Coordinating vehicles in an automated highway

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Abstract. The paper summarizes the design of an Automated Highway System (AHS). The design objective is to increase highway capacity. We assume the availability of certain elements: vehicles with appropriate sensors and actuators, highways with appropriate sensors, and the ability to communicate between vehicles and between a vehicle and the highway. The design specifies how these elements are configured and controlled, and how the 'intelligence' that carries out the control tasks is distributed among the vehicles and the highway infrastructure. One control task—the coordination of the movement of vehicles—is discussed in detail. The paper also presents a simulation suggesting that it is possible to increase highway capacity through automation.

1 Introduction

The paper summarizes design features of an Automated Highway System (AHS). The design objective is to increase highway capacity. We assume the availability of certain elements: vehicles with appropriate sensors and actuators, highways with appropriate sensors, and the ability to communicate between vehicles and between a vehicle and the highway. The design specifies how these elements are configured and controlled, and how the 'intelligence' that carries out the control tasks is distributed among the vehicles and the highway infrastructure.

The paper also presents a simulation of the AHS using SmartPath. SmartPath is a microsimulation: the system elements and the control policies are each individually modeled. Several elements and policies are parametrically specified. The user can change these parameters to understand how the AHS would perform in terms of highway capacity, traffic flow, and other performance measures of interest to transportation system planners and drivers.

The AHS design and work that implements aspects of the design are described in several PATH reports.[2] The overall design is summarized in §2. §3 explains how the task of coordinating the movement of several vehicles is carried out. §4 presents a simulation suggesting that it is possible to increase highway capacity through automation.

We now describe how you as a driver may experience the AHS. See Figure 1. To drive your car over a three-lane AHS, you enter from an on-ramp and safely join the traffic in lane 3—the rightmost lane. You announce your destination by voice or keyboard entry. Your vehicle's on-board computer communicates your destination

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[2]See [1, 2, 3, 4] and the references therein.

to the roadside computer which assigns the lane number (1 or 2) that you should occupy for most of your trip. Suppose it is lane 1. The roadside computer also tells your vehicle at what point along lane 1 it should start changing lanes so that it can exit. We summarize these instructions by saying that the AHS assigns a *path* to your vehicle.

You then instruct your car's computer to take control. The computer will try to maintain a trajectory close to the assigned path. It begins by steering your car to change to lane 2, and then to lane 1. It will then keep your car in lane 1 until you are close to your exit. It then changes lane twice and re-enters lane 3. The computer then alerts you to take over control, and you then drive your car to the off-ramp. We refer to lane 3 as the *transition lane*, since cars on that lane may be driven manually or under automatic control; lanes 1 and 2 are *automated lanes*, since cars on these lanes are automatically controlled.

A major objective of the AHS is to increase highway capacity. This objective is achieved in part by organizing in platoons the traffic within each automated lane. A *platoon* is one or more vehicles traveling together as a group with relatively small spacing. Inter-platoon spacing is large.[3] For example, with an average platoon size of 15, intra-platoon distance of 2 m, inter-platoon distance of 60 m, vehicle length of 5 m, and speed of 72 km/h, the maximum flow through an automated lane is over 6,000 vehicles/hour—triple the flow achieved today.

In summary, the AHS tasks are to assign a lane to each vehicle, to steer it to its assigned lane, and to organize traffic in platoons in the automated lanes.

2 AHS control system architecture

The AHS tasks are carried out by the three-layer controller hierarchy of Figure 2. The implementation of the control system requires a communication system that supports the exchange of information between controllers in the vehicles and in the roadside. The control and communication systems are briefly described here.

The basic unit of automation is the *platoon*, which consists of one or more vehicles traveling together as a group with relatively small spacing. The first vehicle in the platoon is called a *leader*, the others are *followers*. A one-vehicle platoon is called a *free agent*. Thus at every moment of time, a vehicle under automatic control is either a leader, a follower, or a free agent, see Figure 3.

[3] Organizing traffic into tightly packed platoons with large inter-platoon spacing increases safety. Consider two vehicles, and suppose the first vehicle decelerates rapidly. If the following vehicle is very close it will collide but the relative speed on impact will be very small. If the following vehicle is far away, it can decelerate without colliding.

2.1 Control system

We discuss each layer of Figure 2 starting from the top. The link layer controllers are in the roadside; each vehicle has its own platoon and regulation layer controllers.

The *link layer* controllers are responsible for the smooth flow of traffic in each automated lane. There is one controller per highway section. A section is several kms in length, and its link layer controller sets the target platoon size—*optsize*—and a target platoon speed—*optspeed* for that section. These variables are based on macroscopic information about traffic flow, congestion, and incidents. A link layer design is proposed in [5].

The *platoon layer* controller of a vehicle determines which of three maneuvers the vehicle should execute, so that the vehicle trajectory is close to its assigned path, and so that its platoon size and speed are close to the target values designated by the link layer. The three maneuvers are illustrated in Figure 4. In *merge*, two platoons join to form one platoon. In *split*, one platoon separates at a designated position to form two platoons. In *change lane*, a free agent changes lane. Merge and split are initiated by a leader's platoon layer controller; change lane is initiated by a free agent's platoon layer controller. Followers do not initiate maneuvers; however, they may request their leader to initiate a split.

In order to carry out a maneuver safely, the platoon layer controller initiates a structured exchange of messages—a *protocol*—with the leaders of neighboring platoons. At the end of the exchange, the platoon layer secures agreement from those neighbors that the maneuver can be safely executed. Once agreement is reached, the platoon layer instructs the regulation layer to execute the maneuver. Thus a protocol coordinates the movement of neighboring vehicles to ensure safe maneuvers. The protocols are described in the next section.

The *regulation layer* of a vehicle implements at each instant of time one of five feedback laws selected by its platoon layer. When a vehicle is a follower the *follower law* maintains the required tight spacing with the vehicle in front of it in its platoon. When a leader is not engaged in any maneuver the *tracking law* keeps the target speed while maintaining a safe headway from the vehicle in front of it. The *merge law* causes a leader to join the platoon in front of it. The *split law* decelerates the appropriate vehicle in the platoon until it reaches a safe headway from the platoon in front it. Finally, the *change lane law* steers a free agent to the adjacent lane. Follower law designs are proposed in [6, 7, 8, 9].

The *physical layer* in Figure 2 refers to the vehicle dynamics. This layer receives steering, throttle and brake actuator commands from the regulation layer. It returns to the regulation layer information needed to implement the five feedback laws: its own vehicle's speed, acceleration, engine state, etc; its speed and distance relative to the vehicle in front of it; and so on.

In summary, the link layer assigns *optspeed* and *optsize*; the platoon layer selects which maneuvers to execute in order to follow the assigned path, coordinates that maneuver with neighbors, and maintains platoons; the regulation layer implements the maneuver selected by the platoon layer.

With this sketch of the AHS control system we can better describe how your vehicle is controlled. At any time, the vehicle is either a free agent, a leader or a follower. It enters lane 3 as a free agent. Its platoon layer negotiates the change lane protocol twice with the neighbors' platoon layer, at the end of which your vehicle is in lane 1. While in lane 1, its platoon layer attempts to merge with other vehicles to form platoons of size *optsize*; and it may alternate several times its role between follower and leader as vehicles join and leave its platoon. When the vehicle is near its exit, the platoon layer negotiates one or two split maneuvers at the end of which the vehicle is a free agent. It now negotiates two change lane maneuvers, re-enters lane 3, and returns control to you.

2.2 Communication system

Three kinds of communication capabilities are needed to implement the control system, see Figure 5. First, vehicles within a platoon need to exchange information required by their platoon and regulation layers. Second, leaders of neighboring platoons need to exchange protocol messages for the merge and change lane maneuvers. (No exchange is needed for split.) It is required only that such exchange be possible within a certain communication range, D_{comm}. Third, leaders need to receive the target variables from the link layer in the roadside. (The roadside-vehicle links are not shown in the figure.) We assume that these communication services are available with no error or delay.

3 Platoon layer

We describe the platoon layer protocols.[4] Each vehicle maintains the following 'state' information:

- ID of the vehicle
- Highway number of the vehicle
- Lane number of the vehicle
- Highway section number of the vehicle
- Position of the vehicle relative to the highway section
- Platoon ID, same as the ID of its leader
- Platoon *optsize* in the highway section
- Platoon *optspeed* in the highway section
- Position of vehicle in platoon; position 1 indicates leader
- Number of vehicles in platoon
- Vehicle speed
- Vehicle acceleration

[4]The report [3] presents a formal specification of the protocols described here. The specification is then verified for correctness. The language COSPAN is used for this purpose [10, 11].

- Flag indicating whether vehicle is engaged in maneuver (Busy flag)
- ID of tail (last) car in platoon
- ID of back car (the car behind) in platoon; this ID is 0 for tail car

ID is fixed when the vehicle enters the AHS. Highway number, lane number, and section number are updated as needed; *optsize*, *optspeed* are obtained from the link layer. Lane number changes after a lane change maneuver; platoon size and position of vehicle change after a merge or split maneuver. Vehicle speed and acceleration depend on the regulation layer. The leader sets the busy flag whenever it is engaged in a maneuver. The flag is used to ensure that a platoon is engaged in at most one maneuver at a time. This simplifies the platoon layer design.

The platoon layer controller is separated into two sub-layers. The upper, supervisor sub-layer determines which maneuver to execute, and instructs the lower sub-layer to carry out the appropriate protocol exchange. The design assumes that a message establishes a link giving the vehicle receiving the message access to the sender's state until the maneuver is complete.

3.1 Merge

The supervisor issues a merge instruction only if the vehicle is a leader in its assigned lane (and if it is not busy). Figure 6 shows the sequence of events that follow a merge instruction, and Figure 7 shows how the protocol works. B is the leader of the rear platoon which initiates merge, and A is the leader of the platoon in front of B.

B checks its platoon size. If it is smaller than *optsize*, B tries to locate a platoon in front of it and to merge with it. B's distance sensor has a certain maximum range, D_{range}, and it can locate a platoon in its lane within distance D_{range} from it. Suppose this happens. B then sends it a *request_merge* message. If the vehicle receiving the message is a follower, it forwards the message to its leader, namely A. A then checks its busy flag, and if that flag is not set, and if the size of A's and B's platoons combined does not exceed *optsize*, A sends an *ack_request_merge* message to B; otherwise it sends a *nack_request_merge*, which causes B to wait for some time and repeat its merge request.

Upon receiving *ack_request_merge*, B updates its state by changing the platoon ID to that of A, and sends a message to its followers to do the same. When this updating is complete, B's platoon layer controller instructs its regulation layer to execute the merge feedback law. That law causes B to reach a pre-specified distance from the tail car of A's platoon. During this time, the distance from A's platoon is continuously sensed, and the execution of the maneuver is aborted, and A is notified, if another vehicle has moved between the two platoons. (While B is accelerating, the rest of its platoon, under the follower feedback law, maintains platoon formation.) When B's regulation layer has completed the maneuver it returns control to its platoon layer, which transmits *comp_merge* to A. A then updates its state (the platoon size and tail car ID are changed), and sends a message to its followers to update their state. At the end of the update the two platoons are joined and the maneuver is complete.

3.2 Split

A supervisor issues a split instruction to its own vehicle only if it wishes to change lane. There are also cases when the leader tells a specific follower to split, either to accommodate a change lane by another vehicle, or because the platoon size exceeds *optsize*. There are two cases of split depending upon whether the leader or a follower wants to split. Figure 8 summarizes the event sequence for both cases, and Figures 9 and 10 illustrate how the protocol works.

If the leader A wishes to split, it sends *request_split* to A_2 (Figure 9). A_2 then updates its state (replacing its platoon ID by its own ID), and tells its followers to update their state. When A_2 receives *update_complete* from the tail, it sends *ack_request_split* to A and the latter breaks off, i.e. updates its own state to reflect the fact that it is now a one-car platoon. The maneuver is then complete. At this point A_2 is a leader, and it is not engaged in any maneuver. Its regulation layer therefore executes the tracking law, which causes it to decelerate until it is at a pre-specified distance, D_{safe}, from the platoon in front of it.

If a follower, say A_m, of A's platoon wishes to split, it sends *request_split* to A, see Figure 10. Upon receiving this message, A checks if its busy flag is set, and if it is not, it replies with *ack_request_split*, and instructs A_{m-1} to change its back car ID to 0, so that A_{m-1} is now the tail car of A's platoon. A_m updates its state (since it is now a leader), instructs its followers to update the state. When the tail car A_n has updated its state, it returns *update_complete* to A_m. A_m now instructs its regulation layer to execute the split feedback law, which causes A_m to decelerate until it is distance D_{safe} from A's platoon. When that distance is reached, A_m sends *split_comp* to A, and the maneuver is complete.

Recall that a vehicle can change lane only as a free agent. Therefore, if a vehicle within a platoon wishes to change lane, it must first become a free agent. This requires one split if the vehicle is first or last in the platoon, otherwise it requires two splits.

3.3 Change lane

A vehicle's supervisor initiates a change lane maneuver in accordance with the path assigned to it when it entered the AHS. If the vehicle is not a free agent, the supervisor initiates the required split(s) at the end of which it is a free agent.

Suppose A is a free agent in lane 1 and wishes to change to lane 2 (see Figure 4). It can do so only if there is adequate space in lane 2 and no vehicle in lanes 2 or 3 is planning to move into that space. The change lane protocol ensures this condition. It is assumed that A is equipped with sensors that determine the presence or absence of a vehicle within 30 meters from it in lane 2, and within 18 meters from it in lane 3 (see Figure 11). The vehicle can change lane under one of the following three conditions:

1. No vehicle is detected in lanes 2 and 3; A can move to lane 2.
2. No vehicle is detected in lane 2, but a vehicle is detected in lane 3 (vehicle C in Figure 4); A then requests that vehicle not to move into lane 2.
3. A platoon is detected in lane 2. A then conducts a protocol exchange with the platoon in the manner described below.

Figure 12 describes the sequence of events that must occur before A changes lane, and Figure 13 illustrates how the protocol works in the third case. (The two other cases are straightforward.)

Suppose A has detected vehicle B_m in lane 2. It sends *request_change_lane* to B_m which it forwards to its leader, B. If B is busy, it sends a *nack_request_change_lane* to A. If it is not busy, it returns *ack_request_change_lane*. At this point B determines how to create a space in lane 2 in order to accommodate A's change lane. B's decision is based on the location of A relative to B's platoon:

Case 1. A is alongside the front third of B's platoon; in this case B decelerates to create a space for A in front of B's platoon.
Case 2. A is alongside the rear third of B's platoon; in this case B asks A to decelerate and use the space behind B's platoon.
Case 3. A is alongside the middle third of B's platoon. B then decides to split its platoon at the appropriate vehicle (B_n in Figure 13 (case 3)). B_n performs a split. At the end of the split, space is created for A in front of B_n.

When space has been secured, A's platoon layer instructs its regulation layer to execute the change lane feedback law. During this execution, the regulation layer continuously senses its assigned space. If another vehicle has moved into that space, the maneuver is aborted and B is informed. After the maneuver is successful, A updates its state and informs B that the maneuver is complete.

4 Simulation example

This section presents a simple example using the program SmartPath [12]. The simulation time is 180 sec. The AHS has one automated lane, one transition lane, and three entrances. Entrance 1 is located at 0.5 km, entrance 2 is at 1.5 km, and entrance 3 is at 2.5 km from the beginning of the highway. (See Figure 14.)

A 'pulse' of 25 vehicles enters the automated lane every 2 seconds starting at time 0 until 60 seconds, corresponding to a flow of 1,800 vehicles/hour. The pattern is repeated at entrances 1, 2 and 3 except that vehicles enter starting at time 20 seconds, 60 seconds, and 100 seconds respectively. In all, 85 vehicles are created. All vehicles have an initial speed of 25 m/s which is also the value of *optspeed*. The value of *optsize* is 20.

The detection and communication ranges are $D_{range} = D_{comm} = 60$ m. The safe distance, D_{safe} is 20 m for a free agent and 40 m for other platoons. Lastly, intra-platoon spacing is 1 m.

Figure 15 displays the simulation results in the form of a time-distance diagram for each vehicle from the time it enters the automated lane. A vehicle in the transition lane gets displayed in the figure only after it has switched into the automated lane.

The first thing to observe is the process of platoon formation. The pulse of vehicles entering the automated lane starting at time 0 is unable to form platoons of size larger than two since two-car platoons become separated by a distance of 100 m, which is beyond D_{range}. By the time these vehicles have traveled 250 m, they have reached steady state.

Second, most of the vehicles which enter the entrance at 0.5 km have changed into the automated lane after traveling between 0.25 and 0.5 km along the transition lane, although one vehicle had to travel 0.75 km. These vehicles, together with those in the first pulse, form platoons of size up to five vehicles. Steady state is reached at distance 1.25 km, since platoons are separated by more than D_{safe}.

Third, vehicles which enter the entrance at 1.0 km and 1.5 km take more time to move into the automated lane, since the traffic flow in that lane is quite large and it takes more time to create space for the change lane maneuver. Nevertheless, a steady state is reached at distance 3.5 km. Platoon of size up to 15 are formed.

At around 180 seconds, the vehicles are in steady state and they occupy 1,200 m of the automated lane. This is a density of 85/1,200 vehicles/m. Since the vehicles are traveling at 25 m/s, this corresponds to a flow of 6,375 vehicles/hour. The platooning concept is key to this high throughput: in steady state, one finds closely spaced platoons separated by large gaps (of at least 60 m). The example illustrates how entrances should be organized in order to create 'tributaries' feeding the high capacity automated lane.

The large inter-platoon separation and the coordination facilitated by the change lane protocol account for the relative ease with which vehicles from the transition lane join the vehicles in the automated lane. This can be seen in Figure 16 which is a 'blowup' of a small portion of Figure 15. The figure shows how the change lane protocol works.

5 Conclusion

The design of the automated highway system presented here, together with the simulation, suggests that automation can provide significant increases in highway capacity. The technology presupposed by the design is available today either in commercial or prototype form. Thus the challenging task is to integrate these technologies into a working system. Parts of this integration have been demonstrated for example in [13, 14, 15, 16]. Beyond demonstrating the concept of an automated highway lie numerous problems concerning deployment.

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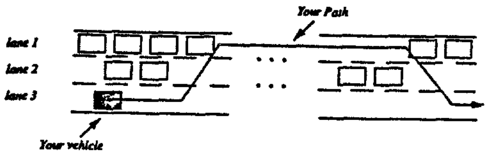

Figure 1: A path assigned by the AHS

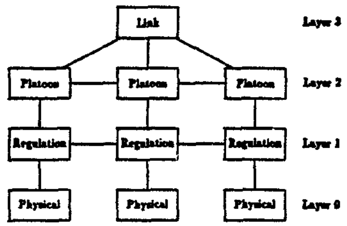

Figure 2: AHS control hierarchy

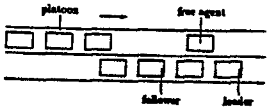

Figure 3: Platoons

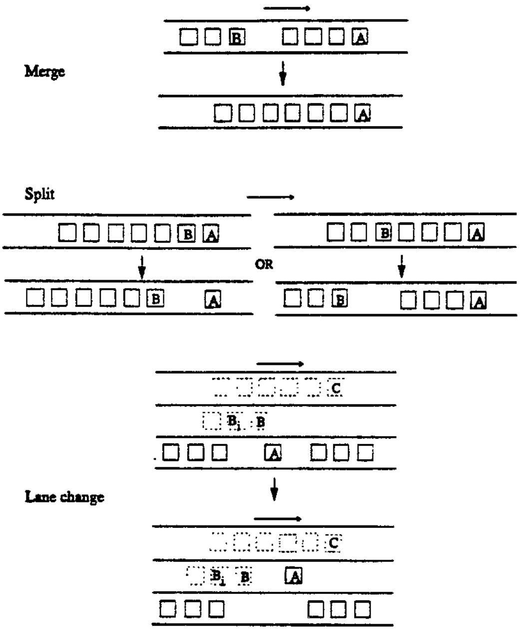

Figure 4: The three maneuvers

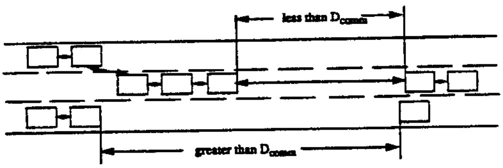

Figure 5: AHS communication system

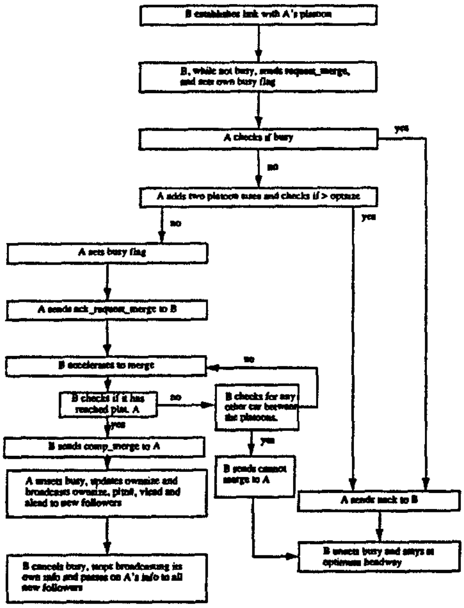

Figure 6: Sequence of events in merge

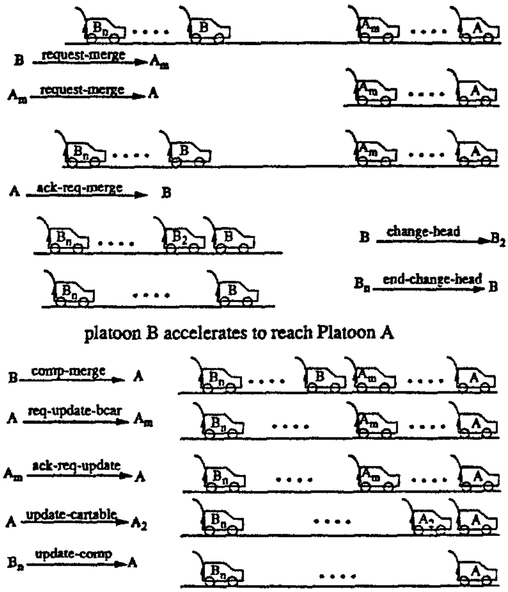

Figure 7: Merge protocol

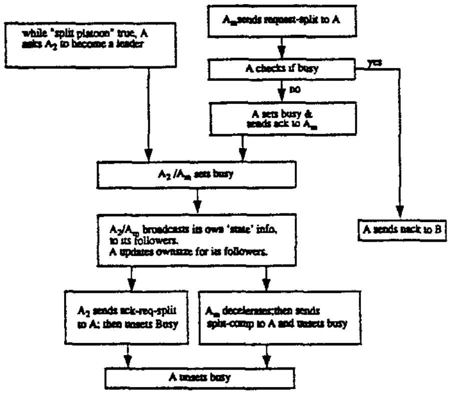

Figure 8: Sequence of events in split

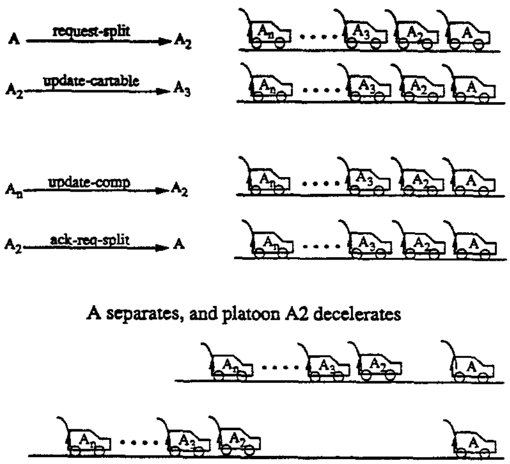

Figure 9: Split protocol: leader wants to break

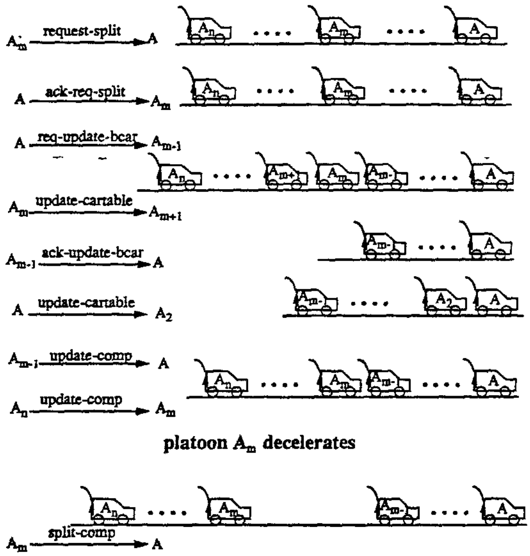

Figure 10: Split protocol: follower wants to break

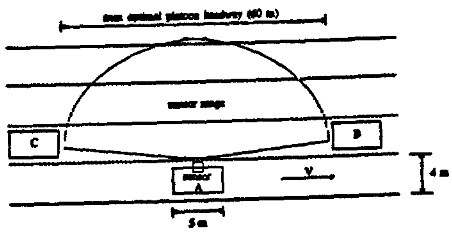

Figure 11: Sensors on vehicle

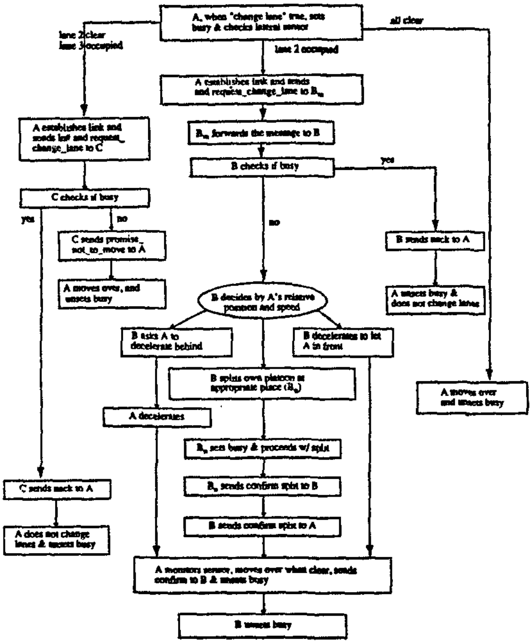

Figure 12: Sequence of events in change lane

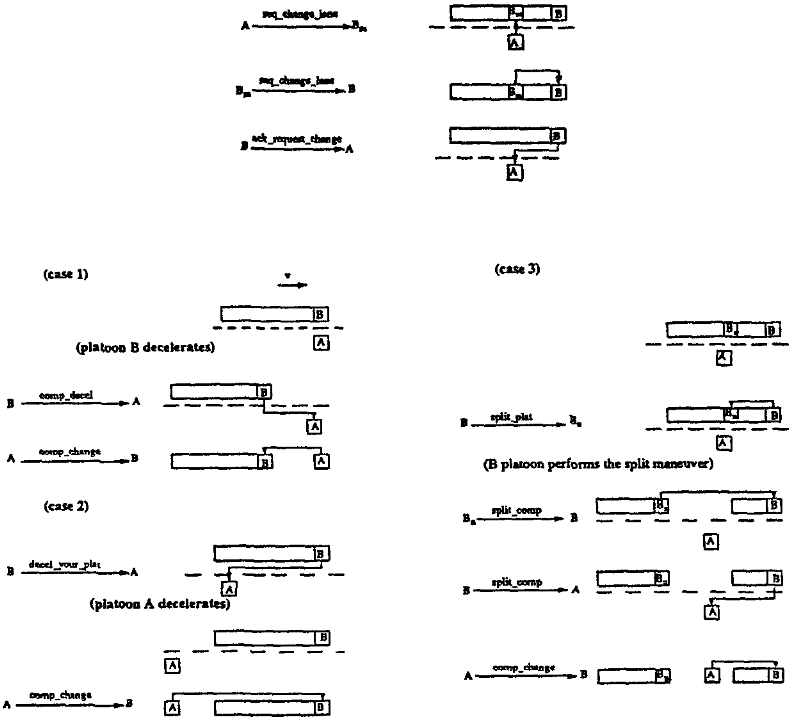

Figure 13: Change lane protocol

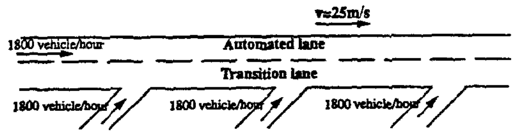

Figure 14: Highway configuration of example

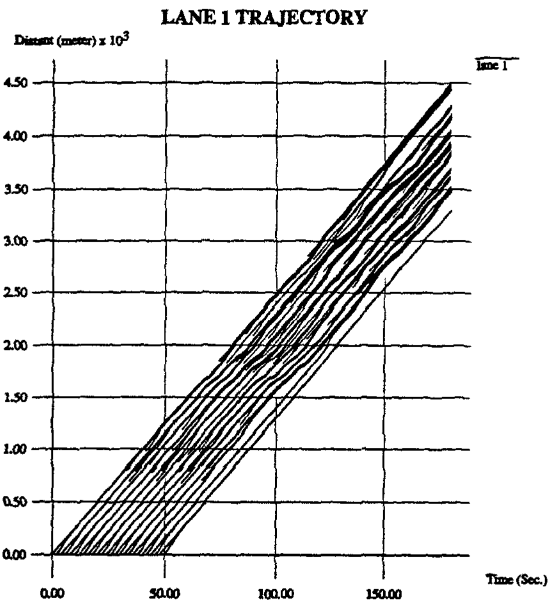

Figure 15: Time-distance diagram of example

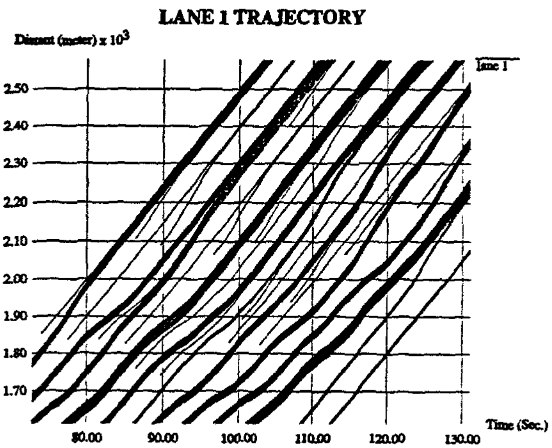

Figure 16: Blowup of portion of time-distance diagram