Entry to and Exit from a Safety-consciously Designed AHS Configuration

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Abstract

This paper proposes entry and exit maneuvers compatible with the automated highway system described in the author’s paper “Configuration and Maneuvers in an Automated Highway System Designed for Optimum Safety” (Hitchcock 1995). It was originally written as a suggested work plan for colleagues within the FHWA-funded Precursor System Analysis for AHS (exit and entry section). Accordingly, some of the questions posed here are intended to be answered by other researchers, in other papers.
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I. SAFETY CONDITIONS

The safety principles governing the configuration of the AHS, and the maneuvers of vehicles on it are, in brief:

- Vehicles are organized into closely spaced platoons, which have an inherently low casualty rate.
- There is a barrier (or divider) between the automated lanes (AL) and manual lanes (ML) on the rest of the right-of-way: vehicles must enter and exit through “gates” in the dividers.
- Platoons do not join together (merge) at speed, either on the ALs or on the transition lane (TL), which is the lane where vehicles change from manual to automatic control and vice versa. This implies that vehicles must join and leave platoons from a close-spaced configuration.

We suggest that these safety principles should constrain our design. We need to agree that the work which purports to demonstrate this is sound, that the judgment that the predicted casualty rates are unacceptable is also sound, and that the levels of reliability required to upset this conclusion are indeed not credible, at least at acceptable prices.

Details of the maneuver protocols and general configuration of the system are described in the author’s paper “Configuration and Maneuvers on an Automated Highway System Designed for Optimum Safety” (Hitchcock 1995).

II. PERMISSIBLE CONFIGURATIONS AT ENTRY AND EXIT

Under normal conditions, vehicles entering the automated lanes from the transition lanes must never preclude vehicles leaving the ALs from reaching their desired exits. Entry protocols must therefore guarantee that all vehicles accelerating to platoon speeds infallibly enter within a given length of transition lane. Thus the entry protocols must direct each vehicle to the proper entry gate at the proper speed and time. Since the haphazard presence of manually controlled vehicles in the transition lanes would make this difficult if not dangerous, a section of transition lane (the entry-maneuver length, or EML) must be reserved to vehicles entering under autocontrol.

Because drivers must not be allowed to resume manual control until an existing vehicle has decelerated to a constant speed (i.e., the brakes are not being applied) and is safely separated from other vehicles, post-exit maneuvers must also be controlled automatically. Since this also
cannot always be done safely if manually controlled vehicles may appear at random, there must be a length of transition lane devoted to exit maneuvers (the exit-maneuver length, or XML) from which manually controlled vehicles are barred.

The remaining section of transition lane is devoted to vehicles changing from manual to autocontrol, before entering the ALs, or from autocontrol to manual, after exiting. In this control-change length (CCL), among other things, manual vehicles join, request takeover, have their fitness verified, and assume autocontrol. At the end of the CCL is a dormitory, to which vehicles not admitted to the ALs are shunted. (Speeds will be low on this part of the TL).

Once under autocontrol, vehicles may enter the automated lanes from the transition lanes (or leave the ALs for the TLs) either individually or as platoons. But in order to exit as a platoon, vehicles that will all use a single exit must be grouped together on entrance. To enter as a platoon, vehicles awaiting entry must be grouped together at random, regardless of their desired exit. Hence there cannot be platooning at both entry and exit.

In the EML, vehicles that have assumed autocontrol are marshalled for the entry maneuver. At the downstream end of this section, one or perhaps more gates permit entry to the ALs. If for any reason they fail to enter (this is a fault condition), they are decelerated sharply, and proceed to the XML. Vehicles exit from the automated lanes to the XML through one of a number of gates. While still under autocontrol they are slowed and separated to a safe spacing. (If failed-entry vehicles enter the XML, they may prevent exit.)

The exiting vehicles under autocontrol now enter the CCL, where they are requested to resume manual control, and leave the TL. If they do not so they are eventually brought to rest in the dormitory. Probably notices will request entering vehicles not to join the TL until most vehicles have had a chance to regain manual control. Alternatively a barrier may prevent entry to the upstream end of the CCL.

The three distinct kinds of TL, which are illustrated in Figure 1, repeat cyclically. Going downstream, they are: CCL, EML, XML. The CCL must be wide enough to permit safe manual driving. The EML and XML will be narrower, separated from both automated and manual lanes by dividers, and legally barred to manual vehicles.

To enter the AL, a vehicle must rendezvous with a platoon (or with a large gap between two platoons). The two maneuvers are very similar, and if the AL is controlled so that the headway between platoon leaders or platoon trailers is constant (the trailer is the last vehicle in the platoon), the maneuvers will be identical. This regular spacing is not necessary, but it is convenient, and it makes the entry/exit layout easier to design. We shall therefore treat a gap as a platoon with zero members: references to platoons may henceforth include zero-member platoons.

Local controllers will organize the entry protocol. They will be able to communicate with both entering vehicles and platoons, and will have as data the positions and speeds of platoon trailers as well as the numbers and positions of entrants. Precisely how much of the intelligence
controlling the maneuvers we describe here will be vehicle-borne and how much infrastructure-borne is not important in the current context. However, it is to be expected that the number and precise location of gates will vary from one EML/XML to another, and that the parameters of a particular point must be held in the infrastructure, so that some limited infrastructure-based intelligence is necessary.

In all cases, when a vehicle, under autocontrol, enters the EML, it will be assigned to a platoon. In most cases there will be only one platoon that it can join if it is not to be brought to rest. Platoons will be separated by 5-10 seconds, and though the average entry flow will usually be less than one vehicle per platoon (approximately 350 - 700 vehicles per hour), there will be occasions when two, three, or more vehicles will be assigned to one platoon. The length of the EML must be such that there is always at least one platoon that a vehicle can join whenever it enters.

**Single-entry configuration**

Here there is only one gate at the end of the EML. On entry a vehicle proceeds along the EML at low speed until a critical moment, when it accelerates at the maximum rate permitted and falls in behind the trailer of a platoon in the AL. Just before rendezvous it will be in direct communication with the platoon trailer, and messages will be exchanged to make the rendezvous precise.

If more than one vehicle in the EML has to join a platoon in the AL, the second and later vehicles in the EML move up behind the one ahead while all are at low speed, and join together to form a pre-platoon, which later accelerates as a whole. Speeds and relative speeds are so low that the merge is not unsafe.

Because platoon members are not ordered as they join the platoon, a member may leave the platoon from any position. The vehicles immediately before and behind the leaver may need to separate slightly to permit it to go, and close the gap as soon as it has done so. (This “merge” is much less dangerous than a full merge between two platoons: see Hitchcock, 1993.) If more than one vehicle leaves the platoon, the foremost vehicle leaves by the first of the series of gates in the XML, the next to leave by the second, and so on.

On exit, a vehicle starts to decelerate at once. The gate positions are such that the second vehicle to leave exits far enough after the first to leave (which originally was physically ahead in the platoon) so that there is no danger of collision in the event of “brakes-on” failure. This is made simpler because as the second vehicle leaves, the first, which is now behind it, is already moving more slowly (see figure 3). Not until deceleration is complete, the brakes are off, and the separation is safe does the driver resume control.

**Single-exit configuration**

This is the reverse of single-entry configuration. Instead of entry as a pre-platoon and exit as several single vehicles, we have entry through several gates to form an ordered platoon as
described by Rao et al. (1993), and exit as a post-platoon. In this configuration, vehicles leave from the rear of the platoon. When the single exit gate in the XML is reached, the vehicle or vehicles that wish to leave split successively from the rear and exit through the gate. When braking is over and separations are safe, the driver may resume control.

For this configuration to work, entry into the platoon must be ordered, with vehicles joining different parts of the platoon, through different gates, according to their destinations. It is not certain that this can be done in all cases while maintaining safe separations between joining vehicles.

This arrangement may also run into problems if a driver wants to change his destination in mid-trip.

**Multiple entry/exit configuration**

This system obviates the need for pre-platoons by providing several gates on the EML. The trailing vehicle of a group joining a platoon joins at the first gate, and the others rendezvous at successive gates as the platoon overtakes them. The exit arrangement is the same as in the single-entry configuration: vehicles may leave from anywhere in the platoon.

*Can we formulate these protocols precisely? Do they work?*

It is clear that the single-entry strategy will work safely if vehicles are brought to rest for platoon formation. It has yet to be demonstrated how a pre-platoon can be formed safely with moving vehicles, what protocols will do this, whether this can ever result in a vehicle or platoon having to be reassigned from one platoon to its successor (does this matter?), and just how serious a brakes-on failure would be for different values of the parameters. We also need to understand how the minimum length of the EML is affected by our choices.

Do we need to study the detail of the rendezvous procedure and exchanges between platoon trailer and pre-platoon leader? Perhaps the leading function in platoon-level protocols, assigned by Hsu et al. (1991) to the platoon leader should be given in part to the trailer?

The author’s paper “Exit from/to an Automated System” (Hitchcock 1992) shows that a system can work in which vehicles leave a platoon and the AL individually. But what if there are more leavers than gates? Also, is there any possibility of conflict between the vehicles leaving one platoon and the vehicles leaving successive ones? What happens if a fault does arise, and vehicles come through from the EML to the XML?

Exit as a post-platoon can clearly be made to work, though there is a need to work out what length of XML is needed. How the individual entry protocol can be made to work without unsafe separations and closing speeds between entering vehicles also needs investigation. It is not intuitively apparent that it is possible in all cases, and if it is not, this concept must fall. A protocol that will only work some of the time is not acceptable. Again, the next stage is to define the required length of the EML.
It seems more likely that the protocol for multiple entries can be made to function at all times. However, it is not clear that this procedure will have any advantages over the others. Should we demonstrate that there is an alternative to the formation of pre-platoons?

**What happens when the AL reaches capacity?**

As the AL approaches capacity, the average size of platoons will increase, and the gaps between them will shorten. Do we need to discuss the effect on our protocols if entry would violate a maximum platoon size constraint? The need to pass messages down the length of the platoon may mean that after a certain length the longitudinal control system will show the “Slinky effect.” This seems unlikely to be a limiting feature.

More importantly, if the gap between platoons is at or near the minimum, how should the entry protocol be modified? Once a vehicle accelerates down the EML it should enter unless some fault arises after it starts acceleration—anything else would prevent exit too often. So the response to a minimum gap must be to cause vehicles to line up, stationary, near the entry to the EML. Do we warn that such queuing is occurring, and give entering vehicles an opportunity to exit via the dormitory? Do we reduce speed on the AL, which may increase capacity slightly? Do we cause following platoons to slip back, which may cause reductions in speed, and perhaps loss of capacity, upstream? Do we restrict entry at EMLs just before ones where flow is always high, or where queues are long? These are link-level questions: to what extent should we discuss them?

These link-level questions are the only ones where it is appropriate to use simulation. In the other cases we want answers that are proved. Are our present simulation tools appropriate?

**What of entry from other automated lanes (AHS networks)?**

If there are several ALs on different rights-of-way, interchanges between them will require special structures. Entry from these will probably be from the left rather than the right. There may need to be different entry protocols to cover this case, especially if pre-platoons have to be formed. Further, if there is more than one AL, the problem of passing over to exit on the desired side will present problems.

It is suggested that these problems may be referred to briefly, but only to exclude them from consideration in the present work. This is for our follow-up funding.

**III. CONFIGURATIONS FOR AUTOMATED TRANSITIONS**

In this paper we have discussed only the situation in which entry occurs from manual freeways. If the ALs are on a separate structure, or if they have separate on-ramps and offramps, the situation is different in that vehicles do not have to enter through a gate. However, there will still be CCLs, EMLs, and XMLs of limited length, so the protocols considered above will still be
necessary. The details of lane-change for entry and exit may be marginally different, though anything that will work with gates will also work without them.

However, unless no ALs that are entered from manual lanes are ever constructed, all vehicles must have control systems that can cope with entry from manual lanes. There may little point in complicating the control system so that it will behave differently on automatic and manual entry. In that case, we should use the same protocols considered here, with the proviso that it must be possible to use the minimum-length-EML protocol, which involves having the entering vehicles stationary.

**REFERENCES**


Figure 1. Layout of transition lanes of an automated highway system

At left, in the control-change length, vehicles enter from the manual lanes onto the transition lane, where the AHS assumes control. Vehicles rejected by the system are shuttled to the dormitory (configuration of the dormitory is still moot). In the central entry-manuever length, vehicles may be formed into pre-platoons at low speed if desired. Once on the automated lane, single vehicles or pre-platoons are added on to existing platoons at the rear (no joining of platoons at speed). At the right, in the exit-manuever length, vehicles exit the automated lane one at a time through a gate onto the transition lane. If more than one vehicle leaves a particular platoon, they leave by separate gates (here the second car in a platoon has already exited and the fifth car is leaving). After they have left, they slow down and as they leave the part of the transition lane that has a barrier, drivers are invited to take control again.