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TRAFFIC CONTROL FOR AUTOMATED HIGHWAY SYSTEMS: A CONCEPTUAL FRAMEWORK

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EXECUTIVE SUMMARY

The task of traffic control for Automated Highway Systems (AHS) is drastically different from and much more complex than its conventional counterpart. This paper proposes a conceptual framework for designing a traffic control scheme. It adopts a top-down approach to defining major design steps starting with high-level feature definition. Since all AI-IS control features materialize through vehicle movements and there exist an infinite number of possible vehicle movements, specifying these movements and verifying that they indeed suffice for the desired features could be extremely complicated. One approach to simplifying such tasks is to define a small number of permissible *moves* as "building blocks" and define all permissible movements in terms of these moves. With the desired features defined, the top-down approach then identifies and defines *moves* and related planning and movement *functions* that are required for supporting the desired features.

Central to traffic control is planning, including system flow planning and vehicle movement planning. The former tries to optimize the *macroscopic* flow of *aggregate* traffic in the AHS while the latter plans for the *microscopic* movement of *individual* vehicles. Making the actual movements according to the vehicle movement plans requires the most detailed data about the immediate neighborhood affecting or affected by the movements. To ensure safety, initiation/continuation/abort conditions for all permissible vehicle moves must be clearly and safely defined at this level of detail. Since vehicle movement plans are generated by various controllers in the AHS, the planned vehicle moves have the potential of conflicting and interfering with one another. Based on key attributes of a move and the concept of initiation/continuation/abort conditions, we are able to define *rigorously* the concepts of *conflict* and *interference* among different moves. Such conflicts must be recognized and resolved in

time for safety; they should also be prevented at the planning stage. Such interferences should be minimized for efficiency. A “running” example defining the traffic control scheme of a simplified AHS operating scenario is provided for illustration.

Although fully automated AHS with advanced traffic control features have the potential of improving performance, conflict recognition and control coordination can potentially be very complex and susceptible to design errors and system failures. This may in turn infringe on AHS safety. This issue should be carefully examined and a balance among capacity, safety, cost and other AHS design objectives should be sought.

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(1) INTRODUCTION

The Importance of AHS Operations

Automated Highway Systems (AHS) have the potential for offering large capacity and safety gains without requiring significant amounts of additional right-of-way. Recent advances in key AVCS (Advanced Vehicle Control Systems) technologies have shown the potential of highway automation. Given these advances, an opportune and challenging area of research is how to operate an AHS. The need for research effort in this area is evidenced by the recent Broad Agency Announcement “Precursor Systems Analyses of Automated Highway Systems” [3] and Request for Applications for an AHS Development Consortium issued by The Federal Highway Administration (FHWA) of the U.S. Department of Transportation.

Design Issues and Options for Operating AHS

In a recent comprehensive treatment of conceptual AHS design, Stevens [10] discussed AHS deployment and operations goals, analyzed AHS characteristics and identified 37 alternative AHS concepts. With a narrower scope, Tsao et al. [14] recently identified many major design issues and options for operating fully automated AHS. They also addressed the impacts of those options on major AHS performance criteria, including safety, capacity, human factors, infrastructure, cost, etc. Tsao et al. [15] recently proposed seven AHS scenarios for a human factors study. A scenario with a technology emphasis can be found in [4]. Traffic simulation and related capacity studies for particular AI-IS operating/traffic control scenarios include [e.g. 8,131. Rao and Varaiya [9] proposed a roadside controller design to regulate speed, access, egress and lane-change activities for flow maximization.

AHS Traffic Control Scheme

In this paper, an AHS is considered fully automated, i.e. one that performs “hands-off’ and "feet-off’ driving. Given the infrastructure of an AHS and the capabilities of the automated vehicles, a principal component of AHS operation is traffic control, i.e. control of movements of vehicles. In an AHS, the roadside control system and the vehicles themselves are responsible for moving the large number of vehicles safely and efficiently. Therefore, the task of AHS traffic control is drastically different from and much more complex than its conventional counterpart. Note the complete absence of human control of the vehicle. Also note that both the decision-making for AHS traffic control and the required intelligence are distributed between the roadside control system and the vehicles. This is a clear contrast to its conventional counterpart.

Since traffic control materializes through vehicle movements and there exists an infinite number of possible vehicle movements, specifying these movements and verifying that they indeed suffice for the desired features could be extremely complicated. One approach to simplifying such tasks is to define a small number of permissible *moves* as “building blocks” and define all permissible movements in terms of these moves. A *permissible move*, or simply *move* for short, is a collection of permissible vehicle movements performed to achieve a particular purpose. Four moves that are fundamental to all AHS will be identified and will be called *basic moves.* Any non-basic move will be referred to as a *maneuver*. Example maneuvers include the lane-change maneuver and on-ramp metering maneuver.

The entire task of traffic control is realized through moves properly executed. These moves must be carefully planned and “assembled”, including selection, sequencing, timing and locating. A complete specification of how AI-IS traffic is controlled will be referred to as a ***traffic** control scheme* in this paper. The task of traffic control consists of three primary components: (i) ***defining*** the permissible moves, (ii) *planning* for the invocation of the permissible moves to satisfy a multitude of objectives and (iii) *moving* the vehicles based on the planned moves.

One approach to specifying a traffic control scheme is the “top-down” approach, i.e. starting from stating the desired high-level traffic control *features* and then identifying *moves* and related planning and movement *functions* that are required to support the desired features. We adopt this approach in this paper.

The planning functions can be put *in* two broad categories: system flow planning functions and vehicle movement planning functions. The former tries to optimize the *macroscopic flow* of *aggregate* traffic in the AHS while the latter plans for the *microscopic* movement of *individual vehicles*. The plans generated are referred to as system flow plans and vehicle movement plans respectively.

The planning responsibility, as well as the authority to issue movement commands to vehicles, belong to and are distributed among many different ***traffic** controllers.* Due to the existence of a multitude of traffic controllers, vehicle movement plans generated by different controllers may *conflict* or ***interfere*** with one another.

The primary responsibility of the movement functions is to move the vehicles based on the vehicle movement plans. Potential conflicts among different moves must be recognized and resolved for safety. A major difference between the planning functions and the movement functions is that the movement functions use the most detailed data about the immediate neighborhood affecting or affected by a move to ensure safety. These data include all those that are obtainable from the sensors on the *vehicles*. However, the input data for the planning process will most likely consist of data that are aggregate, approximate, and forecast in nature. They, in general, lack the required detail for ensuring safety. Therefore, even in the absence of any conflicts, a plan may not be safely executable. For safety reasons, a set of conditions under which a move can be initiated as planned must be specified. Moreover, another set of conditions under which a move can continue as planned or should be aborted should also be specified. These two sets of conditions will be referred to *as move execution conditions.* These conditions are defined in terms of the most detailed traffic condition in the immediate neighborhood where the move takes place. The level of detail required for safety necessitates the inclusion of the information provided by vehicles' on-board sensors, in addition to the information derived from roadside sensors.

AHS traffic control can be viewed as a decision-making process. There are several general frameworks that characterize decision-making processes. We propose a framework for AHS traffic control that is similar to Anthony's Framework for decision-making. (See [e.g. 2] for a concise introduction.) Anthony [1] classified decisions in three categories: strategic planning, tactical planning and operations control. These categories correspond to our system flow planning, vehicle movement planning and (vehicle) movement.

Purpose and Scope of this Paper

Varaiya and Shladover [17], who initiated the research on the general subject of AHS traffic control, proposed a 5-layer open architecture for major AHS control tasks. This paper adopts that architecture and puts it in a bigger framework. Using the five-layer control architecture, Varaiya [16] proposed a particular AHS operating scenario, including a specific traffic control scheme. This paper deals with general AHS operating scenarios.

Taking a decision-making point of view and based on the well-accepted Anthony's Framework as well as the five-layer architecture, this paper proposes a general conceptual framework for designing a traffic control scheme. By defining the concept of a permissible move, the task of the traffic control scheme can be viewed as nothing but (i) planning the invocation of the moves to achieve the traffic control features and (ii) moving the vehicles based on the plans. By further defining the concept of move execution conditions, we are able to define *rigorously* the concepts of conflict and interference among different moves. We will use one simple AHS operating scenario to illustrate the concepts throughout the paper. This "running" example is provided *only* for illustration and is *not* being advocated as a desirable AHS traffic control scheme.

Our research findings point out the distinct possibility, if not definite certainty, of conflicts among different planned moves and the need, if not definite necessity, to recognize and resolve such conflicts before executing the plans. Safety issues related to the physical motions of adjacent vehicles have received some attention in the literature [e.g. 5,6,12], but safety issues involved in conflict resolution seem to have not. We invite further research efforts in this direction.

Conflict and interference recognition is important not only in the implementation of the vehicle movement plans but also in producing these plans. At the stage of planning, the controllers need to plan wisely to avoid conflicts and interferences among planned moves at implementation time. Given good plans, the conflict-related functions serve as a safety net.

Any AHS deployment should be preceded by detailed simulation; our research findings can also be used to design AHS traffic simulators. They are particularly useful for designing a robust *software structure* that can accommodate the study of a variety of different operating scenarios/traffic control schemes. A companion paper [11] proposed a functional architecture for the planning functions. As pointed out by Tsao [11], although fully automated AHS with advanced planning functions have the potential of improving performance, conflict recognition and control coordination can potentially be very complex and susceptible to design errors and system failures. This may in turn infringe on AHS safety. This issue should be carefully examined and a balance among capacity, safety, cost and other AHS design objectives should be sought.

Organization of this paper

This paper is organized as follows. Section 2 defines the concepts of function and feature. It starts the description of the simple AHS operating scenario to be used as a running example throughout this paper. Section 3 defines the concepts of a *move,* a *basic* move and a *maneuver*. It also discusses key attributes of a move. Section 4 discusses the planning functions, including the system flow and vehicle movement planning functions. Section 5 overviews the movement functions. Section 6 discusses the concept of move execution conditions. Section 7 defines the concepts of conflict and interference among different moves. A brief summary of the framework and the value added are given in Section 8. Section 9 concludes this paper.

(2) TRAFFIC CONTROL FUNCTIONS AND FEATURES

This section first defines the concepts of function, feature, controller and traffic control scheme. The running example is then initiated.

(2.1) Traffic Control Functions

In a fully Automated Highway System (AHS), the roadside control system and the vehicles themselves are responsible for moving the large number of vehicles safely and efficiently. The task of traffic control is drastically different from and much more complex than its conventional counterpart. First of all, it must enable the fundamental goal of full automation of driving (hands-off and feet-off) on AHS. Traffic control is also needed to meet several different major AHS performance criteria, e.g. safety, capacity, fuel efficiency, human factors, air quality, etc. In addition, it could be performed for many special operational requirements, e.g. giving priority to authorized vehicles or high-occupancy vehicles, or diverting traffic from the scene of a traffic accident. In this paper, a *traffic control function* , or simply a *function* for short, is defined to be a capability of the AHS that (i) enables full automation, (ii) enhances AHS in one or more performance areas or (iii) enables a specific AHS operation. Since a function can be supported by other functions and a function can support other functions, functions can be organized in a tree structure with multiple levels.

(2.2) Traffic Control Features

A group of related functions that form a prominent high-level characteristic of how traffic moves or how traffic is controlled on an AHS is called a *traffic control feature,* or simply *feature* for short. A feature is said to be supported by its component functions. A feature is also said to be supported by the functions that support its component functions.

A feature may be supported by both *planning functions* and *movement functions.* For a specific feature, the overlap between the functionality of the planning functions and that of the movement functions may vary. On one extreme, there is no overlap and these two sets of functions simply complement each other. On the other extreme, the only difference could be in the level of detail of the input data. For example, the feature of automated lane-change may consist of planning functions, including *lane-change scheduling* (i.e. timing of initiation of lane-change preparation) and *receiving gap identification* (i.e. identifying the two vehicles between which the lane-change vehicle is to move), and movement functions, including the vehicle lane-change negotiation function, gap preparation function and the culminating lateral move. In this case, the movement functions simply follow the planning functions and there is no overlap in functionality. Another similar example would be the feature of metering at an automated on-ramp. A planning function determines the metering rate and the movement functions implement accordingly.

(2.3) Traffic Controllers

The task of traffic control is performed by various (traffic) controllers of multiple layers. The five control layers proposed by Varaiya and Shladover [17] are network, section † , coordination, regulation and physical. Corresponding to each layer is a type of controller. Since controllers of the last two layers reside on the vehicle, we, for the purpose of this paper, combine them into one and call the combined regulation and physical layer and the corresponding controller the *vehicle layer* and *vehicle controller* respectively. We will consider only the four resulting layers in this paper. (When the term layer or controller is used, it refers to one of these four layers or controllers.) For convenience, we will use the term roadside controller to mean the combination of the network controller and all the section controllers. Note that the intelligence required for the planning and movement functions is distributed among the controllers of all four layers and these controllers together perform the complicated task of AHS traffic control. In particular, each of them may create plans, issue commands to implement the plans, monitor their progress and modify the plans, if necessary. Therefore, the distribution of intelligence and responsibility for traffic control is also a crucial part of a traffic control scheme.

(2.4) Traffic Control Scheme

In terms of these general concepts, a ***traffic*** control *scheme* specifies (i) the collection of *all* features, (ii) *all* the functions that support these features, (iii) distribution of intelligence and decision-making among the controllers, and (iv) how the functions and controllers support the features. Clearly, the traffic control scheme is a principal determinant of AHS performance and should be evaluated against all performance criteria.

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† A section, as meant by Varaiya and Shladover, is simply any segment of highway containing no highway-to-highway interchanges. They actually used a different term - *link*, instead of section. Since the term *link* tends to conjure up the connotation that it is the portion of a highway between two nodes (i.e. highway-to-highway intersections) in a graph or network and the name of the top layer (network layer) tends to encourage such a interpretation, we use the mom "graph-theoretic-neutral" term section.

Three major dimensions of the framework - time, functionality and control dimensions - are illustrated in Figures 2.1, 2.2 and 2.3 respectively.

(2.5) A Simple Scenario

We now describe the simple operating scenario to be used as a “running” example throughout this paper. For simplicity, we concentrate on normal AHS operation. Although the following running example does not contain discussion of functions dealing with abnormal AHS operation (e.g. emergency handling after a vehicle/system failure), the proposed framework is a general one and can easily accommodate emergency maneuvers and associated vehicle movement planning functions, if any. We address only the functions and features of this scenario in this section. The rest will be specified in later sections. To avoid confusion between this running example and other *ad hoc* examples, the discussion of this running example is preceded by the label "→ **Example Continued**” and succeeded by the symbol "●" if the example is to be continued later. The symbol ❑ signifies the end of the running example.

Physical Configuration

The AHS is a stretch of shared highway with three lane types: two automated lanes on the left, two manual lanes on the right and one transition lane in between. The AHS does not intersect with any other highway, i.e. it has no highway-to-highway intersections. The number of automated lanes is fixed throughout the AHS.

All vehicles enter and exit the highway through the manual (conventional) entrances and exits on the right. All automation-equipped vehicles wishing to use the automated lanes have to first move manually into the transition lane. After a successful vehicle inspection, they are first switched into the automatic driving mode and then driven into the automated lane automatically. The two automated lanes are dedicated to use by the automated vehicles.

Traffic Unit

To illustrate the point without having to consider an excessive amount of detail, we choose to use a “free-agent” scenario as the example. In a free-agent scenario, the vehicles move individually and do not form any clustered formation with any other vehicles while moving. In other words, the traffic unit is the individual vehicle.

Traffic Control Assumptions

To simplify the example, we make the following assumptions:

(Al) All section controllers synchronize, with one another and with the network controller, in generating plans and issuing movement commands. In other words, they are effectively one single controller. Therefore, we use the term roadside controller to represent the combination of the network controller and all section controllers. (Note that synchronization of the network controller with all the section controllers and coordination, e.g. “hand-off’, between two adjacent section controllers are complex design issues.)

(A2) The roadside controller is continuously informed, without delay, by its own sensors and all the vehicles through communication about the exact traffic condition, including vehicle positions and all other kinematic information, on the AHS. However, it does not know the plans and commands generated by the vehicle controllers.

(A3) Vehicles, through the sensing ability of the roadside control system, the communication between the vehicle and the roadside control system, and the communication among vehicles, have all the information needed for safe driving in the same lane as well as for safe lane changes.

(A4) There is a minimum safety spacing between two longitudinally adjacent vehicles, which may depend on the speed and road condition. At no time and under no circumstances should a vehicle invade this safety spacing between itself and its immediate predecessor.

(A5) Both automated lanes have a common target speed.

(A6) Communication and electronic decision making are instantaneous.

Traffic Control Features

Traffic Control Features are labeled with the prefix FR. Functions performed by the roadside controller alone or by vehicles are labeled with prefixes RF or VF respectively. The prefix RVF in the label indicates that the function is performed jointly by the roadside controller and vehicles.

- (FR1) Fully Automated Driving:
    - (FRl.l) Automated Lane Travel
    - (FR1.2) Automated Lane Selection
    - (FRl.3) Automated Lane Change: including automatic initiation of negotiation/preparation for a lane-change maneuver
- (FR2) Capacity Optimization:
    - (FR2.1) Optimized Lane Assignment
    - (FR2.2) Gap Management/Distribution
- (FR3) Special Operational Requirements:
    - (FR3.1) Preemption/Yielding for Priority Vehicle •

(3) BASIC MOVES AND MANEUVERS

In this section, we first motivate the need to define the concept of permissible move via an analogy between AHS traffic control and computer programming. The concepts of basic move and maneuvers and their attributes follow.

(3.1) Actuator Programming and Computer Programming

All traffic control functions are realized by vehicle movements. All vehicle movements are in the end realized by the actuation of the actuators installed on the vehicles. In a fully automated highway system, traffic/vehicle control can be viewed as programming the actuators on the vehicles to move all the vehicles from their entry points to their departure points safely and efficiently. In other words, on the level of actuation, traffic control can be viewed, given the sensed and communicated information, as *actuator programming*. Obviously, this programming task can be extremely complicated and ways to simplify this task must be developed. We draw an analogy between the concepts of actuator programming and computer programming. For computer programming, machine languages were first developed. To facilitate the task of computer programming, assembly languages were developed. For further programming ease, high-level computer languages have been built upon lower-level languages. The concepts of *subroutine* and *intrinsic function* further facilitate the task. To even further simplify the task, “macros” and “shells” are provided.

The same can and should be done for actuator programming. Between the high-level requirements to control AHS traffic safely and efficiently and the low-level need to program the actuators, intermediate levels of constructs are needed to facilitate traffic control. One way is to define the concept of move. A *move* is a collection of continuous vehicle movements designed to achieve a purpose. Note that a move may be accomplished by more than one vehicles. A major category of vehicle movements is longitudinal movement. In our opinion, the following three longitudinal moves are fundamental for any fully automated AHS.

When there is no safety concern ahead in the same lane, a vehicle moves at the speed limit dictated by the roadside control system. Achieving this requires a collection of continuous vehicle movements. This collection of movements *can* be called the *speed-holding move*. When there is another vehicle in front at a prescribed spacing, the vehicle should maintain that same prescribed spacing behind the vehicle in front. Achieving this requires another collection of continuous movements, which can be referred to as the *spacing-holding move*. This move has also been referred to as ***vehicle-*** *following*. Upon encountering another vehicle in front (either detected by the on-board sensors or informed by the roadside) traveling at a lower speed while maintaining the target speed along a lane, the vehicle decelerates to achieve a prescribed safety spacing †. Achieving this also requires a collection of continuous vehicle movements, which we will call *the safety-spacing-achieving* move. After the safety spacing has been achieved, a spacing-holding move (by the rear vehicle) can maintain the prescribed safety spacing.

Another major category of movements is lateral movement. A vehicle needs to stay at or near the lane center at all times except during lane changes. Achieving this requires a continuous collection

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† A safety spacing here is defined as the distance between two longitudinally adjacent vehicles that is large enough so that the probability of a collision between them is minute if (i) the front vehicle fails and suddenly decelerates at a random rate. with a given probability distribution and (ii) the rear vehicle responds after a reaction delay by decelerating at another random rate with a specified distribution which may or may not depend on the deceleration rate of the front vehicle.

of movements, which we will refer to as the *lane-holding* move.

(3.2) Moves: Basic Moves and Maneuvers

We postulate that all permissible vehicle movements are composed of a small number of *permissible* moves. As a result, a traffic control scheme should also specify *all* the permissible moves and how these moves are assembled, including selecting, sequencing, timing and locating, to achieve the desired movements required by features.

In the absence of a definition, certain moves made by the automated vehicles have been referred to as *maneuvers*. For example, Varaiya and Shladover [17] and Rao et al. [8] referred to lane change as a maneuver, but not spacing-holding (vehicle-following). The distinction seems to lie in the degree of difficulty and occurrence of change in direction, position or speed with respect to other vehicles. Rather than giving a precise definition of the concept of a maneuver, we distinguish it from *basic moves* and define the concept of a *maneuver* simply by exclusion as any non-basic move. By definition, a move is either a basic move or a maneuver.

Basic moves are defined by inclusion. In this paper, we postulate that there exist only four basic moves, which have been explained earlier. They are speed-holding, spacing-holding, safety-spacing-achieving and lane-holding. (In terms of physiology, safety-spacing-achieving can be viewed as a *reflex* and the other three can be viewed as *instincts* and subconscious abilities. However, maneuvers correspond to conscious efforts.)

A question is whether the distinction between a basic move and a maneuver is important or not. We believe that this distinction is essentially semantic. We could have called all vehicle moves maneuvers. What is important, we believe, is their attributes, whether the move is a basic move or a maneuver.

→ **Example Continued:** The function list for the example is expanded to include:

Movement Functions:

(VF1) Safety-Spacing-Achieving Move: Upon encountering a vehicle ahead in the same lane traveling at a lower speed while cruising at the target speed, this function slows down a vehicle so that it does not invade the safety spacing between itself and the vehicle in front.

(VF2) Speed-Holding Move: In the absence of any safety concern ahead in the same lane, this function maintains the target speed that is dictated by the roadside.

(VF3) Spacing-Holding Move: While trailing the vehicle in front at a prescribed spacing dictated by the roadside, this function maintains that spacing.

(VF4) Lane-Holding Move: This function keeps the vehicle at or near lane center. This function can be overridden only by the Lateral Maneuver (part of a lane-change maneuver) during a lane change.

(VF5) Speed-Change Maneuver: This function achieves a different speed (perhaps according to a speed profile). This function could be invoked by either the roadside controller or a vehicle controller.

(VF6) Spacing-Change Maneuver: This function achieves a different spacing behind the vehicle in front. This function could be invoked by either the roadside controller or a vehicle controller.

(VF7) Lane-Change Maneuver: It is performed through cooperation among vehicles without any decisions made by the roadside after the roadside instructs the lane-change vehicle to initiate the lane-change maneuver. Note that initiation of a lane-change maneuver is performed by the roadside controller but is not considered a part of the lane-change maneuver itself. In this example, timing of lane-change maneuver initiation, i.e. lane-change scheduling, is performed by the roadside controller, as will be made clear later. This function consists of the following subfunctions:

(VF7.1) Lane-Change Negotiation: solicits cooperation from vehicles in the vicinity, including identification of the receiving gap.

(VF7.2) Lane-Change Gap Preparation: creates a safe gap for the lane change.

(VF7.3) Lateral Maneuver: makes the lateral movement.

Had the existence of lane merges (where a lane is dropped and two separate streams of automated traffic have to be merged into one) been assumed, the automated driving feature should have included the additional function of *traffic merging*.

Functions VF1 - VF4 are basic moves while functions VF5 - VF7 are maneuvers. •

(3.3) Key Attributes of A Maneuver

We group key attributes of a maneuver in the following dimensions:

(D1) *Cooperation Among Vehicles:*

This attribute pertains to whether two *or more* vehicles need to deviate from the basic moves, i.e. perform maneuvers, to achieve the intended movements. If so, the maneuver requires *cooperation* and is called a *multi-lateral* or a *cooperative* maneuver. Otherwise, it is called a *unilateral* maneuver. (This is consistent with the physiology analogy where cooperation is required when two or more people need to make conscious efforts, e.g. deviating from subconscious instincts, to achieve a goal. Recall a maneuver, as pointed out earlier, can be viewed as analogous to an activity requiring conscious efforts.) Note that these concepts are defined in terms of a worst-case scenario in the sense that a maneuver is multi-lateral if there exists a traffic condition under which its execution would require cooperation among multiple vehicles. For example, a lane change may take place in such light traffic that there are no vehicles near the lane-change vehicle and no cooperation between any vehicles is required. Although this particular lane change involves no cooperation, the lane change maneuver in general is considered multi-lateral. We believe that, for safety, all unilateral maneuvers occur only in one lane and all activities involving more than one lane, e.g. lane change and traffic merging at a merge point, require multi-lateral maneuvers.

We illustrate this concept via the following examples. Creating a gap in front of a vehicle is not a basic move but a maneuver (e.g. a spacing-change maneuver). However, since the move involves only one vehicle deviating from the basic moves, it is a unilateral maneuver. By contrast, creating a gap in rear of a vehicle by accelerating requires a multi-lateral maneuver. This is because the following vehicle, if any, has to deviate from the basic move of spacing-holding too (by not holding the prescribed spacing).

The motivation to distinguish a unilateral maneuver from its multi-lateral counterpart is that the latter is more complex and potentially more dangerous. Note that in defining the basic moves and the maneuvers, *we* use *movement* as the key, instead of the organization or communication among vehicles, to define cooperation. In other words, unilateral moves can very well be made with the surrounding vehicles fully informed through communication.

Note that this cooperation attribute is independent of the controller that issues the command to initiate the maneuver. Cooperation of vehicles to accommodate a lane change is required whether the maneuver is initiated and completely dictated by the roadside or initiated and negotiated by the vehicles themselves.

→ **Example Continued:** Functions VF5 and VF6 are unilateral maneuvers while Function VF7 is a multi-lateral maneuver. •

(D2) *Controller:*

Controllers that may plan and issue move commands include: vehicle controller, platoon controller (residing on the lead vehicle of a platoon), section controller and network controller. To highlight the decision-making role of the roadside controller (i.e. the network controller and section controller), *we* use the term *coordination* to refer to those multi-lateral (cooperative) maneuvers in which the roadside controller makes certain decisions for the participating vehicles after the initiation of the maneuver attempt. For example, if the roadside controller determines the receiving gap, *after* having access to and using the detailed traffic data obtained through the vehicle sensors, then the lane-change maneuver is a coordinated one. If, instead, the roadside controller can abort the maneuver, it is also a coordinated maneuver.

-+ **Example Continued:** The lane-change maneuver is not a coordinated multi-lateral maneuver because the roadside control system plays no role after instructing the lane-change vehicle to initiate a lane-change maneuver (although the roadside control system may continue to provide information about the traffic condition in the neighborhood). •

(D3) *Stages within a Maneuver:*

A multi-lateral maneuver may consist of multiple stages, some of which may involve no coordination. Often, a maneuver can be decomposed into component maneuvers.

→ **Example Continued:** The lane-change maneuver has three stages: negotiation, gap preparation and the lateral maneuver. •

(D4) *Participant:*

The participants of a maneuver include *all* vehicles that deviate from their basic moves to *accommodate* the maneuver through cooperation. For example, a lane-change maneuver is participated in by not just the lane-change vehicle but also some nearby vehicles. Possible participants of a maneuver include platoons and vehicles. For a unilateral maneuver, the only participant is the single vehicle involved. For a multi-lateral maneuver, the participants include all cooperating vehicles and also platoons, as applicable. Also, the participants of a maneuver may vary with time. For example, a vehicle becomes a participant of the metering maneuver at an automated on-ramp when it enters the “waiting area” (after inspection) and loses the participant status after entering the existing traffic stream on the AHS.

(D5) *Time:*

Possible attributes include: how often should a maneuver be invoked, e.g. continuously, periodically or only when certain conditions are satisfied; when to invoke the maneuver and for how long? Note that the invocation may be continuous. For example, the metering maneuver at an automated on-ramp is invoked continuously during AHS operation. So is the merging maneuver at a merge point.

(D6) *Space:*

Possible attributes include: a fixed area, e.g. a network, a section, a merge area, an entrance or an exit; a dynamically-defined area, e.g. where congestion occurs or where an incident occurs; space occupied or affected by moving participants over time; space affecting the moving participants over time. Note that the affected space may be invariant with respect to time. For example, unlike the space attribute of a lane-change maneuver, the space associated with the on-ramp metering maneuver or the merging maneuver may not change with time.

(D7) *Scope:*

The attributes within the three preceding dimensions define the scope of a maneuver. For the focus on actual vehicle movement (as opposed to movement planning) in the conflict study later in this paper, three attributes - the participants, the time interval during which a maneuver is invoked and the space affecting or affected by the maneuver - are important.

(D8) *Operation:*

An operation consists of the assembly of component moves, i.e. basic moves and maneuvers, and the preparation activities required by the moves.

(4) PLANNING FUNCTIONS

This section briefly discusses the two broad categories of planning functions: system flow planning functions and vehicle movement planning functions.

(4.1) System Flow Planning

The system **flow** planning functions deal with *the macroscopic* traffic flow in the system and do not concern themselves with the movement of *individual* vehicles. By their nature, the system flow planning functions are designed to maximize capacity and are performed by the network controller †.

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† The network controller can perform vehicle movement functions too. For example, route selection is naturally performed by the network controller. However, it does not issue commands directly to move vehicles. All such commands are triggered by the controllers at the other three layers.

A component of these system flow planning functions is the system flow monitoring function, which provides feedback to the rest of the system flow planning functions.

→ **Example Continued:** The function list for the example is augmented with the following planning functions.

System Flow Planning Functions (by the Roadside Controller):

(RF1) Target Lane Speed: Assume that there is no difference in target speeds for the two automated lanes. But, the target speed may vary with respect to location, e.g. section. (This is assumed to facilitate the discussion.)

(RF2) Traffic Assignment: This function assigns aggregated traffic (not individual vehicles) onto the highway section/lane to maximize the longitudinal traffic flow while guaranteeing successful exiting for all or nearly all vehicles. •

(4.2) Vehicle Movement Planning

Based on the plans produced by the system flow planning functions, the vehicle movement planning functions *plan* for the *microscopic* movements of individual vehicles.

If planning is interpreted as anything that specifies actions for the future, then even the movement functions have planning elements in them because movements should be carried out with not only what is occurring at the moment but also what might happen in the future, however near it may be. The major distinction between the planning functions and the movement functions, as mentioned earlier, is that the latter require more detailed and accurate information about the traffic condition in a smaller area while the former require information about a larger area but with less detail. In particular, the movement functions, for the obvious safety reasons, require and rely on the most detailed information obtainable by the vehicles through their own sensors, and communication with the other vehicles and with the roadside control system. Although in theory, these two sets of functions can use an identical set of data at an identical level of detail and hence can be combined into one, it seems very unlikely in practice. Also, the planning functions can update the plans using more accurate and more detailed data as the time of implementation nears so that, in theory, there is a “continuum” between the planning functions and the movement functions. However, we, in this paper, assume that the movement functions use distinctively more detailed and accurate information about the traffic condition for safety reasons. This is *the key point* that motivated our distinguishing the planning functions from the movement functions. (The planning functions were the focus of Tsao **[11];** we emphasize the movement functions in this paper.)

→ **Example Continued:** The function list is augmented as follows:

Vehicle Movement Planning Functions:

(RF3) Gap Management/Distribution: This function creates, closes, conditions (i.e., lengthens and shortens) and distributes the gaps to enhance the lateral flow. As will be explained later, this function can also reduce the number of conflicts and interferences among different maneuvers by providing “buffers” that limit the “ripple effect” of maneuvers. Note that this function is independent of the gap creation activities resulting from individual lane change maneuvers.

(RF4) Lane Selection: Based on the traffic assignment produced in the stage of system flow planning, this function determines a path of section/lane for each individual vehicle.

(RF5) Lane-Change Scheduling: The roadside control system is responsible for and only for the timing of lane-change negotiation initiation. The actual negotiation occurs among the involved vehicles.

(RF6) Preemption/Yielding for Priority Vehicle: This function plans for the path of a police or emergency vehicle to enable a fast access to its destination. (Assume that vehicles always stay in the lane center, except during lane changes, even during yielding.) •

(4.3) Support of Traffic Control Features through Basic Moves and Maneuvers

The implementation of the plans produced by the vehicle movement planning functions is realized by the basic moves and maneuvers. In fact, these functions can be viewed as assembling, including selecting, sequencing, timing and locating the basic moves and maneuvers.

→ **Example Continued:** It is clear that the seven vehicle functions **VF1 -** VF7 are sufficient for implementing all the plans produced by the vehicle movement planning functions. For example, to implement the command of gap creation (RF3) issued by the roadside as part of the Gap Management/Distribution function, the roadside instructs the vehicle to enlarge the spacing with the vehicle in front using its Spacing-Change Maneuver (VF6). To make way for a priority vehicle, function (RF6) determines a path, which is then vacated by regular automated vehicles through invocations of Spacing-Change Maneuver (VF6) and Speed-Change Maneuver (VF5). If lane changes are required, either for the priority vehicle or the other vehicles, this function (RF6) calls the Lane-Change Scheduling Function (RF5) to initiate negotiations for lane changes. •

(5) MOVEMENT FUNCTIONS

Accuracy and Sophistication of the Planning Functions

In an AHS, many maneuvers are continuously and concurrently being invoked. Ideally, the planning functions are so sophisticated and accurate that all the resulting basic moves and maneuvers have no conflicts and lead to a safe and efficient AHS operation. However, these planning functions, like most other planning functions designed for other systems, will most likely use forecast, aggregate, approximate and periodically-updated data as input. In particular, traffic demand is uncertain; actual traffic flow on the AHS is difficult to predict with high accuracy; random errors occur in implementing the plans; communication delays and perhaps technical and cost constraints on communication prevent real-time acquisition of detailed data for planning. Therefore, whether a maneuver can actually be safely made as planned or whether an already-started maneuver can continue should be carefully verified.

A Multitude of Controllers

The vehicle movement planning functions may be performed at all four layers. Therefore, plans and the resulting movement commands may be produced by controllers of different layers and different controllers at the same layer alike, e.g. network controller, different section controllers, controllers on different platoon lead vehicles, and different vehicles themselves. Ideally, all the controllers synchronize with one another in generating plans and issuing movement commands through communication. However, in practice, these plans and commands may be *inconsistent*, i.e. there may exist conflicts and interferences in the plans. Before these plans can be considered for execution, such conflicts and interferences must be recognized and resolved for safety, and perhaps efficiency too.

Three Major Components of the Movement Functions

After resolving the conflicts and verifying the maneuver initiation/continuation conditions, the plans are executed through vehicle movements. Therefore, the three major components of the movement functions are verification of conditions for move execution, conflict recognition/resolution for vehicle movement plans, and move execution. These functions will be referred to as the *execution condition verification functions, conflict resolution functions,* and the *move execution functions* respectively. The movement functions also provide feedback to the movement planning functions regarding the progress of the implementation of the vehicle movement plans. If a plan is not implemented as intended, e.g. aborted or cancelled entirely, the controller must be aware or be made aware of this fact so that it can replan accordingly.

(6) MOVEMENT FUNCTIONS: EXECUTION CONDITIONS VERIFICATION

Other than the obvious need for maneuver protocols among the participating vehicles, safe AHS operations require the specification and verification of maneuver/stage initiation and continuation (abort) conditions.

Since a multi-lateral maneuver involves multiple vehicles and may last a significant amount of time, the condition for a safe start and the condition for its continuation (or abort) should be clearly specified. For example, can the lateral maneuver of a lane-change maneuver be initiated when the vehicles in front and in rear of the receiving gap are decelerating? If so, a maximum allowable deceleration should be imposed because it may be dangerous otherwise. As for the condition for continuation, consider the following example. Suppose, at the initiation time of the actual lateral maneuver, all vehicles involved are traveling at a common speed. But, after initiation, either the lane-changing vehicle or the vehicle in front of the gap has to decelerate. A question is whether the lane change maneuver should continue or should be aborted. These examples are provided to illustrate the need to define *rigorously* the conditions for maneuver initiation and continuation. In fact, these conditions should be defined for each stage of a multi-lateral maneuver.

→ **Example Continued:** The specification should be supplemented as follows:

> (Under (VF6))
>
> Spacing-Change Maneuver Initiation/Continuation/Abort Conditions:
> To achieve a new spacing, the vehicle in front must be moving at a constant speed. Continue the maneuver if and only if the front vehicle does not accelerate or decelerate faster than a preset threshold.
>
> (Under (VF7))
>
> Lane-Change Maneuver Protocol:
> If the lane-change vehicle is next to a gap in the destination lane at the time of negotiation initiation, then the two vehicles enclosing the gap, if within the "safety distance", cooperate to ensure a safe lane change; otherwise, the vehicle next to it in the destination lane slows down to create a gap for the lane change. Since the subject of maneuver protocol has been treated more extensively elsewhere, detailed protocol description is omitted. For an example of such a protocol, refer to **[7].**
>
> Lane-Change Maneuver Initiation/Continuation/Abort Conditions:
> After instructed by the roadside controller to initiate negotiation, to actually initiate and to continue negotiation, (i) the lane-change vehicle and the cooperating vehicles, identified by the lane-change vehicle itself, must maintain a constant speed and (ii) the speed differential between these vehicles should not exceed a preset threshold. If the negotiation cannot continue, the whole lane-change maneuver has to be aborted. After a successful negotiation, a safe receiving gap is secured. During gap preparation, if the vehicles are forced to decelerate (e.g. to accommodate the downstream traffic

slow-down), the lane-change maneuver has to be aborted. During the creation of a safe gap, the lane-change vehicle and the two vehicles enclosing the receiving gap, if within the safety distance, achieve and maintain a common, but not necessarily constant speed. More precisely, if any one of the vehicles is forced to decelerate, the other ones decelerate at the same rate to maintain a common speed. A lateral maneuver can be initiated if and only if all these vehicles have maintained a *constant* speed for a preset amount of time. In other words, before the actual lateral maneuver can begin, *the* vehicles have to *wait* until they have reached a constant speed and have maintained that constant speed for a preset amount of time. The continuation condition is less restrictive because aborting a lane change may be more dangerous than continuing it. After initiation of the lateral maneuver, the three vehicles should maintain a constant speed, if downstream traffic conditions allow, until the termination of the maneuver, i.e. successful completion or abort. None of them should accelerate. If any one of them has to decelerate (due to a slow-down in the downstream traffic) with a rate smaller than the preset threshold, the other two do the same to maintain zero speed differential. If any of the three vehicles has to decelerate faster than the preset threshold, the maneuver should be aborted *unless* the lane-changing vehicle is already half-way through the lateral movement into the destination lane, in which case the other vehicles decelerate at the same rate to maintain a common speed. •

(7) MOVEMENT FUNCTIONS: CONFLICT/INTERFERENCE RESOLUTION

Since maneuvers are continuously and concurrently invoked by *different* controllers, conflicts and interference with one another may develop. Since such conflicts may be very dangerous, they have to be recognized and resolved without ambiguity.

(7.1) Conflict: Direct or Indirect

A conflict is said to occur between two or more maneuvers if and only if they cannot *all* be completed as intended, i.e. at least one of them has to be aborted. When the *scopes* of two maneuvers overlap, the conflict is said to be *direct.* Otherwise, it is said to be *indirect.* A set of maneuvers is said to be *consistent* if they do not conflict with one another. The definition of a conflict can be used directly to recognize the occurrence of a conflict.

If one vehicle can engage in at most one maneuver at a time, then the space attribute of the scope is redundant for identifying a direct conflict. (Note that since a maneuver can consist of other maneuvers as components, the maneuver here means the "master maneuver".) In such a case, conflict is easy to identify. The controller plays an important role in conflict recognition and resolution. For example, if there is only one controller that can issue commands for vehicle movements - the network controller, then the consistency of the commands, at least in theory, is easier to achieve than if there is an array of different such command-issuing controllers.

Several different types of indirect conflicts may occur. They could often occur because, to accommodate a maneuver for the objects involved, non-objects of the maneuver must make certain *basic moves* which change the traffic conditions and render the other maneuvers unsafe to continue. Therefore, such an indirect conflict can be said to occur due to the *ripple effects* of the maneuver. (A primary motivation for the Gap Management/Distribution function is to scatter spatially the gaps so that they may not only allow faster lane-change completion but also provide "buffers" that minimize such ripple effects of maneuvers. Therefore, this function may also be thought of as a means to minimize the possibility of conflict.) We provide the following examples.

Conflict: Indirect, Common Maneuver Type & Common Controller

→ **Example Continued:** Assume that the traffic is jammed as shown in Figure 7.1. We provide an example to illustrate the possibility of an indirect conflict between two lane change maneuvers. The (roadside) lane-change scheduling function commands two spatially distant vehicles to initiate their lane change attempts. (Call the two lane changes the front lane change and the rear lane change). Since a gap is needed for each lane change, two separate gaps, called the front gap and the rear gap, should be created. After two separate negotiations, the involved vehicles agree and start to create two separate gaps. To create the front gap, the vehicles behind the intended gap must decelerate. But, this implies that all vehicles involved in the gap creation for the rear gap must decelerate too. Suppose that the gap preparation for the rear gap is not completed before the vehicles have to decelerate to accommodate the front lane change. In this case, the rear lane change has to be aborted. (See the "Lane-Change Maneuver Initiation/Continuation/Abort Conditions".) If the preparation for the rear gap continues, the "double" deceleration might be too fast to be safe. Consider another case as follows. Suppose that the vehicles engaged in the rear lane change need to decelerate to accommodate the creation of the front gap while the lateral maneuver for the rear lane change is taking place. If the deceleration rate is faster than the preset threshold and the lateral maneuver is not halfway through yet, the maneuver has to be aborted. (See again the "Lane-Change Maneuver Initiation/Continuation/Abort Conditions".) Suppose, instead, that the lateral maneuver is already halfway through. Then, although the lane-change maneuver is not aborted, the faster-than-threshold deceleration may make the lateral maneuver unsafe. The example given in this paragraph will be referred to as Example 7.1. •

Conflict: Direct, Maneuvers of Different type & Different Controllers

→ **Example Continued:** After the roadside controller instructs the lane-change vehicle to initiate a lane-change maneuver, it does not issue any commands for the lane-change maneuver itself. The lane-change vehicles and the adjacent vehicles in the destination lane negotiate among themselves for the gap preparation and the lateral maneuver. Since the roadside control system does not know that the two "receiving vehicles" are busy with a lane-change and that the nearby lane change has not been completed yet, it invokes the Spacing-Change Maneuver VF6 (for gap creation), as part of the Gap Management/Distribution function **(RF3),** that calls for the deceleration of the front receiving vehicle. (Recall that although the roadside controller is assumed to have perfect information about the traffic condition, it does not know the plans generated and commands issued by all the vehicles. Had the assumption been that the roadside controller also knows all the plans and commands issued by all the vehicles, it, assuming a set of reasonably good planning functions, would not have issued the gap creation command.) Suppose this command is issued before the gap has been successfully created. Therefore, the scopes of these two maneuvers overlap and one of these two has to be aborted for safety. Note that the controllers are different. The lane-change maneuver is commanded by the vehicles themselves while the gap creation action is commanded by the roadside controller. •

Conflict: Indirect, Different Maneuver Types & Different Controllers

→ **Example Continued:** Assume that the traffic condition is given as shown in Figure 7.2. We provide an example to discuss the possibility of a conflict between a lane-change maneuver and a spacing-change maneuver initiated by the Gap Management/Distribution function. This example is identical to Example 7.1, except that the gap creation is initiated by the Gap Management/Distribution function. Note that the controllers for the lane-change cooperation are the vehicles themselves while the gap creation is commanded by the roadside controller. •

Conflict: Direct, Between a Maneuver and a Basic Move, Common Controller

→ **Example Continued:** During a lane change maneuver, the cooperating vehicles switch from the speed-holding move or the spacing-holding move to the lane-change maneuver. In other words, the lane-change maneuver conflicts with the speed-holding move and the spacing-holding move. This switch is actually a way to resolve the conflict, which leads to the concept of conflict resolution and control hierarchy. The tacit assumption is that the lane-change maneuver, after a successful negotiation, takes a higher priority over the speed-holding or spacing-holding moves. Note that these two lower-priority functions, as well as the lane-holding move, can be viewed as default functions or moves. This motivated the hierarchical conflict resolution approach to be introduced later in the running example. •

(7.2) Interference

Between the two extremes of abort and continuation of a maneuver, there is the possibility of "wait" or "on-hold". This is particularly desirable when some submaneuvers of a maneuver have been realized but the rest of the submaneuvers cannot be initiated because the initiation condition is not satisfied. (In other words, the traffic condition is not bad enough to abort the whole maneuver.) An interference is said to occur between two or more maneuvers if and only if there exists *no conflict* but at least one of them has to *wait* to be completed.

→ **Example Continued:** Same as Example 7.1 except the following. The gap preparation for the rear gap is already completed but the lateral maneuver cannot take place because the vehicles have not been able to reach a common constant speed. To reach a common constant speed, the vehicles have to *wait* at least until the gap creation for the front lane-change is complete. (See the "Lane-Change Maneuver Initiation/Continuation/Abort Conditions".) During the gap creation for the front lane change, the cooperating vehicles for the rear gap will maintain a common speed. After they have been able to maintain a *constant* speed for the preset amount of time, they begin the lateral maneuver. In this case, there exists no conflict because the rear lane change was not aborted. However, there exists an interference because the rear maneuver has to wait. •

(7.3) Conflict/Interference Recognition and Resolution

So far, we have tacitly assumed the existence of a "super overseeing entity" that knows everything about the AHS operation, including the traffic condition, system flow plans and vehicle movement plans. Based on its perfect knowledge, the entity can recognize all the conflicts, direct or indirect, and interferences. However, this is too strong an assumption. Since the ability to recognize conflicts depends on where the relevant information resides and how it *is fused,* the necessity to recognize conflicts should play an important role in the design decision regarding how information and intelligence should be distributed among the different controllers.

Close to the opposite extreme from the assumption of the existence of a super overseeing entity is the following system. It has no centralized information and intelligence at all except that the roadside controller broadcasts the target (maximum) speed. Driving, including lane travel and lane change, is automated but the driver has to issue the request for lane changes. The lane-change maneuver is the only maneuver (non-basic move) supported. Vehicles have enough sensing ranges for safety. In such a system, if a vehicle is currently engaged in a lane-change maneuver, then when that vehicle receives a request by other vehicles to engage in another lane-change maneuver, there is a direct conflict. The identification is easy. The resolution could be easy too. A simple method is to deny any request that "collides" with a current lane-change maneuver. Assuming the same lane-change maneuver initiation/continuation conditions as in the "running example", when an indirect conflict occurs between two lane-change maneuvers, simply abort the one downstream. In fact, the specification for how to resolve an indirect conflict is unnecessary, in this particular case, because the downstream maneuver will be aborted anyway because the continuation condition no longer holds.

There exist many possible resolution methods. Safety and efficiency are two principal criteria in designing such a method and safety is the most important consideration. A simple way would be to define a hierarchy of maneuvers and maneuvers of higher rank have higher priority over their lower-priority counterparts. However, this way, near-completion maneuvers may have to be aborted because of the priority system. Another way would be to give priority to the maneuver closer to completion. Yet another way would be to give priority to the one whose abort would be more dangerous than the others. In any event, we believe that safety is the most important consideration. It is well known that protocol verification, i.e. proper message passing among the participants of a *single* maneuver for coordination, is crucial for AHS safety. (See Hsu [7].) However, equally crucial, if not more so, is the task of verifying the soundness of a conflict recognition/resolution scheme.

→ **Example Continued:** The list of movement functions is augmented to include the following example conflict recognition/resolution function.

Movement Functions:

(RVF1) Conflict Recognition/Resolution Function:

(1) The preemption/yielding maneuvers override all other maneuvers. (2) To ensure a high success rate of exiting, both the Lane-Change Maneuver and the Gap Management/Distribution Function have a higher priority than the speed-holding and safety-spacing-holding functions. (3) For safety, the lane-change maneuver has a higher priority over the Gap Management/Distribution Function. (4) When two lane-change maneuvers conflict with each other, the one upstream has a higher priority. (Note that since the roadside controller does not know the stages the individual maneuvers are at and the two sets of vehicles involved in the two maneuvers may not communicate with one another about the stage, giving priority to the maneuver more near completion may be infeasible to implement.) Cl

In a conventional highway system, the scope of any maneuver can be easily defined. The object of the maneuver is always the vehicle and the controller is always the vehicle (the driver). **The only** two variables are time and space. When two drivers regard a common time-space as under their control, e.g. both intending to change lanes into a common gap at the same time, a conflict occurs. The only way to resolve it is for at least one of the two vehicles to abort the lane-change maneuver. Although fully automated AHS with many advanced traffic control functions have the potential of offering better performance and/or more features, design of a safe and efficient traffic control scheme can potentially be very complex and susceptible to design mistakes and system failures, which may in turn infringe on AHS safety. This issue should be carefully examined and a balance between capacity, safety, cost and other AI-IS design objectives should be sought.

(8) The Framework: A Summary

Key components of the framework are briefly summarized as follows. (Adopted concepts and ideas are accompanied by references.)

(Cl) *Formulization of the concept of move (and maneuver).*

(C2) A top-down approach to defining a traffic control scheme, i.e. from high-level feature definition to detailed definition of supporting moves.

(C3) Specifying, as part of the definition process for each type of move, (i) *key attributes of the move* in the dimensions of cooperation among vehicles, controller, stages within a move, participant, time, space, scope and operation and (ii) *the initialization/continuation/abort conditions,* which go beyond the scope of defining a protocol (i.e. proper message passing among the participants of a move for coordination) proposed by, for example, Hsu et al. [7].

(C4) Three major categories of functions for achieving the features through invocation of the supporting moves (namely, system flow planning functions, vehicle movement planning functions and movement functions): These three categories coincide with the well-accepted decision categories of strategic planning, tactical planning and operations control. This categorization method captures the time dimension of traffic control.

(C5) Forming a feature by combining functions in the three categories: This captures the functionality dimension of traffic control.

(C6) The control system architecture proposed by Varaiya and Shladover [17]: This captures the control dimension of traffic control, i.e. distributing decision responsibility among various controllers of the AHS system to achieve the features.

(C7) Recognition, resolution and prevention of move (maneuver) conflicts/interferences: Various controllers generate vehicle movement plans and these plans may conflict or interfere with one another. Conflicts/interferences are defined based on the key attributes and the initialization/continuation/abort conditions of (C3). (The concepts of conflict and interference have been defined rigorously in Section 7.)

(9) CONCLUSION

To achieve the desired high-level traffic control *features,* the task of traffic control consists of three primary tasks: (i) defining the permissible moves, (ii) planning for the invocation of permissible moves to satisfy a multitude of objectives and (iii) moving the vehicles based on the vehicle movement plans. A traffic control scheme specifies traffic control features, permissible moves, traffic planning functions, and movement functions. The traffic planning functions consist of system flow planning functions and vehicle movement planning functions. The three major components of the movement functions are execution condition verification functions, conflict resolution functions and move execution functions. How these functions support the desired features should also be specified. This includes, in particular, the distribution of intelligence and responsibility for traffic control between the traffic controllers of different layers and different controllers at the same layer alike. How adjacent section controllers should cooperate should also be specified.

The task of traffic control is realized through a small number of basic moves and maneuvers properly assembled, including selecting, sequencing, timing and locating. Each maneuver may have several stages. Initiation and continuation (abort) conditions for each stage of a maneuver must be specified for all maneuvers. In addition to the necessity of maneuver protocols, which have been treated more extensively, conflict recognition and resolution among maneuvers are crucial for AI-IS safety.

At the stage of planning, potential conflicts among different moves (maneuvers) at implementation time should be avoided. Also, potential interferences should be minimized for AI-IS efficiency. Safety issues related to the relative motion of neighboring vehicles have been addressed more extensively. This paper takes a systems view and identifies the safety issues regarding the *movement coordination* of the large number of vehicles on an AHS. Clearly, these safety issues are of a much larger scale. We have developed a framework for specifying and designing a traffic control scheme and illustrated it with a simple example. These concepts can be used in designing AHS simulators and eventually the actual operation of automated highway systems.

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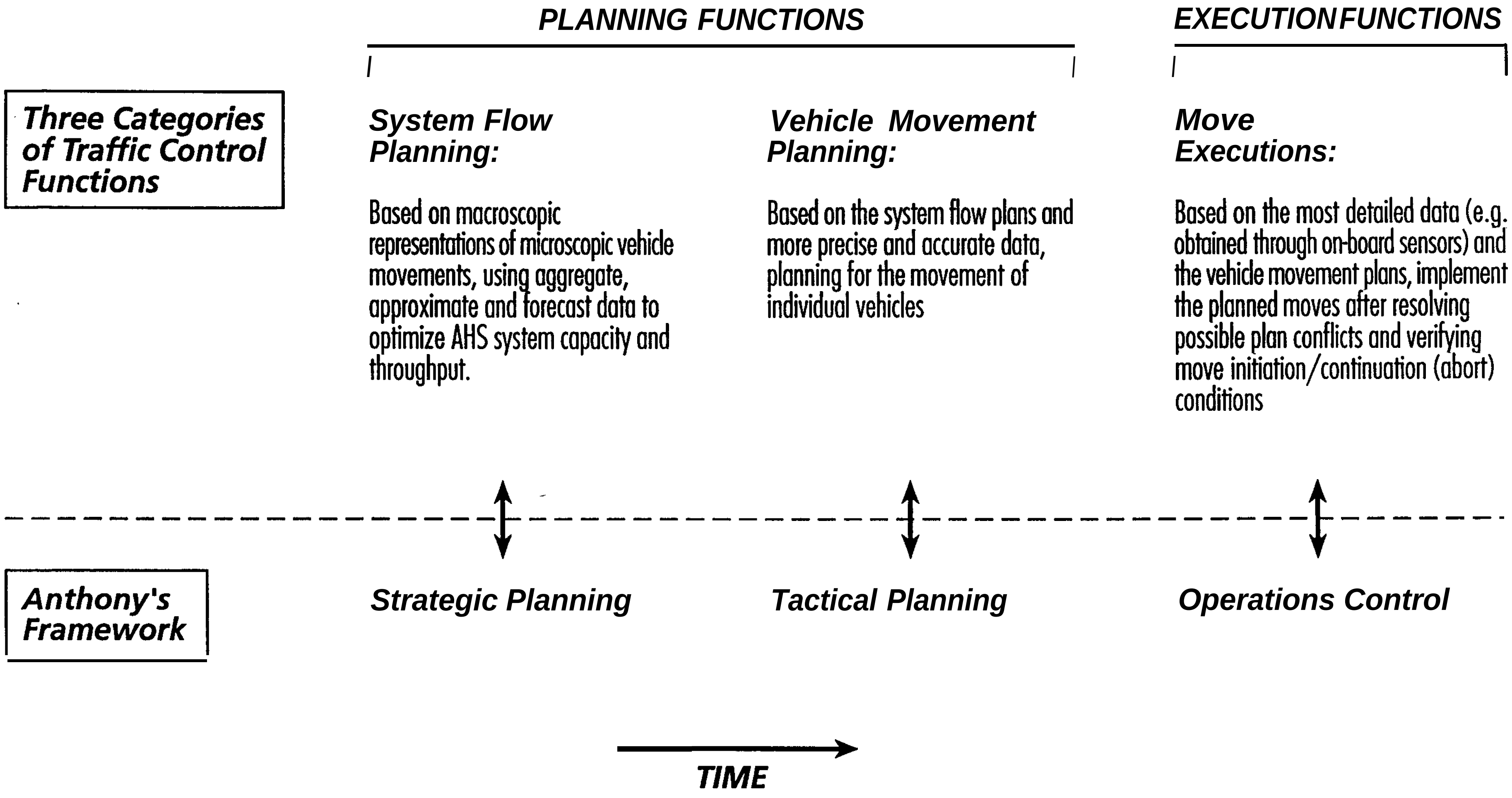
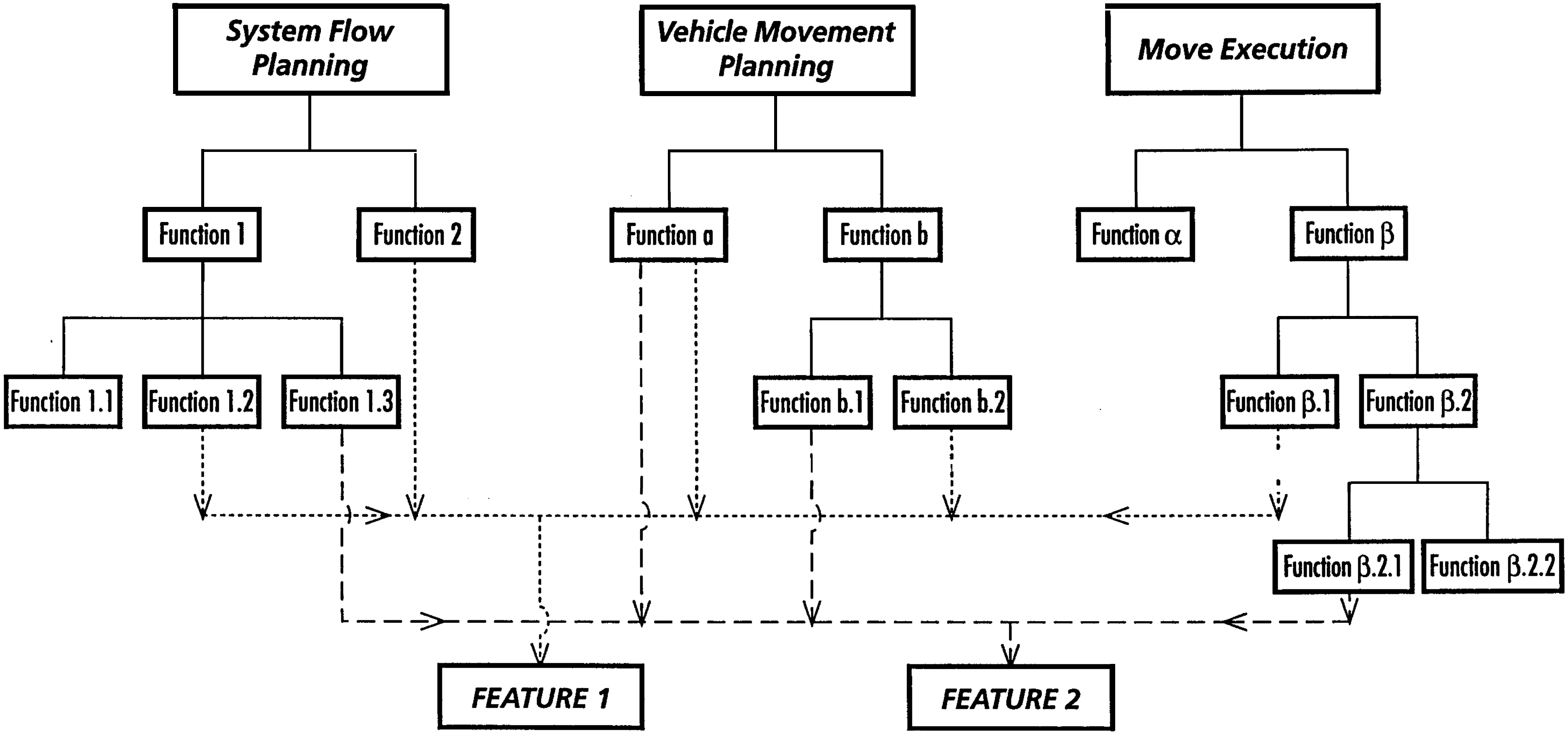


Based on macroscopic representations of microscopic vehicle movements, using aggregate, approximate and forecast data to optimize AHS system capacity and throughput.

Based on the system flow plans and more precise and accurate data, planning for the movement of individual vehicles

Based on the most detailed data (e.g. obtained through on-board sensors) and the vehicle movement plans, implement the planned moves after resolving possible plan conflicts and verifying move initiation/continuation (abort) conditions

Figure 2.1: Categories of Traffic Control Functions (Time Dimension)



arrows indicating support

Figure 2.2: Functions and Features (Functionality Dimension)

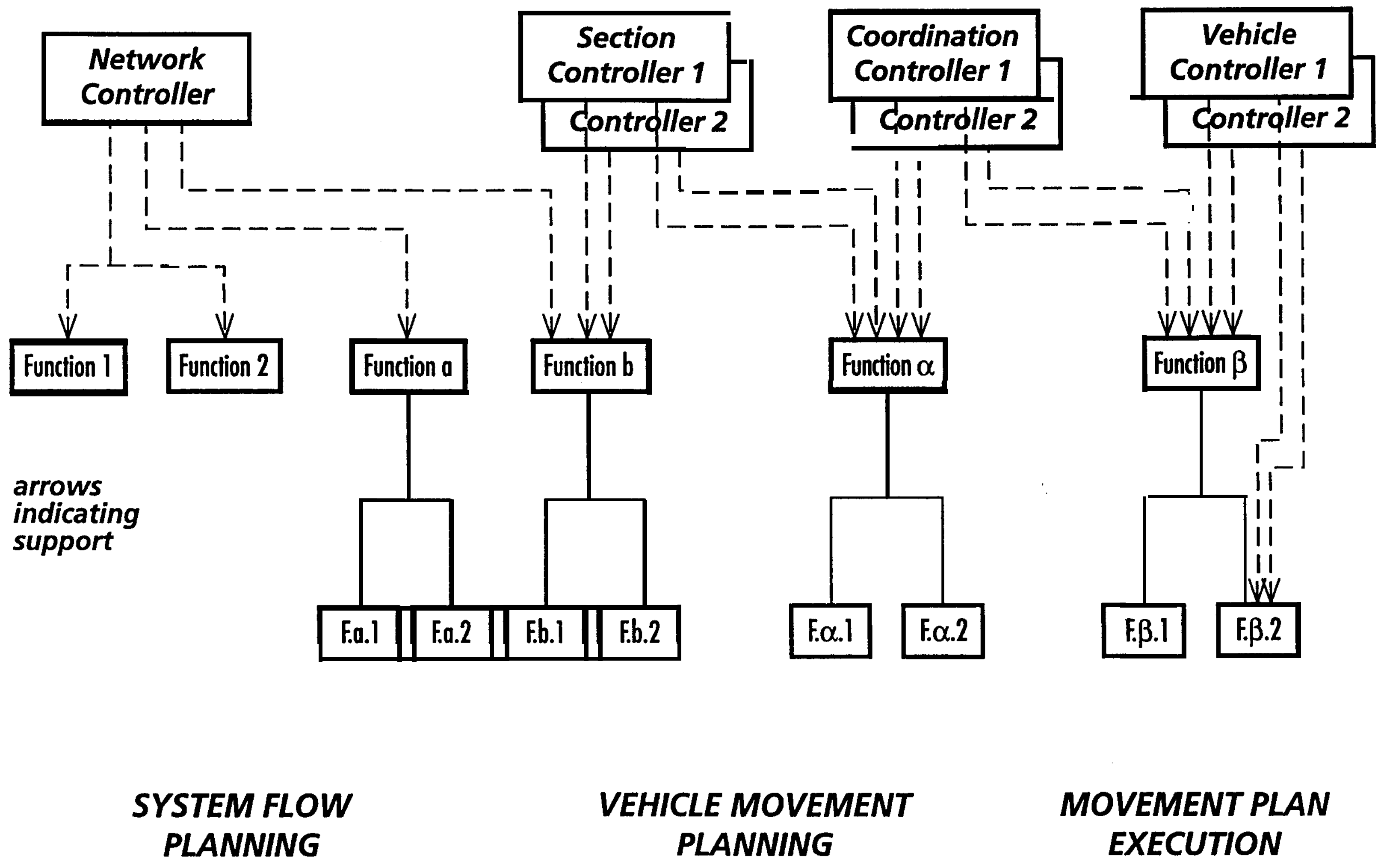


Figure 2.3: Functions and Controllers (Control Dimension)

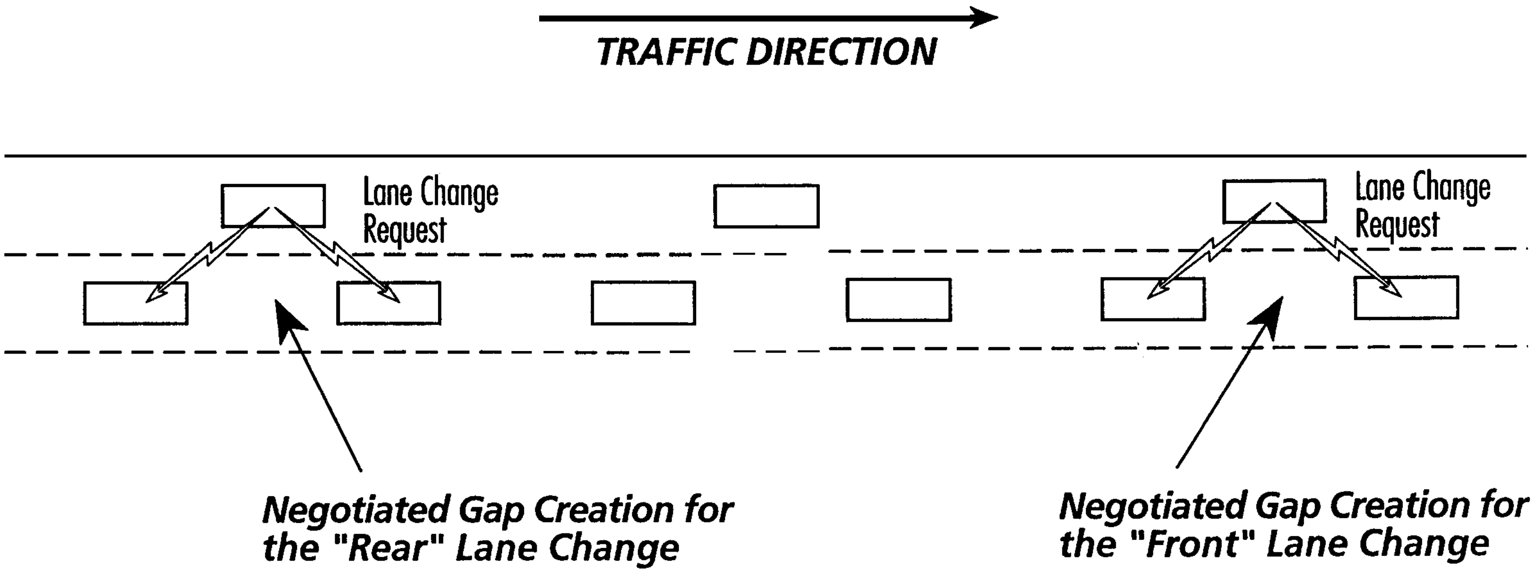


Figure 7.1: Traffic Conditions and Activities of Example 7.1 (Two Automated Lanes)

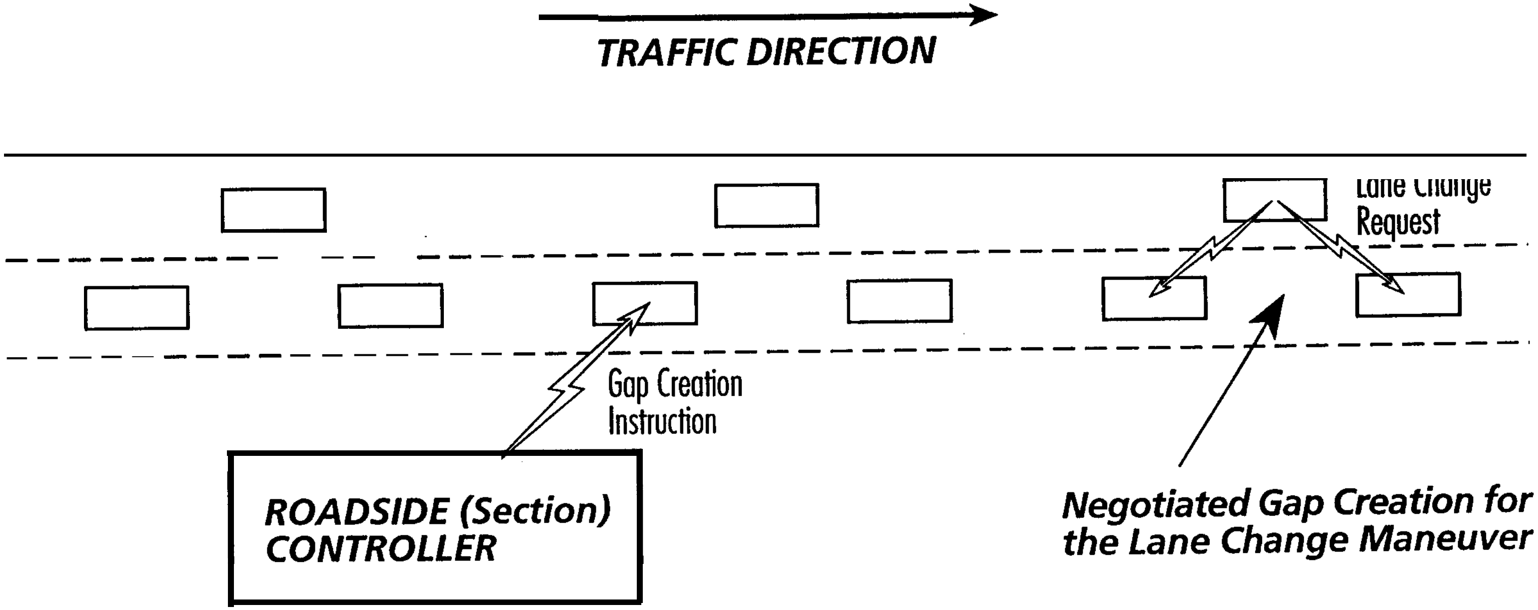


Figure 7.2: Traffic Conditions and Activities of Example 7.2 (Two Automated Lanes)