall the definition $\mu^{-1} = E(d - \Delta)$, we conclude that

$$\text{Average number of delayed platoons} = EM = \frac{S}{D - \Delta}. \qquad (13)$$

As expected, as $D \to \Delta$, $EM \to \infty$, i.e., as congestion (AL flow)increases, the shock wave from an individual maneuver passes through an increasing number of platoons, on average. Another interesting point in (13) is that the average number of delayed platoons grows *linearly* with the size of the initial maximum deviation, S.

Calculating delay

One can now calculate the total delay. This is the extra travel time induced by the shock wave. Suppose that platoon #0 (the entering vehicle) creates a maximum deviation of size S. Then platoons #1, ..., #M will be delayed too, where M is the random variable above. Platoon #i is delayed by the distance

$$S - \sum_{j=1}^i (d_j - \Delta) = S - \sum_{j=1}^i x_j, \; i = 1, ..., M.$$

So the total delay (measured in platoon $\times$ distance, and converted into time by dividing by the average speed) is the sum of these M numbers,

$$\text{Delay} := \delta = \sum_{i=1}^{M}[S - \sum_{j=1}^{i} x_j] = MS - \sum_{i=1}^{M}\sum_{j=1}^{i} x_j \tag{14}$$

We want to calculate $E\delta$, the average total delay.

Introduce the partial sums $y_0 = 0$, $y_i = \sum_{j=1}^{i} x_j$ for $i > 0$, and write $\delta = MS - \sum_1^M y_i$. Then

$$E\delta = \sum_{m=0}^{\infty}[mS - \sum_{i=1}^{m} E\{y_i|M = m\}]P_S(m). \tag{15}$$

Since in (1) we have an expression for $P_S(m)$, it remains only to calculate $E\{y_i|M = m\}$.

Fact We have

$$\begin{aligned} p(y_1, \dots, y_{m+1}) &= p(y_1, \dots, y_m|y_{m+1})p(y_{m+1}) \\ &= \frac{m!}{(y_{m+1})^m} p_{m+1}(y_{m+1}) 1(y_1 < y_2 < \cdots < y_{m+1}) \\ &= \mu^{m+1} e^{-\mu y_{m+1}} 1(y_1 < y_2 < \cdots < y_{m+1}), \end{aligned} \tag{16}$$

where $p_{m+1}(y)$ is given by (11) and $1(\cdot)$ is the indicator function.

Proof The first equation in (16) is Bayes rule. Since $y_{m+1} = \sum_1^{m+1} x_i$, $p(y_{m+1} = y) = p_{m+1}(y)$ from (11). Second, since $y_i - y_{i-1} = x_i$ are iid and exponential, therefore, given y_{m+1}, the y_i are uniformly and independently distributed over $[0, y_{m+1}]$, constrained to $y_1 < y_2 < \cdots < y_{m+1}$. This gives the second relation. Then the third relation follows upon substitution for p_{m+1} from (11). □

We now calculate $E\{y_i|M = m\}$.

$$\begin{aligned} E\{y_i|M = m\} &= E\{y_i|y_m < S \le y_{m+1}\} \\ &= \frac{E[y_i 1(y_m < S \le y_{m+1})]}{E[1(y_m < S \le y_{m+1})]} = \frac{N}{D}, \text{ say,} \end{aligned}$$

where

$$\begin{aligned} N &= \int_0^\infty \cdots \int_0^\infty y_i 1(y_m < S \le y_{m+1}) p(y_1, \dots, y_{m+1}) dy_1 \cdots dy_{m+1} \\ D &= \int_0^\infty \cdots \int_0^\infty 1(y_m < S \le y_{m+1}) p(y_1, \dots, y_{m+1}) dy_1 \cdots dy_{m+1} \\ &= \int_0^{y_2} dy_1 \int_0^{y_3} dy_2 \cdots \int_0^{y_m} dy_{m-1} \int_0^S dy_m \int_S^\infty p(y_1, \dots, y_{m+1}) dy_{m+1} \\ &= \int_S^\infty \int_0^S \frac{y_m^{m-1}}{(m-1)!} dy_m \times \mu^{m+1} e^{-\mu y_{m+1}} dy_{m+1} \\ &= \frac{S^m \mu^m}{m!} e^{-\mu S}. \end{aligned}$$

A slightly more laborious calculation gives

$$N = \frac{iS}{m+1}\frac{S^m\mu^m}{m!}e^{-\mu S},$$

and so

$$E\{y_i|M = m\} = \frac{N}{D} = \frac{iS}{m+1}.$$

Substituting this into (15) gives

$$\begin{aligned} E\delta &= \sum_{m=0}^{\infty}[mS - \sum_{i=1}^{m}\frac{iS}{m+1}]P_S(m) \\ &= \frac{S}{2}\sum_{m=0}^{\infty} mP_S(m) \\ &= \frac{S^2}{2(D-\Delta)} \text{ platoon-meters,} \end{aligned}$$

where we used (13) in the last relation.

Proposition A deviation of S meters on average disturbs $S/(D-\Delta)$ platoons and they suffer a total delay of $S^2/2(D-\Delta)$.

Note We can compare this delay with the case when inter-platoon distance is exactly D. (This requires perfect synchronization of AL platoon formation to achieve equal inter-platoon distance.) In that case platoon #1 is delayed distance $S-(D-\Delta)$, #2 is delayed $S-2(D-\Delta)$, ... , #M by $S-M(D-\Delta)$ and $M = S/(D-\Delta)$. The sum of these delays is $S^2/2(D-\Delta) - S/2$. Thus the random distribution of the inter-platoon distances causes an extra delay of $S/2$, on average.

Calculating capacity

Suppose a platoon creates a deviation of size S meters when it travels l meters. So per l platoon-meters of travel, a platoon imposes an additional delay of $S^2/2(D-\Delta)$ platoon-meters. So congestion cost as fraction of useful travel is

$$\gamma = \frac{1}{l} \times \frac{S^2}{2(D-\Delta)}.$$

Suppose the average trip length is L meters and there are N vehicles per platoon. Assume each vehicle imposes one deviation per trip. (There would be more deviations if there are several automated lanes.) Then $l = L/N$, so

$$\gamma = \frac{N}{L} \times \frac{S^2}{2(D-\Delta)}.$$

We calculate γ for a simple case. Assume: flow = 6,000 v/hour, $N = 10$, speed of 30 m/sec, vehicle length of 5 m and intra-platoon distance of 2 m. So there is a flow of one platoon every 6 sec. and the average inter-platoon distance is $D = 6 \times 30 - 10 \times (5+2) = 110$ m. Suppose $\Delta = 60$ m, so $D - \Delta = 50$ m. Take $L = 10{,}000$ m or 10 km, so that

$$\gamma = \frac{S^2}{10^5}.$$

If $S = 100$ m, which seems high, this gives $\gamma = 0.1$. That is, the average speed is reduced from 30 m/s to 27 m/s, because of slowdowns from disturbances created by entering vehicles. Note that the maximum flow (at the operating speed of 30 m/s) is correspondingly reduced by 10 %, i.e., from 6,000 to 5,400 v/hour. Of course, if the operating speed can be increased by 10 %, the flow of 6,000 v/hour can be maintained.

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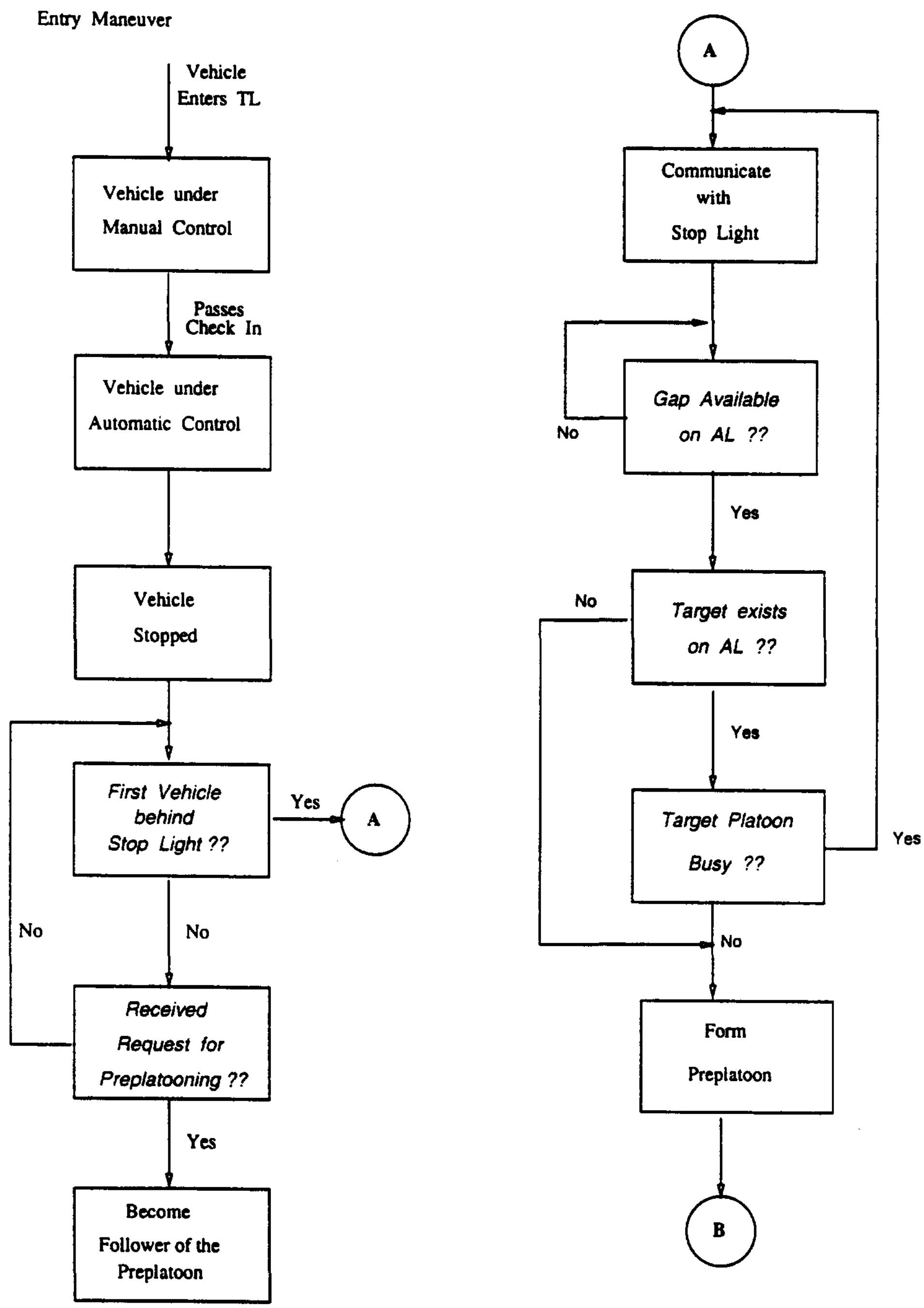

Figure 12: Flowchart for entry manever

Entry Maneuver (Cont...)

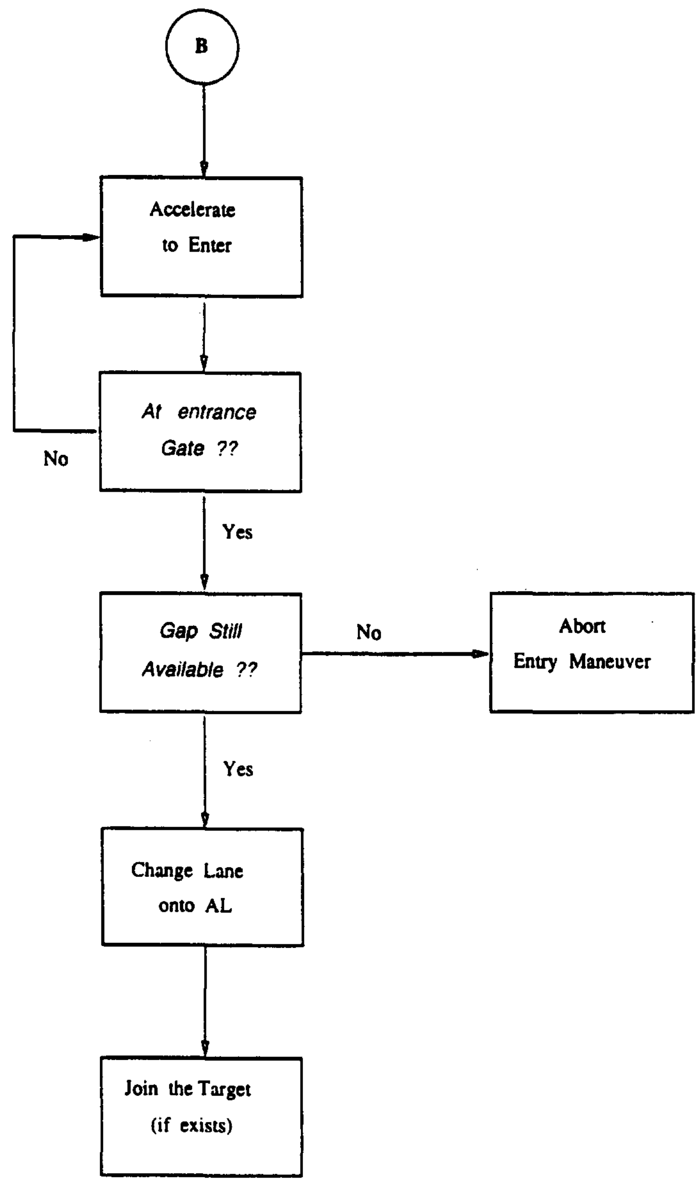

Figure 13: Flowchart for entry manever: continued

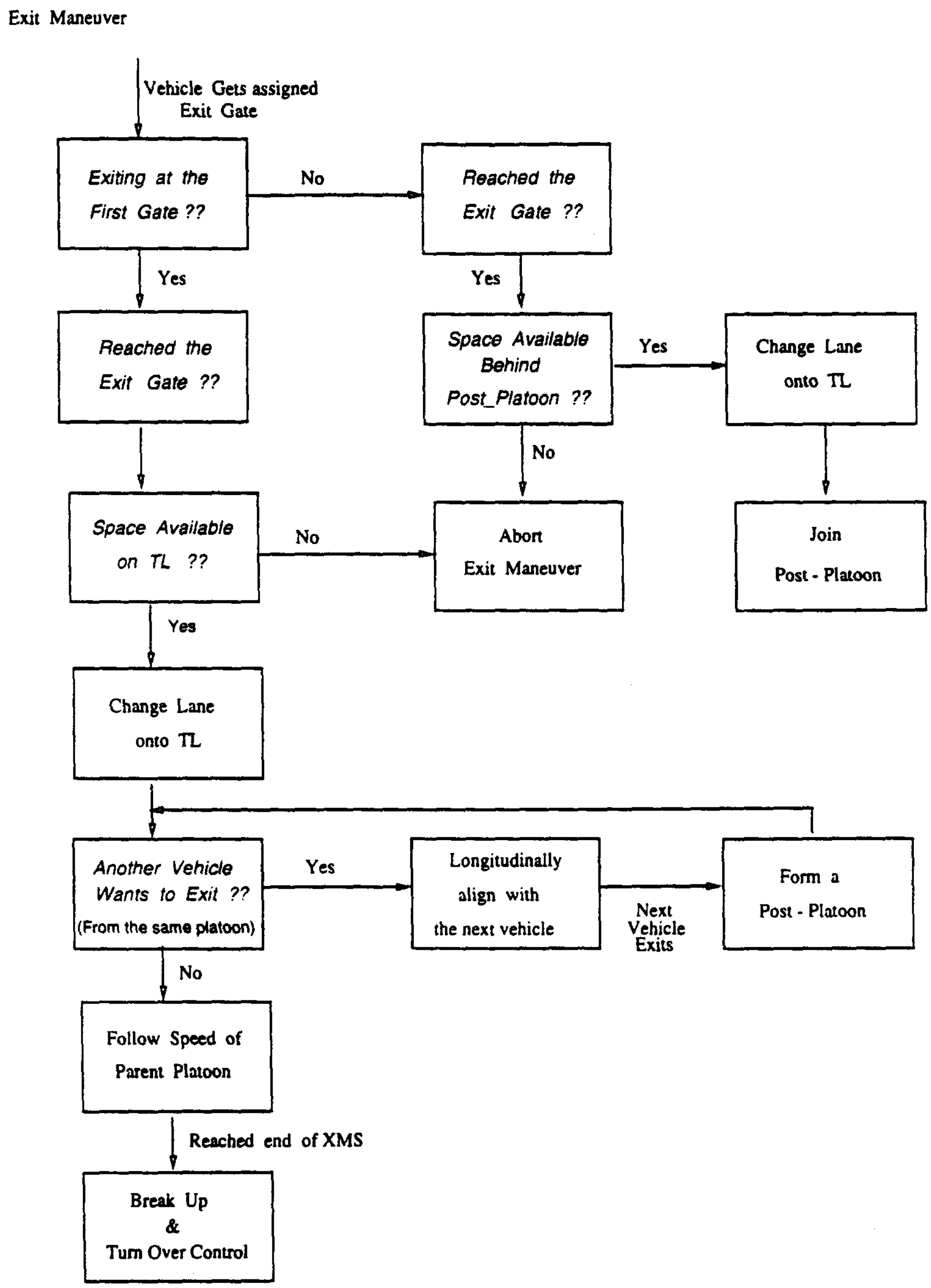

Figure 14: Flowchart for exit manever

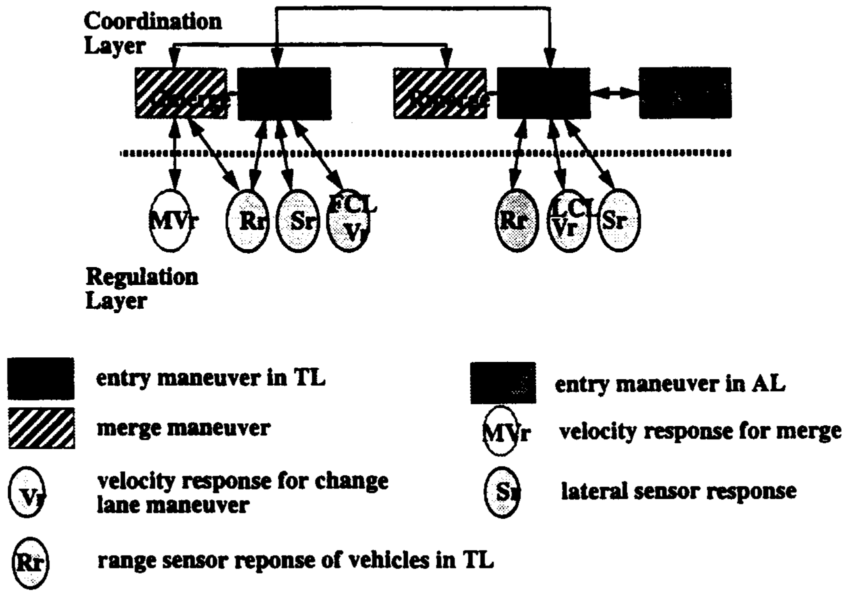

Figure 15: Model for protocol verification

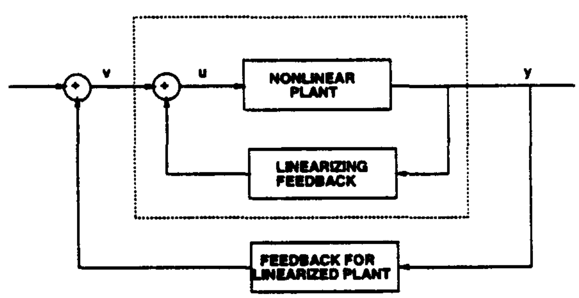

Figure 16: Two stage feedback.

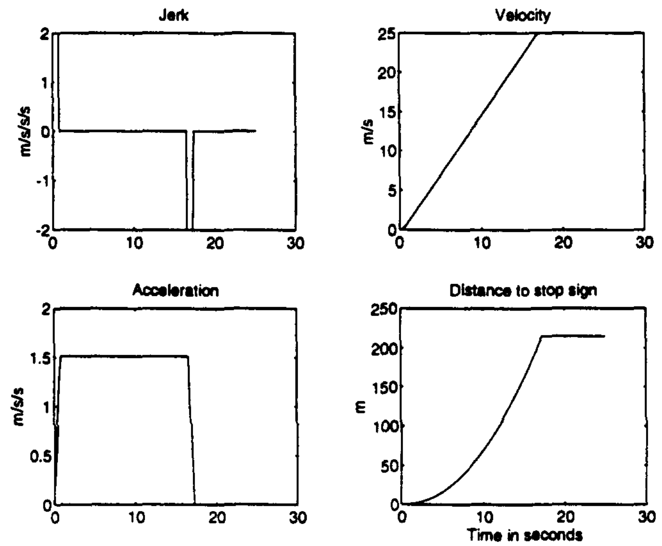

Figure 17: Desired trajectory for accelerate-to-enter

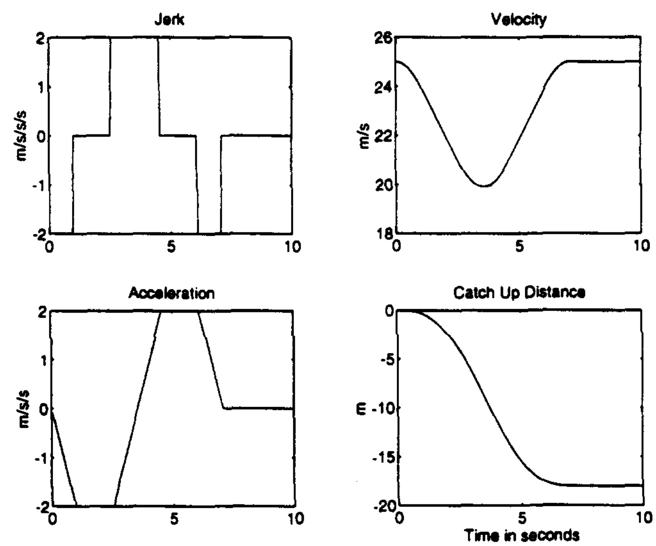

Figure 18: Desired trajectory for catch up

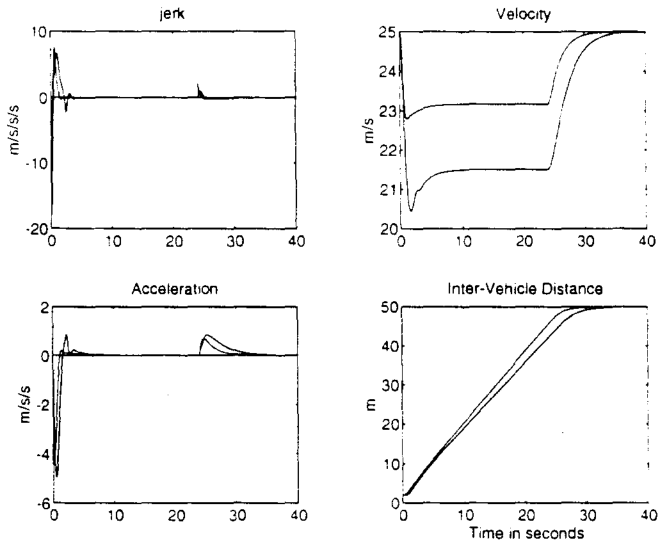

Figure 19: Break up of a three vehicle post-platoon

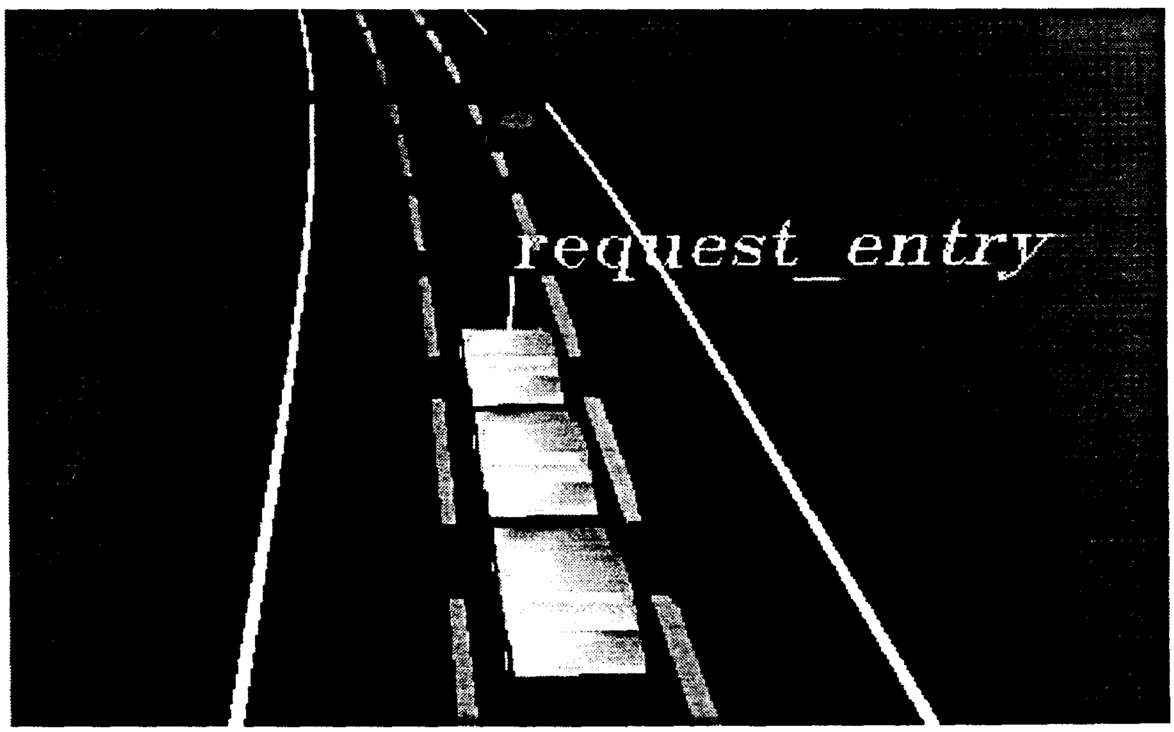

Figure 20: Simulation of entry maneuver—at the stop light

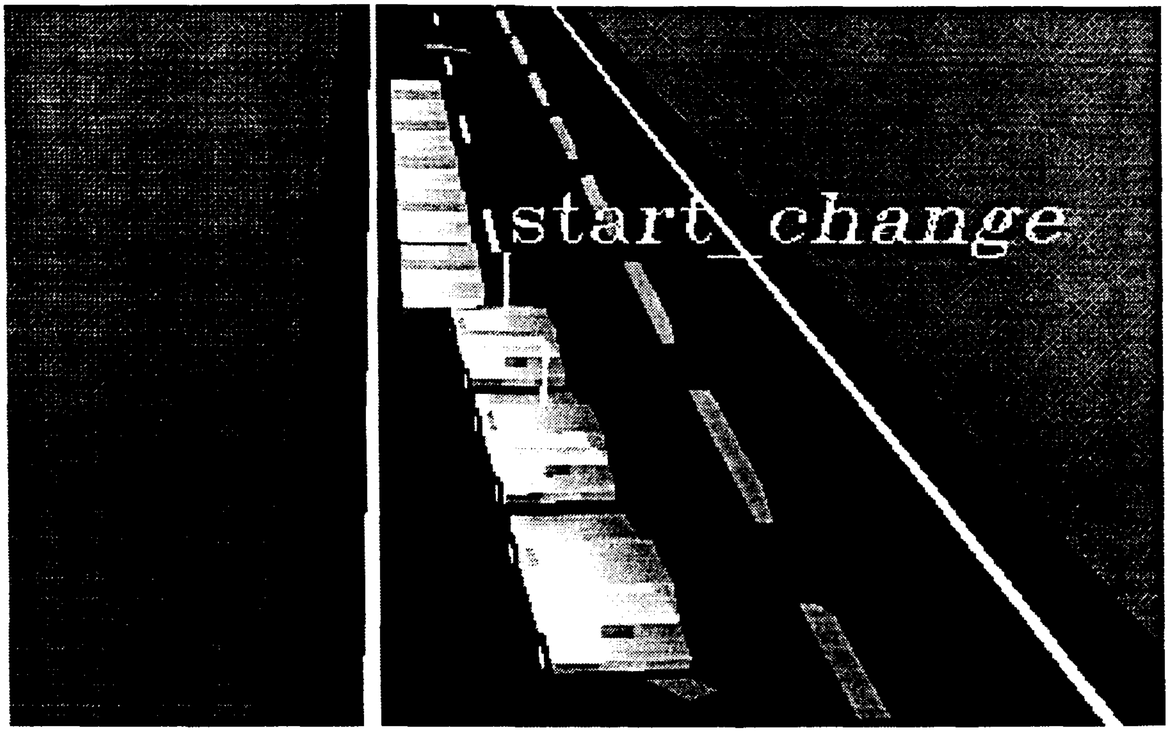

Figure 21: Simulation of entry maneuver—change lane section

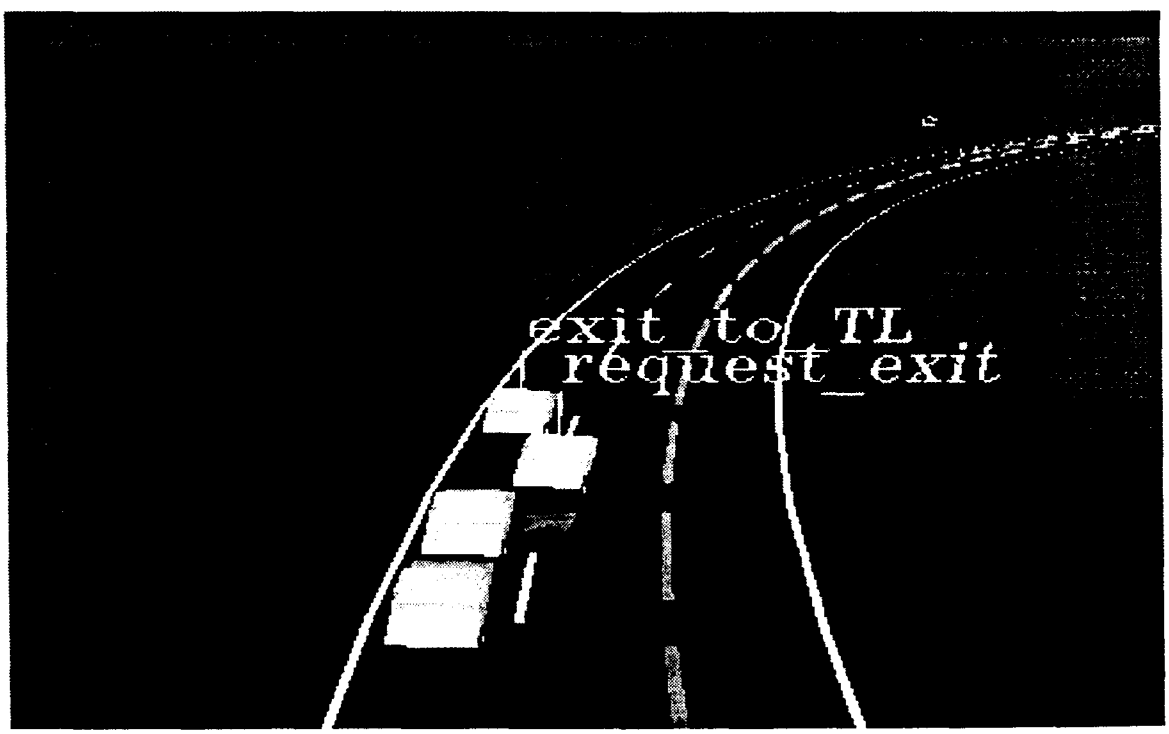

Figure 22: Simulation of exit maneuver—change lane section