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Configuration and Maneuvers in Safety-consciously Designed AHS Configuration

by

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ABSTRACT

This paper sets out a configuration for an Automated Highway System (AHS) which the author believes to have advantages from a safety viewpoint. the configuration and operating principles are described. The scheme requires that vehicles change lane directly from platoon to platoon, and that entry and exit be made also without platoons merging or splitting on the automated lanes. The protocols for the maneuvers needed are described in detail.

The paper is based on one written as part of a proposal to colleagues within the entry/exit project of the FHWA funded AHS Precursor Systems Analysis.

INTRODUCTION: SAFETY CONDITIONS

Varaiya and Shladover (1991) have described a basic architecture for a platooned AHS system in terms of five layers (see figure 1). In this scheme the two upper layers—network and link—manage the distribution of flow between lanes, routes of vehicles and general system parameters. The other three layers form the safety-critical subsystem. The coordination layer organizes *maneuvers* by means of which vehicles and platoons make coordinated movements. They may, for example, change lane, form platoon, enter or exit. Hsu et al.. (1991) have described one possible set-up and show that three particular maneuvers suffice in normal operation. The regulation layer controls the movements of vehicles to execute the maneuvers, while the physical layer reflects the operation of sensors and vehicle controls.

This paper accepts the architecture of Varaiya and Shladover (1991). It describes the maneuvers in normal conditions for another AHS system of one or more automated lanes (*ALs*), which share a structure, on-ramps and off ramps with manual lanes (*MLs*). There is a transition lane (*TL*), for at least part of the length of the freeway, which permits entry to and exit from the ALs. The ALs occupy the leftmost lanes of traffic moving in either direction, and the TL lies between the ALs and the MLs.

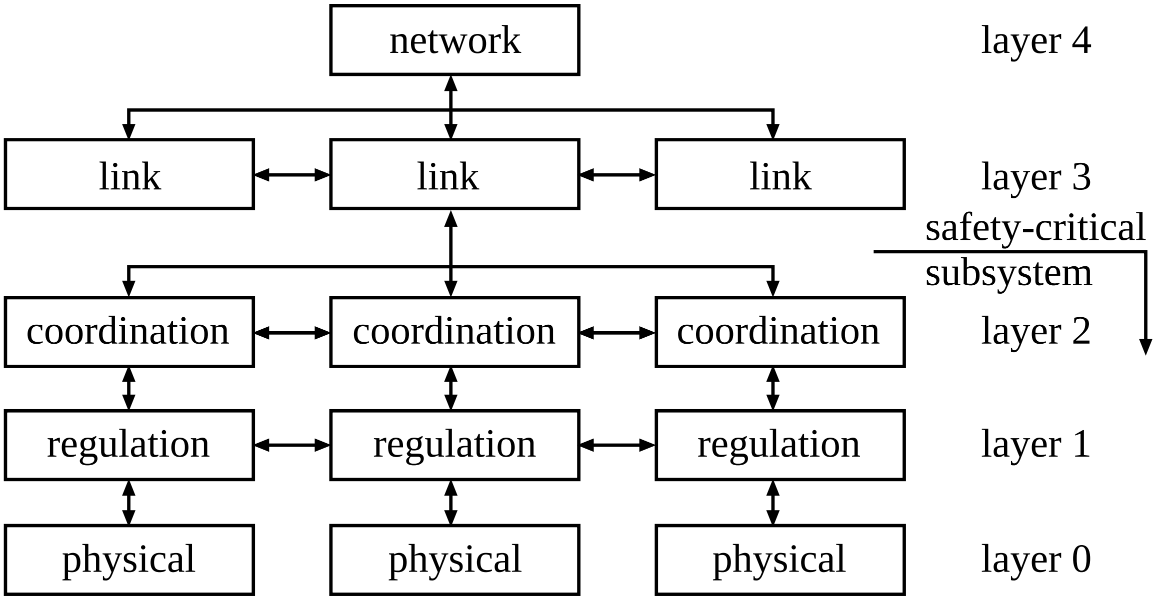

Figure 1. IVHS Control Architecture

This design is intended to conform to certain safety principles, stated below. It is our contention that the features of configuration and operational design described here are necessary to ensure operation without excessive injury to persons.

The safety principles involved are explained in Hitchcock (1993a, 1993b,1994). They are:

a. The vehicles are organized into close-spaced platoons. Hitchcock (1994) shows that other configurations will have a significantly greater casualty rate, unless the automatic braking system has a reliability higher than credible.

b. There is a barrier (or divider) between the automated lanes (AL) and manual lanes (ML) on the rest of the right-of-way. Hitchcock (1993a) shows that if this is absent, an unacceptably high rate of secondary casualties on the ALs results from accidents on the MLs. This implies that vehicles must join and leave through “gates” in the dividers.

   Further, if there is more than one AL and there are no dividers between them, there will also be an unacceptably high casualty rate. This arises because of the possibility of failures in the lateral control system, which again would have to be incredibly reliable to avoid the effect.

c. Platoons do not join together (*merge*) at speed, either on the ALs or on the transition lane TL, which is the lane where manual/auto and auto/manual changes occur. Hitchcock (1993b) shows that if this is permitted, failures in any credibly reliable automatic braking system can again generate an unacceptably high casualty rate. This implies that vehicles must join and leave platoons from a close-spaced configuration.

d. We add a fourth condition, more closely related to the safety of the operators’ jobs than of the users’ skins, that failure to leave the AL at the selected destination must be extremely rare, and arise only in rare fault conditions which the driver can understand, even if he has little sympathy for the decision. Equally failure to enter, unless dictated by attainment of a capacity limit, must be the consequence of a fault. It is not satisfactory for these failures to arise as a result of a random variation.

DESIGN OF SAFETY FEATURES

1. Design of Dividers

When seeing a plan diagram like figure 2, many people reject the idea of a divider because the think it must resemble a “Jersey Beam”—the 90 cm high 60 cm wide concrete structure often used on today’s freeways to protect construction workers during road widening, or sometimes when there is no space for a central median gap.

It is indeed true that failures in the lane-change controls will probably occasionally result in a cars striking the divider end-on. Such an incident will block two lanes and cause congestion. It must be rare enough that such congestion and the damage to the vehicle are acceptable risks. But the design of the divider must be such that there is no injury to persons. To achieve this the divider

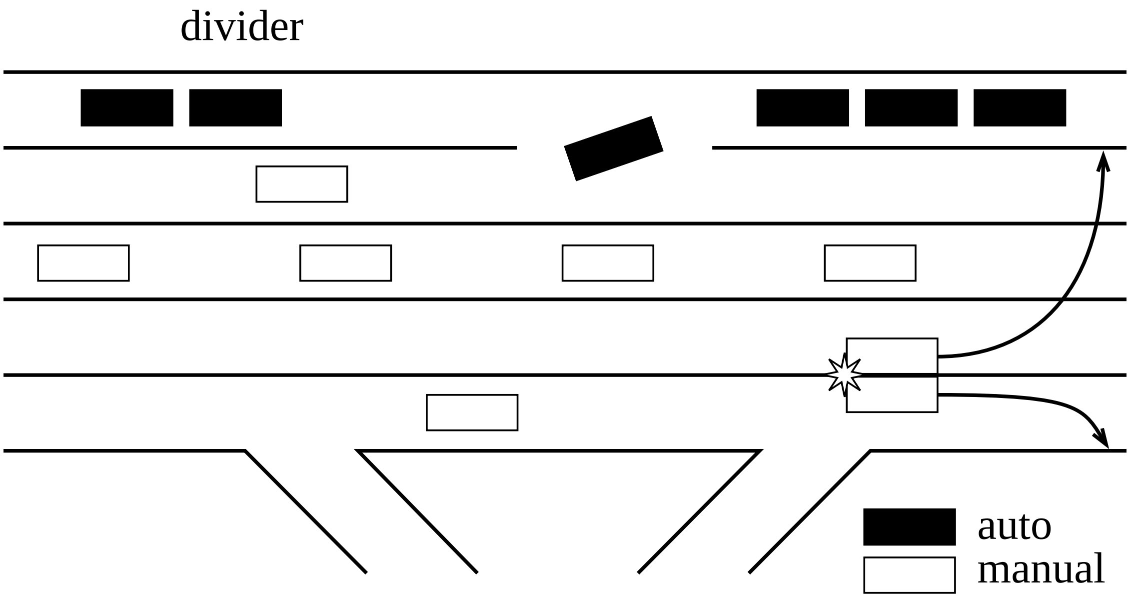

Figure 2. AHS configuration, showing a “relevant accident” and position of divider. The divider separates the automated vehicles from the manual ones, and so prevents the debris from a relevant accident intruding on the AL. Anwar and Jovanis (1993) discuss the frequency of such accidents. Hitchcock 1993a shows that they would lead to many fatalities in automated vehicles in the absence of a divider.

must offer strong resistance to vehicles which are driven against it from the side, but only sufficient resistance to produce decelerations of around 1 g (10 m/s^2) when struck end-on. The divider should not break the passenger compartment.

Figures 3 and 4 show two ways in which this may perhaps be achieved. The author is not a structural engineer, and offers these “designs” as indications only of the possibilities. Experiences shows however, that it is necessary to point out that it is possible to construct dividers with the right properties.

Figure 3 shows a divider suitable for the AL/TL or AL/ML border. Here the divider must provide protection against the debris of a “relevant accident” in the sense of Anwar and Jovanis (1993). A “relevant accident” (see figure 2) is one in which a collision on the manual lanes (beyond the control of the AHS) projects, if not prevented, debris to the left lanes, where the ALs are. Such debris can approach the divider at an angle of 90^0 or more. The divider will need to be about I meter high, so that it does not obstruct the car occupants’ view, but it will interfere with the opening of the door. Near a gate, and above 5-15 cm from the ground, it consists of vertical rectangular members, perhaps 15 cm by 2.5 cm, with the longer side perpendicular to the line of motion of the traffic. Braces are provided to prevent twisting. If the divider is struck from the end, the one-inch thick members will bend, and slow the vehicle down. Struck near right angles, the divider will resist penetration. Well removed (?100 m) from the gate, other designs will be permissible.

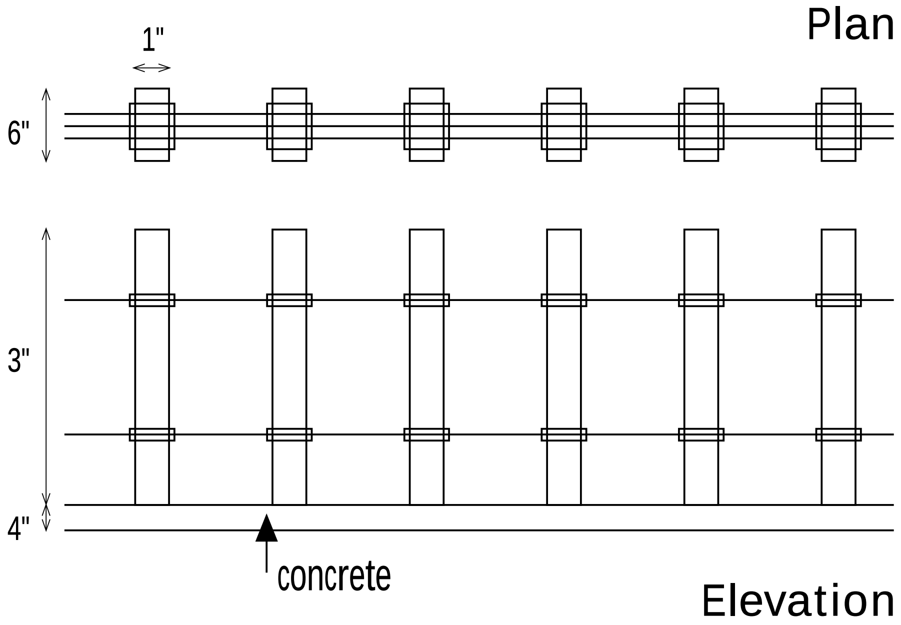

Figure 3. AL/TL divider. It consists of vertical rectangular struts with the short side (? 1") parallel to the direction of motion. A vehicle striking the end of the barrier, e.g. while entering the AL, meets relatively resistance but is stopped eventually by bending the struts. One striking transversely meets strong resistance and cannot penetrate to the AL. Braces are provided to prevent the struts twisting.

Figure 4 shows a divider suitable for an AL\AL border. It is no more than 23 cm high, so that a car door will open over it. Near the gate it is lower so that if a vehicle runs on to it, its wheels will straddle the divider. As such, as the vehicle proceeds the divider becomes higher, and the vehicle's axles will encounter energy-absorbing material like sand or corrugated metal which it will run over or crush. Everything will happen under the passenger compartment, which will not be penetrated. Between two narrow (2.5 m ?) ALs, a vehicle cannot achieve any large transverse speed, so that a low barrier suffices.

2. Design of gate

The term "gate" is used to describe a gap in the divider through which a vehicle can change lane. It is not proposed that there should be any moving component. The length of the gate should be as small as possible, consistent with permitting all vehicles to pass with comfortable occupants. It may be desirable to provide electronic markers which help that part of the vehicle control system which deals with lane changes to locate the maneuver appropriately in relation to the gate. It may also be desirable to provide in the infrastructure some check that a lane change will not side-swipe another vehicle. Finally, some communication equipment may be provided at the gate, for example to provide the system speed in the new lane to a changing vehicle. These latter features will depend on detailed system design and are not relevant to the present discussion. Gate length is, however, basic.

We take the experimentally-based conclusions of Caywood et al. (1977) about maximum acceleration and jerk. For lateral motion they recommend a maximum acceleration of 0.24 g and a

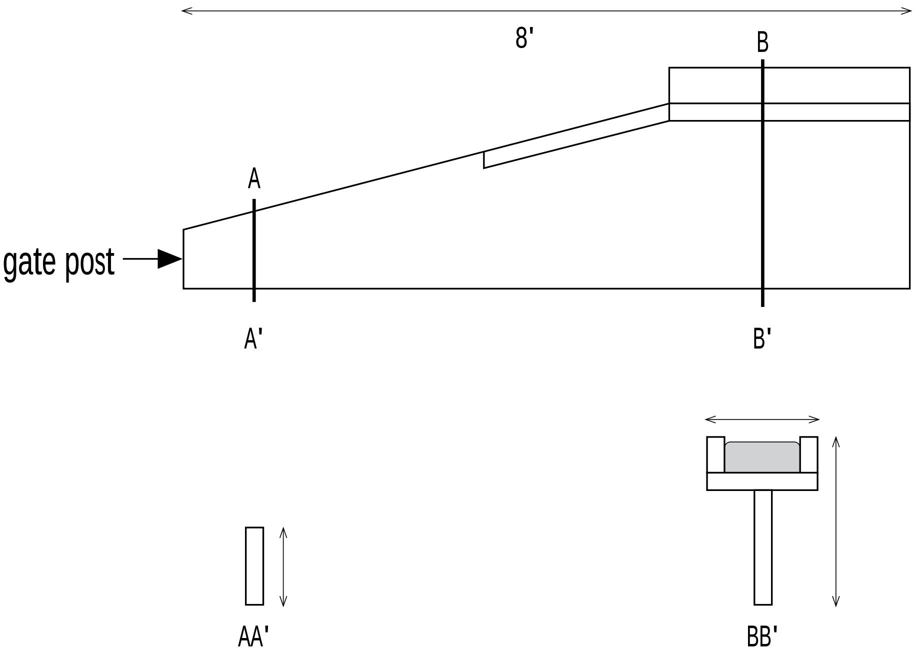

Figure 4. AL/AL divider. This is so low that it will pass under a car. It permits door opening in emergency. If a lane changing vehicle comes to straddle it, the sand on the top accumulates against the axles and slows the vehicle, but not too quickly. AA' is the crossection at the edge of a gate: BB' is 8 ft downstream of this.

jerk of 0.12 g/s. An ideal transverse velocity profile for lane change is as sketched in figure 5. We assume longitudinal speed, **v**, does not change during the maneuver, and the minimum length of gate is therefore the speed times the interval over which a lane-changing vehicle may overlap the divider, whose width will be called γ. This may be slightly reduced if the vehicle is initially displaced a small distance, δ, from the center of its lane towards the non-gate side. However, it cannot be assumed that all vehicles will follow the ideal trajectory, and allowance must therefore be made for an error in lateral displacement of ε. The gate length will also depend, clearly on the maximum width, α, of a vehicle at divider height, and the lane width β.

We have carried out the calculation for the following values of the parameters:

$\alpha = 2.5$ m (8' 4"); $\beta = 1.875$ m (6' 2"); $\gamma = 0.05$ m; $\delta = 0.25$ m; $\varepsilon = 0.25$ m; $\mathbf{v} = 30.0$ m/s.

With these values the gate turns out to be very nearly 80 m long, and clearly this value will not be very sensitive to any of the parameters.

3. Location of Gates

A gate offers the opportunity for a control system failure to cause a vehicle to wander into the wrong lane. This is dangerous. Gates are required for lane changing, and the danger cannot be avoided altogether, but it can be reduced in the following ways:

a. Anwar and Jovanis (1993) report that some 50% of “relevant accidents” occur within 50 m of an off- or on-ramp. Unprotected gates between TL and AL in this region should be avoided.

b. One possible source of intrusion is a within-platoon collision which causes lateral displacement of a automated vehicle. The lateral control system will resist this, but may not succeed. Such a displacement is clearly more likely if the road curves: straight sections are therefore preferred locations for gates.

MANEUVERS

The only coordination-layer maneuver that is possible or necessary in this regime is changing lanes through gates. Entry and exit are clearly special cases of this. There are a number of variations, all of which can readily be accommodated within one lane-change maneuver protocol. The variations arise because one or more vehicles may pass through a gate consecutively, and because a vehicle can join a *receiving platoon* or leave a *giving platoon* at the front, middle or rear.

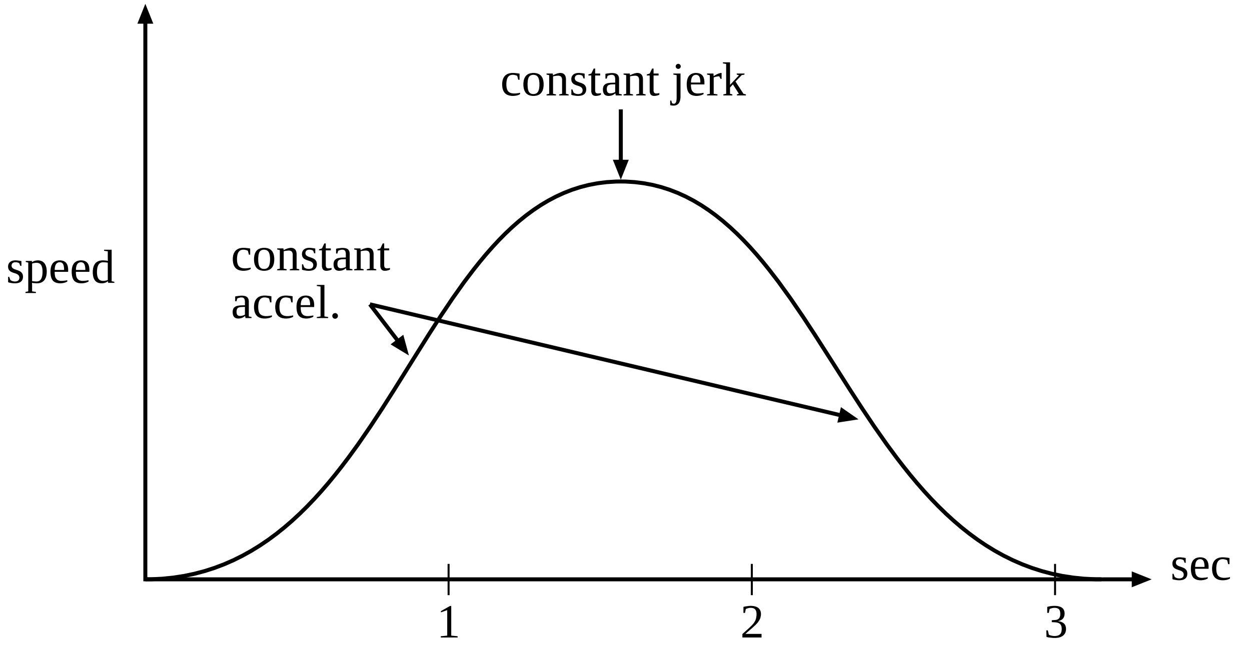

Figure 5. Transverse speed profile for lane change. The curve is made up of constant-jerk and constant acceleration sections. The area beneath it equals lane width.

1. Changes in intra-platoon spacing

In normal operation there is to be no large-scale merging of platoons, and consequently there can be no splitting. Vehicles will join and leave platoons by passing through a gate from an adjacent lane into position as a platoon member. There may have to be a marginal increase of the space between a vehicle leaving a platoon and its neighbors in the giving platoon, to allow room to turn and space to react to the strong aerodynamic forces which the leaving vehicle will experience.

If this is necessary at all, the required increase in spacing can hardly exceed 0.5 m. or so. Further, if a receiving platoon is to admit a lane changer into its middle, the vehicles in it must separate by a little more than a vehicle length to create space for it. Hitchcock (1993b) shows that this creates no additional danger.

Similarly, after a lane change is made, the vehicles in the receiving platoon may need to adjust intra-platoon spacings to more normal values. The usual intra-platoon aspects of the control system should accommodate this without special orders. Those in the giving platoon may need to close up the gap left by the parting vehicle. Hitchcock 1993b shows that while this maneuver does involve some additional danger, it is much less than that of a merge across the full interplatoon spacing. However the casualty rate is more than tripled if the closure is over two or more vehicle lengths, and increases rapidly as the gap gets larger.

It seems impossible to devise maneuvers which do not involve closure over one vehicle length, and here the related risk is accepted. However we insist that each closure should be complete before another starts in the same platoon (they last about 5 seconds) and that closures involve one vehicle length only.

2. Changes in interplatoon spacing

With no merging or splitting, once a platoon is formed near the beginning of an AL it will retain its identity for a considerable distance—it can only disappear if at some point it contains only vehicles whose destination is the next exit, or if they all join another platoon in an adjacent lane. This latter may be desirable in some fault conditions, but reduces capacity in normal conditions. The number of platoons per km of road is thus more or less fixed by entry arrangements in the upstream two or three entry points.

There are other possibilities which are not excluded on safety grounds, but here we shall assume that in fact a form of point-following control[1] is used for platoons, so that the platoon leaders (or perhaps the platoon trailers) are at a constant headway (of the order 4 to 7 seconds). If a platoon vanishes because its members all depart, a gap is left ready for vehicles to enter and join as though it were a full platoon. It is convenient to regard such a gap as a platoon of zero members.

At low flows it is unlikely that so many vehicles wish to join a platoon at a given point that the interplatoon safety spacing is violated. In this region the distribution of numbers of platoon members at any point is a Poisson one, with the mean of the distribution proportional to the flow at that point. If it is assumed that arrivals of vehicles at entry points are random and uncorrelated, this result is readily proved, provided all vehicles are equally likely to have each destination (though some destinations may be more attractive than others). At higher flows it is more likely that the demand, if satisfied would violate the safety spacing. If this happens a variety of reactions is possible, and they can be combined:

a. refuse admission to some vehicles, leaving entry queues;

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[1] Point-follower cohis a control scheme in which the control system creates a series of equally-spaced electronic marker points which move along the AL with the same constant speed. It is sometimes called “slot control”.

b. cause some or all following platoons to slip back;

c. reduce speed so as to reduce the safety spacing. This will be effective initially, but as speeds drop, capacity increases more slowly and them starts to reduce.

Which is chosen is a question for the design of the link level maneuver protocols, and is not immediately relevant here. Provided safety spacings are not violated, the choices do not involve safety considerations.

In any event, the number of platoons per unit length is a constant of the system (6 platoons/ km looks reasonable). As will be seen, if there is more than one AL, it facilitates lane changing if their leaders are normally adjacent.

3. Change-lane protocol

We shall describe one possible protocol for a single vehicle to move from the center of the giving platoon through a gate to the center of the receiving platoon in a 2-plus AL system in which intelligence is concentrated in the vehicles. The leaders of the two are adjacent. Every vehicle contains an odometer which is zeroed at a *gate-marker* in each lane a small way upstream of each gate. Thus each vehicle can state the longitudinal position of its front and rear to an accuracy of a few cm. The markers are aligned, so that relative positions in each lane are known. There is also a *turn-marker* in each lane which indicates to a turning vehicle where its turn should start.

Further, each vehicle has a record of its own length, and the platoon leader has a record of the length of each vehicle in the platoon, so that the nominal position of each vehicle's end is known to the leader. This phrase, nominal position, excludes variations which the within-platoon controls will attempt to zero. Sensors on all vehicles can detect the rear of vehicles in an adjacent lane ahead of them, and the fronts of adjacent vehicles behind them. This implies that a low divider (see figure 4) is present, which permits sensing across it.

Figure 6 shows the position before the maneuver starts and labels vehicles A, a, B, b, C, c and X. X is the vehicle which will change lane, and other capital letters refer to the giving platoon. Lower-case letters refer to the receiving platoon.

We shall call the normal intra-platoon separation δ. There is a known function β**(t),** which describes the average longitudinal displacement of a vehicle changing lane from the separation which the longitudinal control system is aiming for. This displacement arises from the interaction of the control system with aerodynamic forces and other variable forces which occur during lane change. Here **t** = 0 at the turning marker, and $\beta(o) = 0$ also. β is positive if the forces cause the vehicle to increase its separation. β' and β'' are maximum and departures c| β**(t)** from zero thus:

$$\beta' \geq \beta(\mathbf{t}) \geq -\beta'' \text{ for all } t,$$

There is also an additional margin γ to allow for uncertainties which arise because aerodynamic effects will depend on the wind, because there will be variations in behavior between different marques of vehicle and control system. There may also be random effects. See also figure 7.

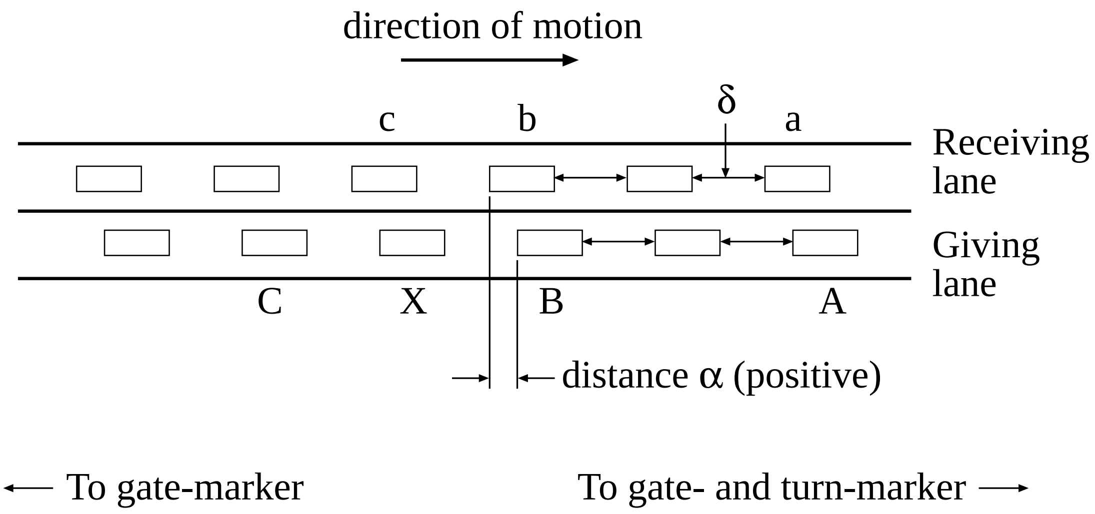

Figure 6. Change lane maneuver: positions of vehicles mentioned in protocol.

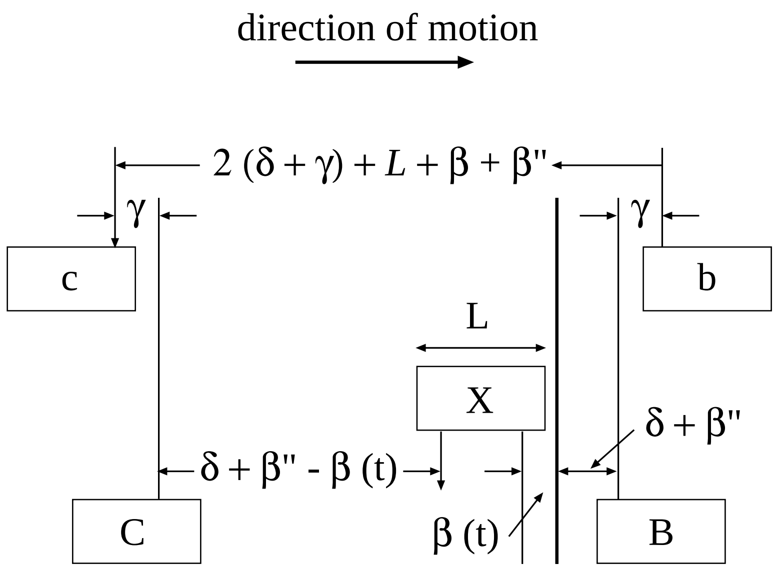

Fig 7. Change lane maneuver, illustrating nomenclature of longitudinal separations.

Precise values will need to be examined in detail, but intuition[2] suggests that γ will be about 0.25 m, β' will be around 0.35 m and β'' will be less than 0.1 m, while δ will be 1 m. The length of X will be called **L**.

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[2] The “argument” goes like this. In normal operation the control system keeps vehicles in position in a platoon within ± 5-10 cm. The aerodynamic forces are a large sudden disturbance and a displacement of several times the normal size, so a displacement of three plus times this size is possible. This gives 35 cm, in the direction of the aerodynamic force, ie rearwards. This gives β'. However, the control system is heavily damped and overshoots in the control system are around zero. Let us say the maximum value of overshoot, β'', will not exceed 10 cm. Finally, we need an allowance for differences between marques in both directions. Perhaps the mean of β' and β'' will do for γ.

Our example protocol is now as follows. The presence of an underline (_) in a word indicates that the word is the name of a message.

1. X has passed the gate marker, and sends to A request_change_lane.
2. A examines its busy marker and its length, and either returns nack_change_lane to X, or sets “busy” and sends OK_change(X, **L**, **y**) to a. This message identifies the position of the front of X and L. y is the maximum distance A can advance on the platoon ahead of it.
3. a examines its busy marker, and either sends nack_OK to A or sets busy and sends ack_OK to A.
4. If A receives nack_OK it resets busy and sends nack_change_lane to X. Else it sends ack_change_lane(L) to X and C.
5. If X receives nack_ .. no further action. Else X sets its platoon following distance to $(\delta + \beta'')$. It may displace itself laterally away from the gate.
6. On receipt of ack_change_lane(L), C assumes the position of temporary leader, advises vehicles behind it, and starts to transmit control messages back. It attempts to follow X at a distance $(\delta + \beta')$. C stores the value of L.
7. a identifies b as the vehicle whose rear is closest to the front of X. It calculates α as the offset between the rear of B and the rear of b (sign as in fig. 5). It sends drop_back(**L**) to c. If $(\gamma - \alpha) < \min(\mathbf{L/2}, \mathbf{y})$, it also sends go_for($\gamma - \alpha$) to A. Else it sends go_for(0) to A, and drops back $(\gamma - \alpha)$.
8. On receipt of drop_back(L), c assumes the position of temporary leader and transmits control messages to the vehicles behind it. It attempts to follow b at a distance $2*(\delta + \gamma) + \beta' + \beta'' + \mathbf{L}$. When it has attained a distance $2*\delta + \gamma + \beta' + \beta'' + \mathbf{L}$, it sends got_back to a.
9. On receipt of go_for(x) A accelerates slightly, until it is a distance x ahead of a (or, if x is -ve, it decelerates)
10. When a has both received got_back and dropped back $(\gamma - \alpha)$ if it has to, it sends in_pos to A.
11. When both in_pos has been received and A is as far ahead of a as requested, A sends all_OK to X.
12. If X reaches the turn marker before receipt of all_OK, it sends time_up to A.
13. If A receives time_up or no_go (see step 17), it checks whether there is another gate within (say) 250m. If there is it sends next_gate to X and C, and next_gate_1 to a. On receipt of next_gate_1, a sends next_gate_2 to c. If there is no gate near, A sends abort_change to X and C, and abort_change_1 to a. It resets busy. It decelerates to realign itself with a.
14. On receipt of abort_change, X and C revert to usual control laws. C ceases to be a temporary leader.
15. On receipt of abort_change_1, a sends abort_change_2 to c.
16. On receipt of abort_change_2, c resets its desired separation from b to δ. It ceases to be a temporary leader. When it has closed the gap with b, it sends closed_up to a.
17. On receipt of closed_up, a resets busy.
18. (May succeed 12). When X reaches the turn marker, it checks that b is at least $\gamma + \beta''$ ahead of it, and c is at least $\gamma + \beta'$ behind it. If these conditions are not satisfied it sends no_go to A. Otherwise it sends I_go to A and C and its lateral control commences the change-lane maneuver.

    From here on, no external message indicating a fault condition will cause the maneuver to abort.
19. On receipt of I_go, A sends change_on to a.

20. On receipt of change_on, a sends change_on_1 to c.
21. On receipt of change_on_1, c accepts the timing given by the turn marker as valid for longitudinal control.
22. On receipt of I_go, C accepts the timing given by the turn marker as valid for longitudinal control.
23. Initially, X’s longitudinal control will attempt to keep a distance $\delta + \beta''$ behind B, achieving $\delta + \beta'' + \beta(t)$, while checking that it is always at least $\gamma + \beta'' + \beta(t)$ behind b. When it is around half-way over, it will switch to keeping $\delta + \gamma + \beta'' + \beta\mathbf{(t)}$ behind b, while checking that it is always at least $\beta'' + \beta\mathbf{(t)}$ behind B. (If the check fails we have a fault condition, which needs not be discussed here.)
24. When C reaches the turn marker it sets its timer to $(L + \delta)/v$, where v is the system speed. Throughout the maneuver C will attempt to stay $\delta + \beta' - \beta\mathbf{(t)}$ behind X.
25. Initially c will attempt to remain $2*(\delta + \gamma) + \beta' + \beta'' + \mathbf{L}$ behind b. As the maneuver progresses it will be able to identify X and when the sighting is certain it switches to remaining $\delta + \gamma + \beta' - \beta(t)$ behind X.
26. When X has fully changed lane it sends Im_thru to a and c. It attempts to remain δ behind b. When it is reasonably near this target it sends X_close to a.
27. When a receives Im_thru it sends change_over to A. It also updates its control data and transmits control messages to the new platoon.
28. When c receives Im_thru, it ceases to act a temporary leader, and accepts control messages for the new platoon from a. Thus it attempts to remain δ behind X. When it is reasonably near this target it sends c_close to a.
29. When a has received both X_close and c_close, it resets busy.
30. On receipt of change_over, A sends change_over_1 to C. It also updates its control message.
31. On receipt of change_over_1, C resets its desired separation from B to δ. It ceases to be a temporary leader. When it has closed the gap with b, it sends closed_up to A.
32. On receipt of closed_up, A resets busy.

A flow-diagram is given in figure 8.

4. Variations on change-lane

Some changes to this protocol will be necessary in special circumstances. Included, by implication, is the case where the receiving platoon is too short for a gap to be formed opposite the changer. Here the receiving platoon must drop backward far enough for the changer to join its end. In this case the vehicle c in the above description does not exist, and its actions can be omitted from to the protocol. Note that at step 29, busy can be reset on receipt of X_close while at step 17 busy can be reset on receipt of abort_change_1.

In the case where the changer is the last vehicle in the giving platoon, so that C is absent, it should be noted that, besides omitting the steps referring to C’s actions, A can reset busy at step 30.

The adjustments where the changer is the platoon leader are a little more complex -here most reference to A about the sending or receipt of messages should be changed to refer to C, and C does not surrender its leader status.

More important changes occur when the change is to or from the TL.

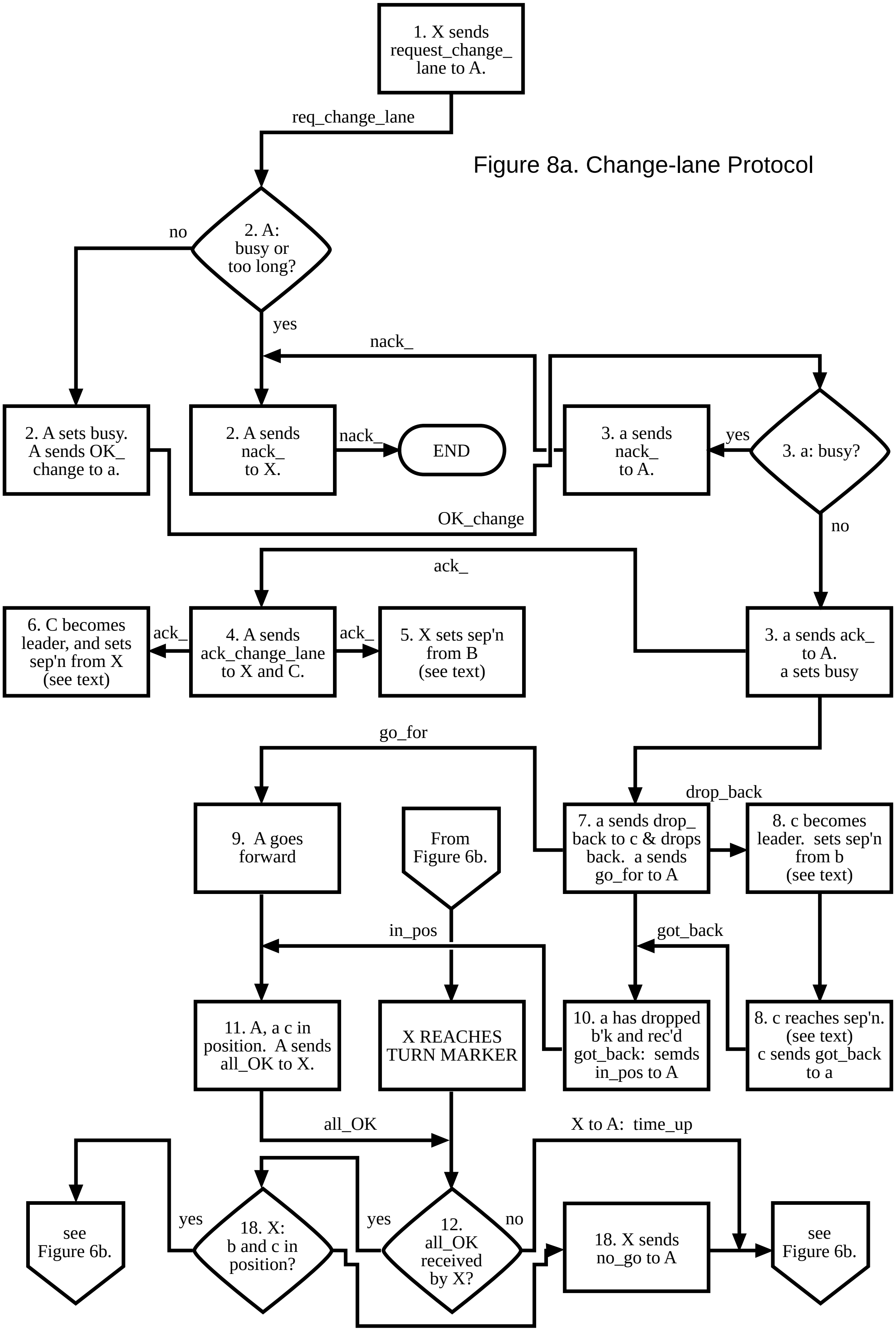
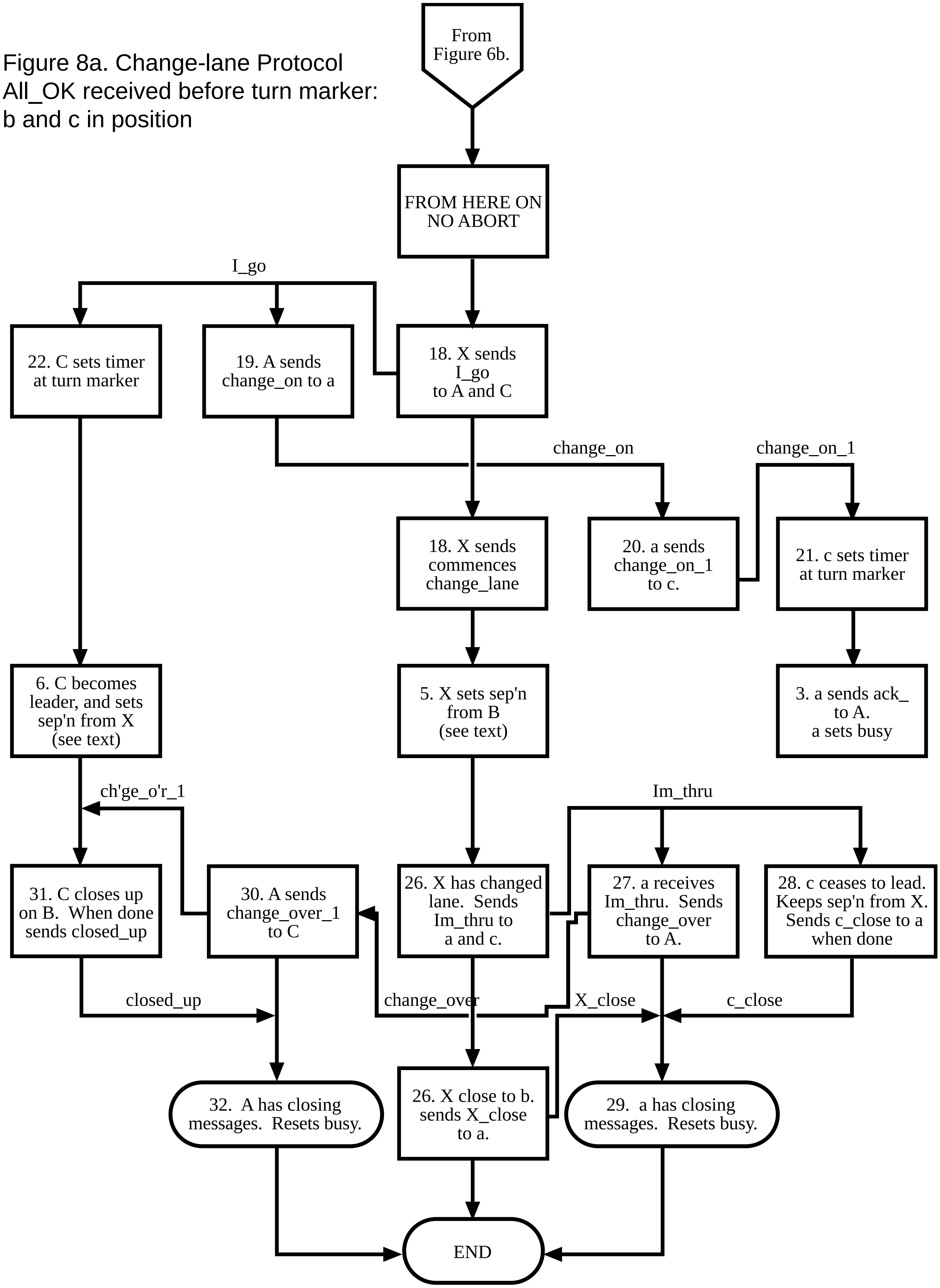


Figure 8a. Change-lane Protocol

Figure 8a. Change-lane Protocol
All_OK received before turn marker:
b and c in position



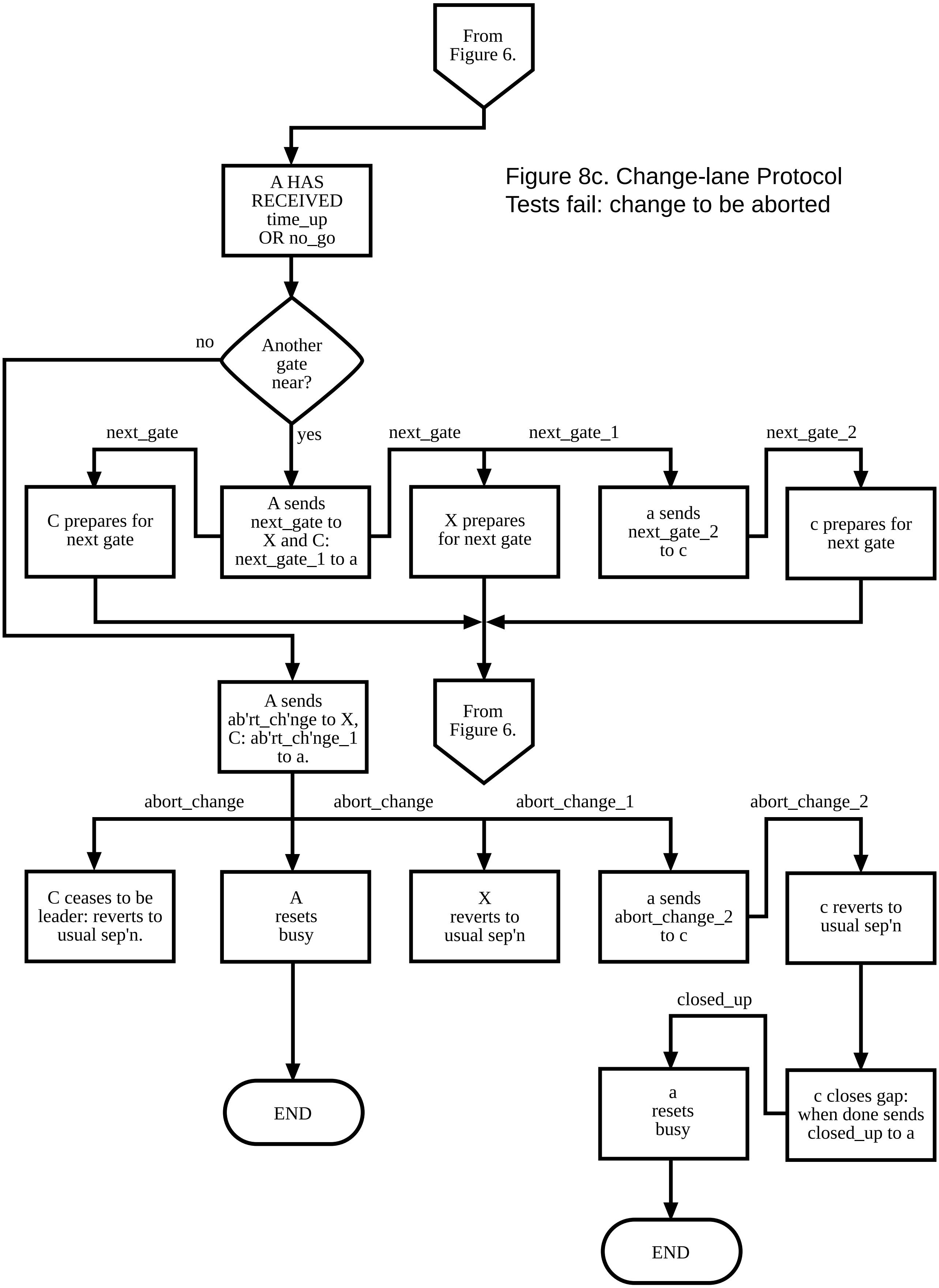


Figure 8c. Change-lane Protocol
Tests fail: change to be aborted

5. Change-lane at entry

If the change is an entry, then (see paper about entry and exit) the entry will always take place at the rear of the receiving platoon, and may be by a preplatoon of vehicles, headed by A. The early stages of the maneuver are controlled from the roadside by R, which has data about the timing and length of each passing platoon, headed by a, and trailed by b. In this case the function $\beta(i, n, t)$ will depend on the number, n, of vehicles in the preplatoon and the position of the i th vehicle within it. It refers to the expected separation between the vehicle i and the one ahead of it if $i > 1$. $\beta(1, n, t)$ is the difference between A and the point trajectory it is trying to follow, caused by variable forces during the change-lane. The steps are:

1. R determines that n vehicles can join the platoon headed by a. n is the least of the number permitted by the platoon length and the number demanding entry. R sends to a entry_for(n).
2. a examines its busy marker and either sends nack_entry to R, or sets busy and sends ack_entry to R.
3. If R receives nack_entry it will wait the next platoon. Otherwise it instructs A and the following (n - 1) vehicles to set out on a prescribed trajectory, calculated so that A will rendez-vous with b at the gate. Vehicles behind A will adopt following distances $(\delta + \beta''(i, n))$ behind their predecessor. A will act as platoon leader, sending control messages back.
4. As A passes the gate marker, it should be at full AL speed. The divider will be a low one and it should perceive b ahead of it by a distance exceeding $(\gamma + \beta''(1, n))$. If these conditions are not satisfied there is a fault condition: A sends no_entry to R and no_entry_1 to a. A will receive further commands from R which do not concern us here.
5. On receipt of no_entry_1, a resets busy.
6. If the conditions in (4) are satisfied, A adjusts its following law to remain a distance $(\gamma + \delta)$ behind b.
7. Arrival at the turn marker should follow quickly. A’s lateral control will commence the change-lane maneuver. A will zero its time, and its longitudinal control will try to remain $(\gamma + \delta)$ behind b, achieving $(\gamma + \delta + \beta(1, n, \mathbf{t}))$. As each following vehicle reaches the turn marker, its lateral control, will similarly commence the change-lane maneuver and zero its time, and try to remain $(\delta + \beta''(i, n) + \beta(i, n, \mathbf{t}))$ behind its predecessor.

From here on no external message, or message from R, will cause the maneuver to abort.

8. As each vehicle completes its change-lane the target following distance is set to δ, and when each vehicle finds this is reasonably nearly achieved it sends X_close(i) to a.
9. When a has received all n X_close messages it resets busy, and updates its control message.
10. When A receives the updated control message it resets busy, ceases to act as platoon leader, and passes the control message on.

6. Change-lane at exit

At exit, similarly, the roadside controller R is involved. R will be aware of the number of vehicles in a platoon headed by A which wish to exit, and of the position and trajectories of other auto-controlled vehicles on the relevant part of the TL. There should be no manually controlled vehicles here. If, as a result of an earlier fault there are such vehicles present (we call them M), R is aware of their position and speed and so can forecast bounds on their behavior. Here we describe the maneuver primarily as it affects one only of the exiters which we call X. B is ahead of it, and A is behind it. The case where the leader changes lane, so that $X = A$ is covered briefly in what follows. On arrival at the exit, A should not be busy. However, if there is a fault somewhere, it is possible that it is. In this case R will be aware of this, and some no_can_do messages (see 4 below) will have been sent.

The protocol proceeds as follows.

1. Some distance before the exit A sets busy and sends to X query_go.
2. Query_go is received by the driver of X. He/she should send either yes_go or change_exit(n), nominating a changed exit point.
3. If A receives change_exit(n) it sends change_exit_1(X, n) to R which will update records accordingly. If A receives no reply by the time the gate marker is reached, it sends wake_up to X, and change_exit_1(X, 1) to R, causing the projected exit of X to be at the following exit.
4. As A passes the first gate marker it receives exit_gate(X, i [X’, i’, ...]) nominating which gate in the series at the exit is appropriate to X. (In some conditions where there is a previous fault it is possible that R may determine that it is impossible for X to exit at its desired destination. In this case a message no_can_do(X) is passed to A, for passage to the driver and request for a change_exit message. Administrative explanations and apologies will follow in due course.)
5. As the i th gate marker is passed A sends exit_here(L) to X and C. X sets its following distance to $(\delta + \beta'')$. C sets its following distance to $(\delta + \beta')$, and stores the value of L, it assumes temporary leadership and transmits control messages to vehicles behind it.
6. Meanwhile, R is monitoring the movement of M if it exists. If it appears that M will be too close to X at exit, it sends dont_go(X) to A. This will be followed by a second exit_gate(x, i, X’, i’, ...) message and possibly some no_can_do messages.

After A has passed the turn marker, no message will cause the maneuver to abort.

7. When X reaches the turn marker, its lateral control starts the change-lane maneuver. It sets its timer to zero, and its longitudinal control attempts to remain $(\delta + \beta'' + \beta(t))$ behind B. If X is A, its longitudinal control tries to remain $\beta(t)$ behind the point it is following, and sends take_over to C. A resets busy.
8. When C reaches the turn marker it sets its timer to $(L + \delta)/v$ (where v is the system speed), and tries to stay $(\delta + \beta' - \boldsymbol{\beta}(\mathbf{t}))$ behind X. If C receives take_over it assumes platoon leadership and transmits control messages. C also sets busy.
9. When X has exited it sends Im_out to R. Thereafter, R will cause it to decelerate, on a prescribed trajectory which will keep it out of the way of other exiters. In due course will offer the driver manual control. Detail and further action will not be discussed here.
10. When R receives Im_out it assumes control of X’s trajectory, and sends hes_out to A (or C if X was A).
11. When A receives hes_out it sends change_over to C. It updates its control message. If X was A, then C will attempt to close up on the point it has to follow, but further exits can follow at once. If there are none, C resets busy.
12. When C receives change_over it ceases to act as platoon leader. It sets its desired separation from B to δ. When it has closed the gap reasonably well it sends closed_up to A.
13. On receipt of closed_up, A will send any further exit_here messages which are needed (see step 5). If there are none, A resets busy.

In some fault conditions an entire platoon will have to change lane or exit. The protocol for this is not discussed here.

DISCUSSION

The protocols proposed here have not been verified[3]. They have not been shown to be complete, either in the sense of Hsu *et al.* (1991)—i.e. that they do not lead to any position where further actions are undefined, or in the more rigorous sense that they imply that every vehicle will, unless a fault intervenes, exit at its desired destination. It is believed, however, that both these conditions are met.

Further, they are not unique. Clearly they can be changed in many places to substitute sensor action for message-passing or *vice versa*. More radical alternatives may also be possible.

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[3] The terms "verified" and "complete" have specialized meanings in this context. (see Hsu et al. 1991). It was an objective of the work reported here in proposed protocols which could then be verified—i.e. shown by mathematical process to lead always to a safe condition. This work was done by associated workers (Sach, Datta, and Varaiya) whose work is not yet published.

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