Investigations into Achievable Capacities and Stream Stability with Coordinated Intelligent Vehicles

B. S. Y. Rao, P. Varaiya, and F. Eskafi

Determination of the achievable capacity of an intelligent vehicle highway system (IVHS) was undertaken. The IVHS architecture proposed by earlier researchers in which vehicles coordinate their behavior to form short-headway platoons on an automated lane was examined. Although many estimates of potential capacity of such an IVHS have been derived, they all assume that steady-state flow already has been reached. In such an IVHS, entrance and egress of vehicles are the primary causes of traffic stream disturbance, ultimately dictating the flow rates that can be sustained reliably. Therefore the focus of the investigation was on entrance and egress strategies. A detailed simulator, SmartPath, models the passage of individual intelligent vehicles along the highway and was used to examine transient behavior of the traffic stream under various conditions. Three different strategies were examined for allowing vehicles to enter and leave automated lanes and measuring the corresponding maximum flow rates that are attained. The length of time it takes vehicles to enter an automated lane and therefore to build up high flows was also measured. Finally the effects on flow of vehicles leaving an automated lane were measured, thus indicating that this would be the major source of traffic stream disturbance. It was concluded that, although maximum theoretical capacity cannot be attained, through prudent design of entrance and egress strategies, extremely high throughput can be sustained.

Many claims have been made about the potential capacity benefits of intelligent vehicle highway systems (IVHS). Close formation platooning (*1–3*) appears to offer the greatest potential of all systems proposed for capacity increase through automation, but no reliable measure of attainable capacity is available. Most calculations on potential capacity increases rely on a simple kinematic calculation assuming some maximum platoon size (N), inter- and intraplatoon spacing (d and Δ), vehicle length (l), and average speed (v). For example, to calculate flow in vehicles per hour per lane we can use

$$\text{Flow} = \frac{3600vN}{N(l + d) - d + \Delta} \qquad (1)$$

Because this assumes that all platoons are at maximum size, the average platoon size $\overline{N}$ is sometimes substituted for N (*4*). Such calculations implicitly assume that high levels of flow can be built up arbitrarily on a lane without inducing instability of the traffic stream or affecting flow in other lanes in the process. Furthermore these forms of analysis give no information of the tolerance of the traffic stream at such high flows to anticipated regularly occurring disturbances such as those caused by entrance and egress of vehicles from automated lanes.

California PATH, Institute of Transportation Studies, University of California, Berkeley, Calif. 94720.

The claim of this paper is that the major source of capacity limitation in such an IVHS will arise from behavior of the traffic stream as vehicles attempt to join and leave the automated lanes (*5*). To determine the attainable capacity of a close-formation platoon IVHS it is necessary to examine in detail how high flows will be built up on a lane in practice and also how such high flows will withstand the disturbances mentioned above. To this end we employ a detailed simulator, SmartPath (*6*), which models interactions between intelligent vehicles operating within the architecture described earlier (*3*). This level of detail allows one to derive quantitatively the effects of entrance and egress of vehicles to and from an automated lane and to test various strategies for achieving lane changes, thereby allowing the optimization of this key maneuver.

It is concluded that whereas entrance and egress of vehicles cause stream instabilities, it is still possible to attain substantial increases in capacity through platooning, although not by quite as much as may be predicted through simple kinematic calculations.

THE SIMULATOR

SmartPath simulates an automated highway system (AHS). Details of various aspects of the particular AHS that is simulated are available in several Partners for Advanced Transit and Highways (PATH) reports (*3,7–9*). SmartPath is a microsimulation: the system elements and control policies are each individually modeled. Several elements and policies are specified parametrically, allowing the user to change these parameters and thereby investigate any performance variations that may be caused.

SmartPath is built using the process-oriented simulation environment Csim (*10*). Each vehicle on the AHS is modeled as a separate process under Csim, facilitating an accurate representation of the parallelism of each vehicle's operation. The simulation models the behavior of vehicles from the moment they attempt to enter the AHS from an on-ramp until the time they leave at an off-ramp. Vehicles attempt to reach their (individually) prespecified lane, and if that lane is an automated one, they attempt to form platoons. SmartPath models the communication between vehicles that is necessary to achieve these goals (*8*).

The simulator updates information about each vehicle at a rate of 0.1 sec, simulation time. This rate of update allows SmartPath to model realistically the dynamic behavior of vehicles as they follow various control policies, adjusting acceleration and steering to perform various maneuvers.

Maneuvers

SmartPath allows vehicles to perform only three basic maneuvers, the communication protocols and detailed description of which may be found in earlier work (*8*). The three maneuvers are merge, split, and change lane.

- Merging allows a single vehicle or platoon in an automated lane to join the platoon in front and become one platoon. This can occur only when the two parties are close enough to communicate and initiate the process and if the new platoon will be smaller than the maximum allowed platoon size.
- Splitting breaks a platoon in an automated lane into two separate, autonomous platoons. The new platoon at the rear must decelerate until it is a safe distance behind the one in front.
- Changing lanes allows vehicles to change safely from their lane to the adjacent one. A lane change can occur only when a sufficiently large gap is present in the destination lane. If such a gap is not present, the vehicle that wishes to change and the obstructing vehicle or platoon decide between themselves how to create a gap by decelerating one or the other party or by splitting a platoon to make the gap. Only single vehicles are allowed to perform this maneuver. A single vehicle platoon is called a free agent.

Using these three maneuvers as basic building blocks, larger and more complex operations, such as changing lanes to join a platoon or exiting the automated lane, are achieved. Note that, as specified previously (*3*), only one maneuver per platoon is permitted at any time. These maneuvers are implemented using detailed control algorithms proposed for automated vehicles (*11,12*). SmartPath therefore accurately simulates the behavior of automated vehicles that operate using these algorithms.

Manually Controlled Vehicles

SmartPath currently has no satisfactory way of modeling the behavior of a completely manually driven vehicle. One of the many car following models proposed (*13–15*) could be implemented to overcome this deficiency. However, to use SmartPath to study situations in which coordinated automated vehicles interact with other types of vehicles we assume that in our AHS all vehicles are equipped with at least the technology to perform autonomous intelligent cruise control (AICC), which is deployed at all times on the highway, except when coordinated operation is selected by the driver. (We define AICC technology as a means of implementing the longitudinal control of a vehicle on the basis of the measurement of its speed and distance relative to the vehicle in front of it, together with measurements of its own state.)

Although this appears to be a major assumption it is arguable that the imminent advent of commercially available AICC systems will ensure that long before the first coordinated vehicles are ever sold a large proportion of vehicles will be AICC equipped. Essentially AICC is the tracking law as stated above that allows us to model "manually controlled vehicles" within SmartPath as platoons of maximum possible size so that the tracking law will always apply.

Example Output

The output of SmartPath can be displayed as a time-distance diagram for each lane. Figure 1 shows a detail from such a diagram for an automated lane. In the diagram shown some platoons have already been formed and vehicles entering the lane attempt to join those platoons. The diagram shows how platoons adjust their speeds to maintain safe headways as the situation around them changes.

EXPERIMENTAL FRAMEWORK

The general framework used is shown in Figure 2. We simulate a two-lane highway with several on- and off-ramps. We assume that the inside lane is the automated lane and that the adjacent lane is a transition lane in which traffic from an on-ramp is attempting to merge into the automated lane, or traffic from the automated lane is attempting to leave at the next off-ramp. Currently, therefore, we assume no permanent flow in this lane (see the section on shortcomings). We define

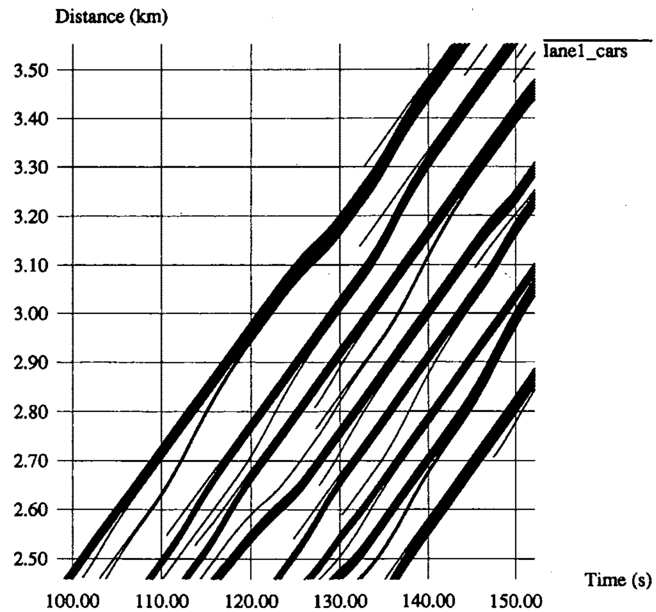

FIGURE 1 Portion of a time-distance diagram of the output of SmartPath for an automated lane. Many platoons already have formed by this stage, and individual vehicles that enter the lane attempt to merge with these platoons. Platoons adjust their speeds to maintain safe headways at all times.

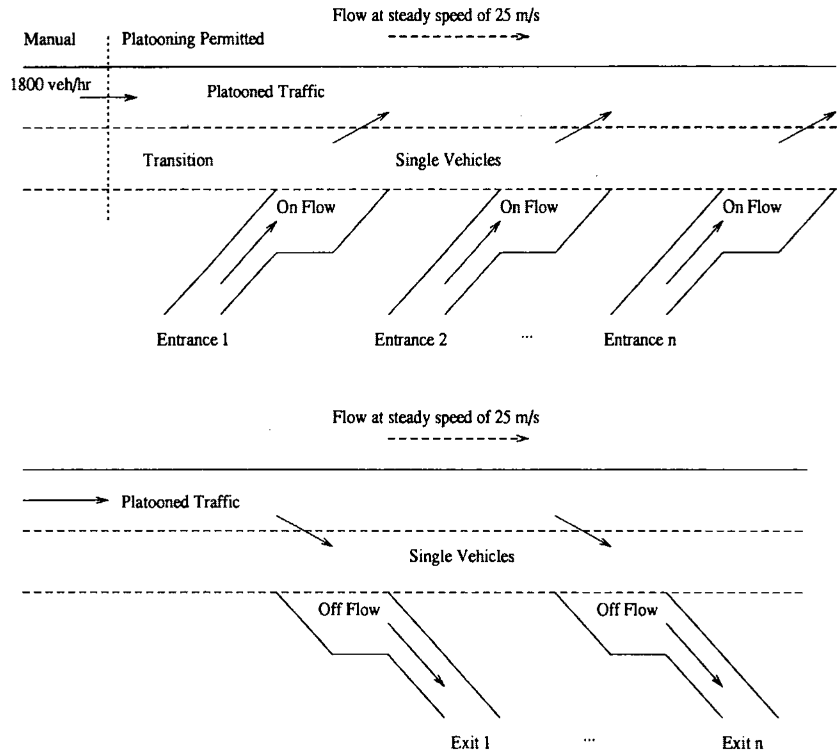

FIGURE 2 Diagram of the scenario modeled.

permanent flow in the transition lane as being those vehicles that travel in that lane to their destination without any desire to use the automated lane.

Initially a stream of vehicles at 1,800 vehicles/hr is on the inside lane, traveling at 25 m/sec under manual control. The vehicles are spaced randomly with headways drawn from a distribution of headways determined through measurement of traffic on highways (*16*). All vehicles are equipped with automation technology. At a certain point (the 0-km mark on all time-distance diagrams in this paper) all vehicles on the inside lane are able to use their automation facilities, and they begin to form platoons according to the methodology described above.

After some distance the traffic stream will be at steady state, and after this distance we place the first on-ramp. We define traffic in a section of highway to be in steady state when

1. All vehicles in that section are traveling at the desired constant speed,
2. All vehicles are in platoons (possibly of size 1) whose lead vehicle either cannot detect the platoon in front of it or cannot platoon with it because of maximum platoon size restrictions, and
3. No vehicles in that section are attempting to begin a maneuver.

Each subsequent on-ramp is placed such that traffic that entered from the previous on-ramp has merged into the automated lane and this lane is once more at steady state (see Figure 3). Off-ramps are placed similarly.

Using this framework we wish to determine the following:

- What is the maximum attainable flow in the automated lane?
- What is the maximum sustainable on-ramp flow rate?
- What is the distance that it takes vehicles entering at an on-ramp to merge into the inside lane?
- What is the effect on stream stability of vehicles entering and leaving?
- What is the maximum rate of egress of vehicles that can be supported?
- How long does it take vehicles to leave the automated lane?

Because all of these are, to some extent, random variables that are dependent on the initial headways of manual traffic on the inside lane and on how exactly platoons are formed, we obtain results after Monte Carlo simulations to attempt to average out the effects of the random behavior. The simulation is run 100 times with different starting headways (all drawn from the same distribution) and the cumulative results are analyzed. To allow results to be obtained within a reasonable time frame we generate a 40-sec section of traffic and monitor the progress of this "sample" as it proceeds along the highway. Flow rates are therefore scaled according to the subsequent time spread of this sample given that it started as a 40-sec sample. For example, if after some traffic has been added to obtain a total input flow of ϕ it is found that the sample now occupies 50 sec (because of deceleration of some vehicles to make room for others), we must calculate the effective flow rate as $(40/50)\phi = 0.8\phi$. This applies in reverse if the sample is found to compress.

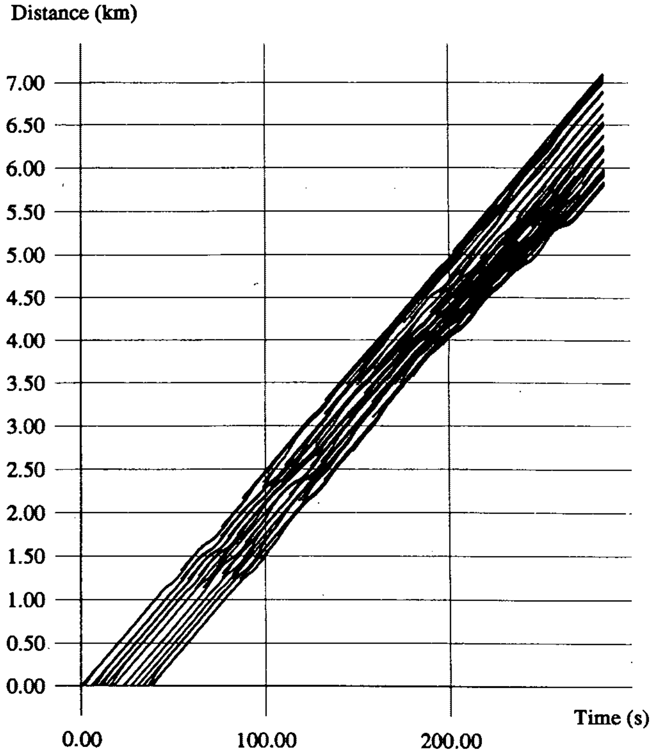

FIGURE 3 Time-distance diagram for the automated lane in an AHS using entrance-egress strategies described in Case 1.

Assumptions

We now state the assumptions on the behavior of the automated vehicles and choose values for critical parameters such as interplatoon distance.

Behavior of Vehicles

We assume that platooning is possible only in the automated lane and that vehicles are able to communicate occasionally with each other to perform maneuvers and also frequently with each other when entrained as platoons. We assume that drivers are able to activate their automation equipment at some point either when their lane becomes the automated lane or when they are in the transition lane after entering from an on-ramp. We assume that each driver does this at the earliest opportunity to ensure that vehicles enter the automated lane as soon as possible. Once under automatic control we assume that the vehicle will enter the automated lane initially as a free agent, although there may be other vehicles nearby (but a safe distance away). We assume that a vehicle that is a free agent or a leader of a platoon will follow a control law that will keep the vehicle at the defined target speed and always at a safe distance (Δ) from the vehicle in front.

We also assume that vehicles in the transition lane follow this control law, consistent with the previous assumption that all drivers enable their automation equipment on entering the transition lane.

We assume that vehicles travel on the automated lane until close to their exit. They then initiate a maneuver to leave the lane; once they are in the transition lane drivers resume control of the vehicle, allowing them to exit.

Range of Detection

A fundamental parameter is D, the range of detection of a vehicle. Although line-of-sight devices with ranges of up to 150 m have been reported (*17*) this figure may change radically in adverse lighting conditions, poor weather, and when rounding a bend. We assume that the simulated highway segment is largely straight and that the weather is fair; thus, D = 70 m. We also assume that this sensor is sampled at 10 Hz, giving a possible maximum sensing delay of $\tau_s = 0.1$ sec.

Rates of Acceleration and Deceleration

Acceleration and deceleration rates vary enormously with road conditions, tire conditions, and weather. It has been suggested that deceleration rates of only 0.25 g can be attained under the worst cases (*18*), but recent field tests by PATH researchers at San Diego have shown that, under optimal conditions, deceleration rates of 0.9 g can be achieved for emergency braking. For comfort we limit the maximum braking and acceleration to $-0.2\,g$ and $0.2\,g$, respectively, but during emergencies we assume the maximum deceleration $a_{\text{max}_d} = -0.5\,g$ can be achieved.

Actuator Delays

We assume that the actuator delay τ_a is 0.2 sec for full braking to be effected. This value is based on experiments with actuators to be used in PATH test vehicles.

Speed

The speed depends on D, the maximum deceleration, a_{max_d} and a reaction time $\tau_r = \tau_a + \tau_s$. We set the speed such that single vehicles (or platoons) can stop before colliding with any vehicle decelerating in front of it. Because vehicles can only see a distance D ahead, we conjecture that the worst case for a vehicle (or platoon) is when an object that is already stationary is detected at the limit of its detection capability. Therefore

$$\upsilon = \sqrt{a_{\text{max}_d}^2 \tau_r^2 + 2a_{\text{max}_d} D} \quad (2)$$

which with figures given yields 24 m/sec $< \upsilon <$ 28 m/sec. We set υ = 25 m/sec as a convenient value for our simulations.

Interplatoon Distance

Because the speed was chosen to enable safe stopping on encountering a stationary object, interplatoon spacing (Δ) must serve to prevent collision with a platoon that is always within range of detection. If the platoon in front should brake suddenly and the platoon behind is able to apply similar braking power after some reaction period (τ_r), we can say

$$\Delta \geq \frac{1}{2} a_{\max_d} \tau_r^2 + \tau_r v \tag{3}$$

which, given our assumptions, gives $\Delta \approx 8$ m. This is infeasible for two reasons:

- Without some method for checking that all vehicles entering the AHS satisfy criteria concerning minimum levels of performance of equipment it cannot be assumed realistically that every platoon has similar braking characteristics. It may be that the trailing platoon will not be able to decelerate at the same rate as the one in front because of worn brakes or poor tire quality, necessitating a significant increase in Δ (*18*).
- Even if there existed a method for ensuring that the above assumption could be made, there is (to our knowledge) no lead vehicle control law that can maintain such spacings without requiring a huge control effort or frequent interplatoon communication (not supported in our architecture).

Therefore we increase Δ to 30 m, which is more reasonable from a control standpoint and is also safe.

Intraplatoon Distance

This distance parameter (d) is the spacing between the front of a car and the rear of the preceding car in a platoon and is set to 1 m. This value of d will lead to a (low relative velocity) collision between two consecutive vehicles in a platoon if their communication system fails and a rapid deceleration is called for before this failure is detected. The frequent communication system is checked several times a second and any vehicle failing to receive information from its platoon leader could simply decelerate gently, preventing any collisions in the remainder of the platoon, until it is at rest. In other instances the communicated information should keep platoon partners from hitting each other (*12,19*) even in the event of sudden braking.

Maximum Platoon Size

Platoon size (N) is not an independent variable but rather, because of the adaptive nature of this system, varies with the demand flow. However, it is currently thought that platoons larger than 20 are difficult to control and, in fact, large platoons make egress more difficult, so we set $N_{\max} = 20$.

Shortcomings in the Simulation Methodology

One area in which SmartPath is currently deficient is the control law for the lead vehicle of a platoon. (To our knowledge no clear control law for lead vehicles in platoons has been proposed in the published literature. Merely maintaining a constant speed is not sufficient to cope with all eventualities.) The law used calculates the deceleration a vehicle must apply at each instant on the basis simply of the distance and relative velocity of the vehicle in front such that a collision is always avoided (*6*). The same law is also used for vehicles in the transition lane, and its crude nature leads to situations of traffic stream instability that we believe can be avoided through prudent design of this law. It is therefore not currently possible to simulate any permanent manual flow in the transition lane, although there is work in progress to develop a more satisfactory lead vehicle control law.

THREE CASE STUDIES

We examine three different policies governing entrance to and egress from the automated lane, all implementable using the basic merge, split, and change-lane maneuvers.

Case 1: Basic Model

In this study the entrance and egress policies are as follows. Vehicles entering the automated lane from a transition lane do so immediately if no vehicles are within the safe distance. If a vehicle in the transition lane is adjacent to a platoon it will enter in front of it if the vehicle is toward the front third of the platoon, behind it if the vehicle is toward the rear third of the platoon, or the middle of the platoon otherwise. In all cases the whole platoon, split platoon, or vehicle must decelerate to the safe interplatoon distance before the lane change occurs. Merging may then take place as a separate maneuver afterward. Vehicles that wish to leave the automated lane do so from the rear, front, or middle of the platoon, but all of these maneuvers entail a deceleration to safe separation before the lane change.

In the scenario simulated for this case, vehicles enter the automated lane (which starts at 0 km) and begin to platoon together. On-ramps at 1, 2, 3, and 4 km are supplying vehicles at a regular metered rate of one every 2 sec (1,800 vehicles/hr), all of which attempt to merge into the automated lane, thereby theoretically achieving flows on the automated lane of 3,600, 5,400, 7,200, and 9,000 vehicles/hr. There is an exit at 7 km, and vehicles attempt to leave the automated lane from about 5.5 km at a rate of 900 vehicles/hr.

From Figure 3 we can see that although high flows can be attained, rider comfort would be low because each platoon decelerates and accelerates many times in reaction to vehicles in front. The primary culprit of this behavior is the vehicles entering the automated lane before joining a platoon. In this model, such vehicles must decelerate to Δ behind the platoon before joining the lane and then merging with the platoon. This causes a large change in headway to the platoon behind, which must react, although the change in headway is merely transient.

From Figure 4 we see that high on-ramp flows can be supported. It can be argued that 1,800 vehicles/hr is close to the maximum that an on-ramp can be expected to supply, given that the lane capacity of a highway now is around that value.

Vehicles leaving the automated lane cause large stream disturbances because splitting to allow vehicles out results in the back portion of the platoon decelerating until it is Δ behind

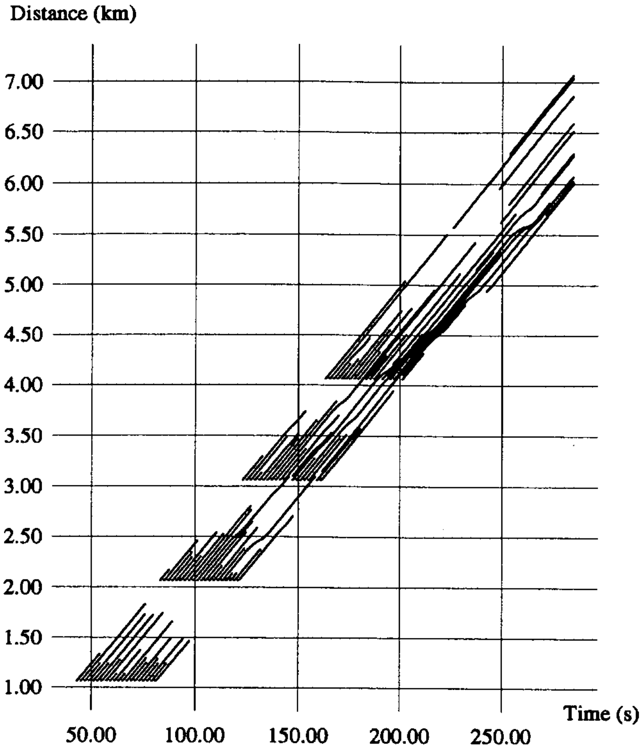

FIGURE 4 Time-distance diagram for the transition lane using entrance-egress strategies described in Case 1. Vehicles leaving the automated lane are found in the transition lane after 7 km.

the vehicle that wants to leave. In this case an egress demand rate of only 900 vehicles/hr causes a 25 percent drop in flow (Figure 5).

Case 2: Improved Merge and Lane Change

To improve rider comfort, the strategy for joining the back of a platoon was altered such that a vehicle could now be considered part of the platoon it will eventually join from the moment its request for a merge into the automated lane is acknowledged. It knows it will join that platoon, so it enters the automated lane only $2d$ behind the platoon and then merges with it. This should smooth out traffic flow disturbances and also make this maneuver safer. We expect that when a vehicle's headway is less than Δ but not as low as d the vehicle is at greatest risk of a high relative velocity collision, and by minimizing the amount of time a vehicle spends in this "gray zone" we claim that the maneuver is rendered less dangerous.

In the scenario simulated for this case vehicles enter the automated lane (which starts at 0 km) and begin to platoon together. On-ramps at 1, 2, 3, and 4 km supply vehicles at a regular metered rate of one every 2 sec (1,800 vehicles/hr), all of which attempt to merge into the automated lane, thereby theoretically achieving flows on the automated lane of 3,600, 5,400, 7,200, and 9,000 vehicles/hr. There is an exit at 7 km, and vehicles attempt to leave the automated lane from about 6 km at a rate of 1,800 vehicles/hr.

Figure 6 shows that the strategy has the required effect for traffic joining the automated lane, and it can be seen that (near entrances) platoons deviate from optimal speed far less often and with less magnitude. High flows are again achieved, and Figure 7 shows that high on-ramp flows are maintained.

Once again it was found that egress of vehicles caused a large drop in flow (Figure 5). This is mainly because of the split maneuver that causes a large change in headway to the vehicle behind the splitting platoon. This problem is exacerbated when either more than one vehicle has to leave a platoon or a number of consecutive platoons split at about the same time, causing a cascading shock wave that travels upstream.

This is a potentially worrysome problem because it implies that vehicles must begin to try and leave the automated lane long before their exit and also coordinate their actions via a higher (link) level to minimize the chances of causing massive stream turbulence—the former being unappealing and the latter being difficult to implement.

Case 3: Sorting by Exit Positions

In this strategy we allow vehicles to leave a platoon only from the back. This strategy allows easy egress and causes minimum change in headway for the platoon behind because the exiting vehicle can pull out of the lane after decelerating only a few feet.

However, to allow this action to take place we must allow vehicles to join a platoon only if the rearmost vehicles will leave the lane before those in front. We therefore sort vehicles as they attempt to join platoons. This is easily accomplished within the framework of the architecture specified previously (*3*) and requires only a small extra burden on the lead vehicle. When a request for a merge with a platoon arrives it is accompanied by an exit number. The lead vehicle then passes this down the platoon until a vehicle replies that the exit number corresponds to an exit after its own. At that point in the platoon a split will occur and the new vehicle may join. This strategy will have several effects:

- Exiting the automated lane is made easier at the expense of greater turbulence in both the transition lane and the automated lane as vehicles enter.
- Vehicles will have to be fed into the highway at lower rates but at more numerous entrances to allow the transition lane traffic to sustain the flow disruptions.
- "Opportunistic" merging of platoons will not be possible now unless the exit number order is maintained. This type of merging occurs after a split to allow a vehicle out or, more importantly, if there is more than one automated lane or if two automated lanes merge at any time.

In the scenario simulated for this case there are on-ramps at 1, 2, 3, 4, 5, and 6 km that are supplying vehicles at a regular metered rate of one every 4 sec (900 vehicles/hr), all of which attempt to merge into the automated lane, thereby theoretically achieving flows on the automated lane of 2,700, 3,600, 4,500, 5,400, 6,300, and 7,200 vehicles/hr. There are 10 exits starting at 8 km and continuing at 1-km intervals thereafter. At 7.25 km, vehicles for the 8-km exit (about 1 in 10 of the vehicles on the automated lane) attempt to leave. Similarly at 8.25 and 9.25 km vehicles attempt to leave for their exits.

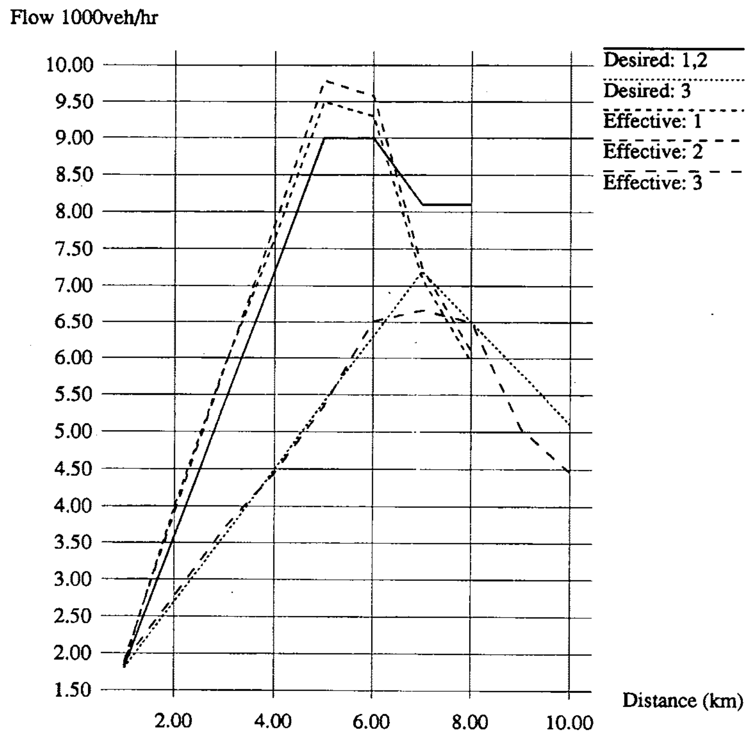

FIGURE 5 Effective flow actually found on the automated lane, measured at 1-km intervals, compared with input flow. Input flow is the existing flow on the lane plus any flow from an on-ramp that is trying to enter the lane or minus any flow that is attempting to leave the lane. Data for all three entering and exiting strategies are included. For Cases 1 and 2, the sustainable on-ramp flows are 1,800 vehicles/hr per ramp, but for Case 3 it is 900 vehicles/hr per ramp. Flows build up quickly, but in Cases 1 and 2 any exiting (at a rate of 900 vehicles/hr in these cases) leads to stream disturbances, which cause "spreadout" of the traffic sample, resulting in severe breakdown of flow. Case 3 shows how exiting of vehicles at this rate can be supported, although a lower maximum flow is initially attained.

Figure 8 shows that egress is indeed very smooth. In this simulation each vehicle was randomly allocated 1 of 10 possible exits so that at each exit approximately ⅒ of the maximum flow would try to leave (about 700 vehicles/hr). Note that the platoons that are formed are smaller but more numerous because random merging between platoons is now not possible.

A relatively high flow rate is achieved only after six low supply entrances (see Figure 9), and unlike the previous two cases in which effective flow exceeded input flow, in this case the flow begins to peak at about 6,500 vehicles/hr (Figure 5).

CONCLUSIONS

It is clear from our results that no matter what the potential capacity of an automated lane, it is the behavior of the traffic stream near entrances and exits that will ultimately determine access and egress rates, achievable flows, and rider comfort. In this paper we have discussed three possible strategies for allowing vehicles to enter and leave an automated lane. Appropriate design of these strategies can improve all of the above factors and also expedite the task of designing a suitable control law for lead vehicles by eliminating unwanted deviations in detected headways and relative speeds.

From our investigations we can state that platooning operating under the architecture and assumptions proposed previously (*3*) can achieve peak flows greater than 9,000 vehicles/hr rapidly and while maintaining safety and stream stability, but that these rates of flow cannot be sustained. Attempting to allow vehicles to leave causes significant stream disturbance, bringing the sustainable flow rate down to about 5,500 vehicles/hr. The main cause of stream disturbance at exit points is the current split maneuver. An attempt to eliminate the necessity for this maneuver near exits without requiring a change of protocols and basic maneuvers has been described but is seen to have several fundamental drawbacks.

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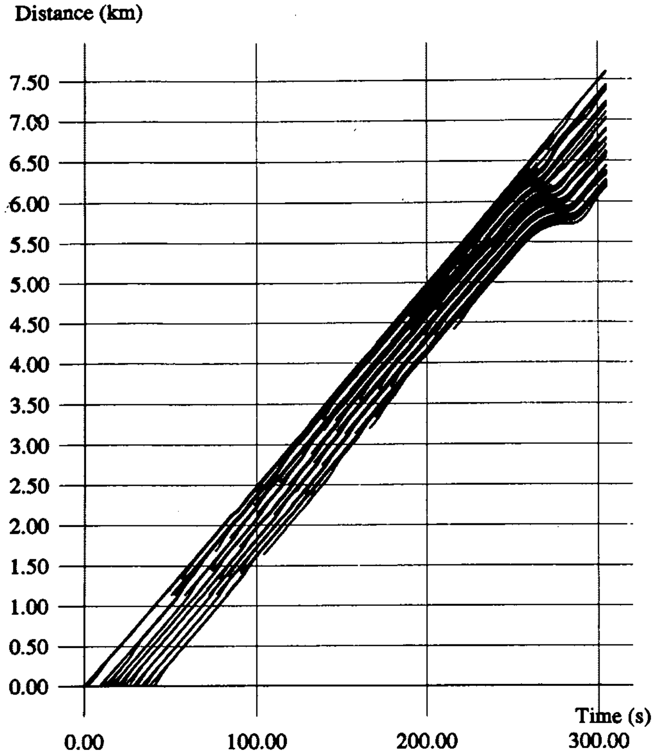

FIGURE 6 Time-distance diagram for the automated lane in an AHS using the entrance-egress strategies described in Case 2.

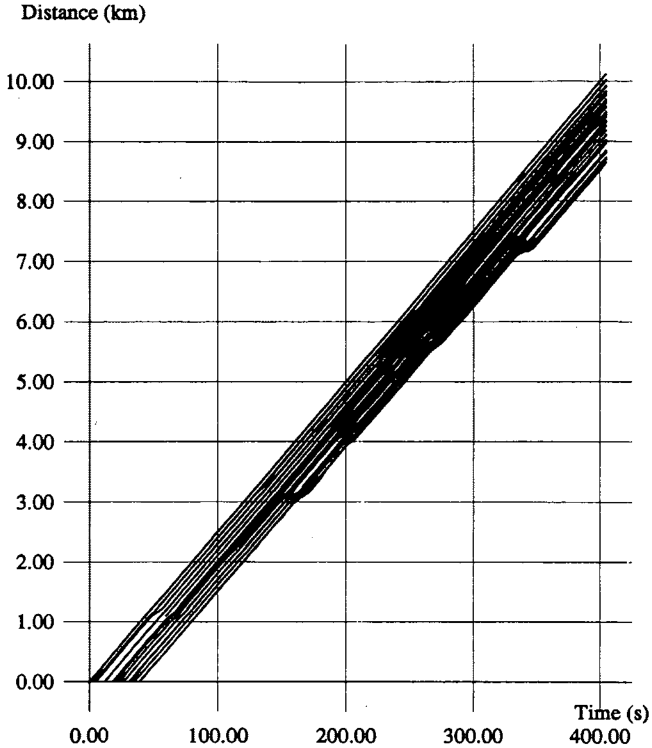

FIGURE 8 Time-distance diagram for the automated lane in an AHS using the strategy described in Case 3 in which platoons are formed according to the exit point of vehicles.

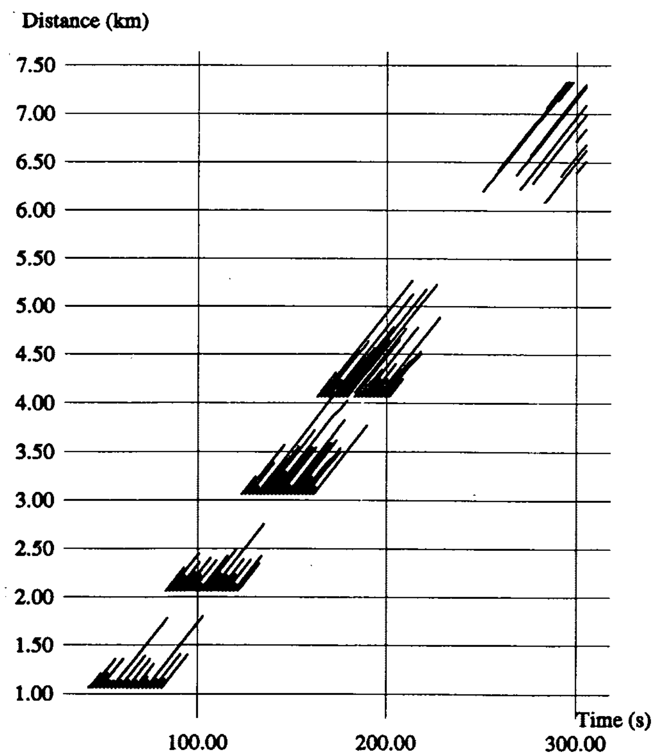

FIGURE 7 Time-distance diagram for the transition lane using entrance-egress strategies described in Case 2. Vehicles leaving the automated lane are found in the transition lane after 7 km.

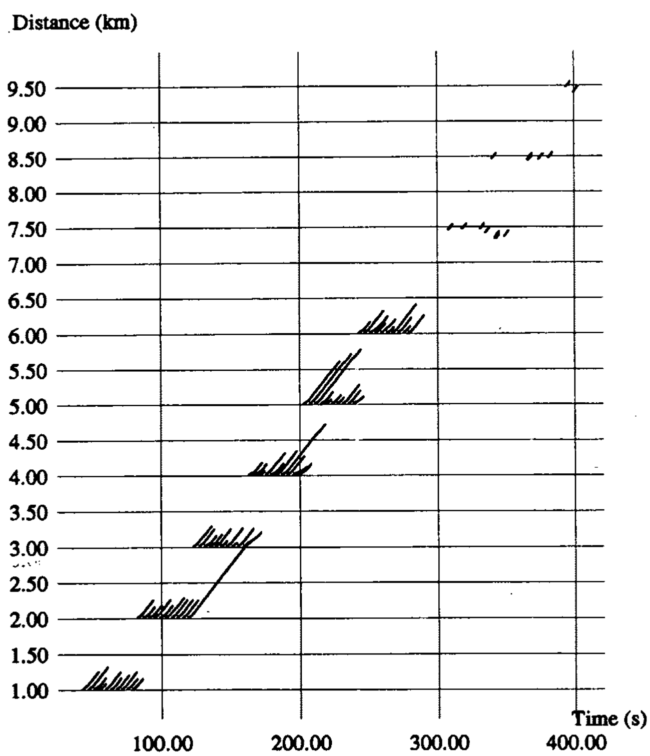

FIGURE 9 Time-distance diagram for the transition lane using strategy described in Case 3. Vehicles leaving the automated lane are found in the transition lane after 7 km.

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