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A Functional Architecture for Automated Highway Traffic Planning

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ABSTRACT

In a fully automated Automated Highway System (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 operating an AHS is drastically different from and much more complex than its conventional counterpart. Resulting from a large number of design options, there exist many possible ways to operate an AHS. Each of these possible operating scenarios will support a different set of functions. A crucial task in AHS R&D is to evaluate and compare these potentially large number of different AHS operating scenarios with respect to the achievable capacity.

To enable simulation of various operating strategies without requiring massive program modification or database change, a flexible software structure and robust database design are required. This in turn necessitates a robust AHS functional architecture that guides the development and evolution of the required simulation tools. This paper identifies major traffic planning functions useful for optimizing the capacity of one or more major AHS operating scenarios and organizes them in a robust architecture that is modular, hierarchical, complete, expandable and integratable.

Key Words: AHS, Traffic Planning, Functional Architecture, Traffic Simulation

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EXECUTIVE SUMMARY

In a fully automated Automated Highway System (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 operating an AHS is drastically different from and much more complex than its conventional counterpart. Recently, many design potions for operating fully automated AHS have been identified. Major options include: types of vehicles automated, isolation of automated traffic from manual traffic, erection of barriers between lanes, platooning, distribution of intelligence and decision-making between vehicles and roadside.

Resulting from the large number of design options, there exist many possible ways to operate an AHS. Each of these possible operating scenarios will support a different set of functions. A crucial task in AHS R&D is to evaluate and compare these potentially large number of different AHS operating scenarios with respect to all major performance criteria. This research was conducted in the context of evaluating, optimizing and comparing *the capacity* of *various* AHS operating scenarios via *computer simulation.* A straightforward way of comparison is by way of developing one computer simulator for each possible operating scenario. But, this is not efficient. To enable simulation of various operating strategies without requiring massive program modification or database change, a flexible software structure and robust database design are required. This in turn necessitates a robust AHS functional architecture that guides the development and evolution of the required simulation tools. From the view-point of analytical modeling, such an architecture is necessary for the efficient formulation and decomposition of the AHS capacity optimization/comparison problem.

Given the physical configuration and the vehicle/system automation capabilities of a particular AHS operating scenario, the capacity is determined primarily by its traffic planning functions. Therefore, this paper focuses on the capacity-optimizing traffic planning functions. This paper identifies

major traffic planning functions useful for optimizing the capacity of one or more major AHS operating scenarios and organizes them in a robust architecture that is modular, hierarchical, complete, expandable and integratable. It also points out how the functional contents may vary with respect to the specifics of an operating scenario.

AHS capacity-optimizing traffic planning functions can be put in three broad categories: system flow planning functions, vehicle movement planning functions and vehicle movement execution functions. System flow planning functions seek to optimize the *macroscopic* traffic flow in the system and do not concern themselves with the movement of *individual* vehicles. Based on the system flow plans, vehicle movement planning functions plan for the *microscopic* movements of individual vehicles. Vehicle movement execution functions implement the planned route, trajectory and maneuvers for each individual vehicle while resolving potential conflicts among different maneuvers for safety. These three categories of functions match the three decision categories in the Anthony's decision-making framework, namely strategic planning, tactical planning and operations control. The distinction between the two types of planning functions matches the well-accepted way of distinguishing detail level of traffic study, namely macroscopic vs. microscopic.

1 INTRODUCTION

In a fully automated Automated Highway System (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 system control is drastically different from and much more complex than its conventional counterpart.

1.1 Specific AHS Operating Scenarios

Varaiya and Shladover [1] proposed a specific way of organizing the fully automated traffic (platooning), a set of necessary control tasks and a five-layer control system architecture to partition these tasks. Varaiya [2] partitioned schematically the process of AHS design into five different steps: functional specification, control system architecture, control system design, physical design and communication system design. Functional specification is a set of functions that an AHS will support. A control system architecture defines subsystems and assigns control functions to individual subsystems. Assigning these subsystems to controllers on vehicle and on the roadside and designing the controllers are part of control system design. Physical design involves specification of hardware and software of the control system. Communication system design requires specification of a logical communication architecture, a communication system design and a physical implementation. Based on [1] and these steps, Varaiya [2] outlined key features of one specific AHS, showed how core driver decisions are improved, proposed a basic AHS control system architecture, and offered a design of some control subsystems. Other specific AHS operating scenarios can be found in [3,4,5].

1.2 Various AHS Design Options

In a recent comprehensive treatment of conceptual AHS design, Stevens [6] discussed AHS deployment and operations goals, analyzed AHS characteristics and identified 37 alternative AHS concepts. With a narrower scope, Tsao et al. [7] recently identified many major design options and issues for operating fully automated AHS. (In this paper, an AHS is considered fully automated, i.e. one that performs "hands-off" and "feet-off" driving). They also addressed the impacts of the options on major AHS performance criteria including safety, capacity, human factors, infrastructure, cost, etc. The emphasis of those paper is on the breadth of the issues, options and impacts.

Major design options for operating fully automated AHS include [7]: types of vehicles automated, isolation of automated traffic from manual traffic, erection of barriers between lanes, platooning, distribution of intelligence and decision-making between vehicles and roadside. Important issues associated with these options include the following. Ideally, all vehicle types should be accommodated on AHS. However, vehicle uniformity as well as isolation of automated traffic from manual traffic simplify AHS technologies and operations and hence increase the feasibility of highway automation. Erection of barriers is motivated by safety [8]. Platooning, i.e. organizing and moving vehicles in a clustered formation, is motivated by both safety and capacity. Distribution of intelligence and decision-making impacts AHS technologies and operations in many different ways.

1.3 Motivation of This Research

Resulting from the large number of design options, there exist many possible ways to operate an AHS. Each of these possible operating scenarios will support a different set of functions. A crucial task in AHS R&D is to evaluate and compare the *capacity* of these potentially large number of different AHS operating scenarios through both computer simulation and analytical modeling of AHS traffic. This research was conducted in the context of evaluating, optimizing and *comparing* the capacity of *various* AHS operating scenarios via *computer simulation.* A straightforward way of comparison is by way of developing one computer simulator for each possible operating scenario. But, this is not efficient. To enable simulation of different operating strategies without requiring massive program modification or database change, a flexible software structure and robust database design are required. This in turn necessitates a robust AHS functional architecture that guides the development and evolution of the required simulation tools. From the view-point of analytical modeling, such an architecture is necessary for the efficient formulation and decomposition of the AHS capacity evaluation/optimization problem.

1.4 The Focus and Scope of This Research

Since capacity gain has been a primary motivation for AHS, its investigation is crucial. Research activities on this subject include [e.g. 9,101. In addition to capacity optimization, AHS traffic control can be performed for other major performance criteria, e.g. safety, fuel efficiency, human factors, air quality, etc. This paper focuses on the capacity. Given the physical configuration and the vehicle/system automation capabilities of a particular AHS operating scenario, the capacity is determined primarily by its traffic planning functions. Therefore, we focus on the capacity-optimizing traffic planning functions.

Traffic control can also be performed for many special purposes not intended to optimize capacity, e.g. ensuring speedy access to the scene of an accident by emergency vehicles and giving priority to authorized or high occupancy vehicles. We do not address control functions designed specifically for those purposes. Decision making and the supporting intelligence for traffic control may be distributed among various subsystems/controllers of an AHS in many different ways. This paper identifies the high-level decisions to be made for capacity optimization but, to ensure the robustness nature of this architecture, does not specify the distribution among possible subsystems/controllers. In other words, we concentrate on functional specification, the first step of the five-step design process proposed by Varaiya [2].

1.5 The Purpose of This Paper

This paper identifies major traffic planning functions useful for optimizing the capacity of one or more major AHS operating scenarios and organizes them in a robust architecture that is modular, hierarchical, complete, expandable and integratable. It also points out how the functional contents may vary with respect to the specifics of an operating scenario.

This research extends the *functional* ***specification*** part of the work of [1,2]. It identifies functions that one or more possible major AHS operating scenarios may support, in addition to the basic functions identified in [1,2] for a specific AHS operating scenario. Unlike the emphasis of [2] on improving the *driver* decisions, this research stresses equally the *system* decisions afforded by the full highway automation. The architecture to be proposed in this paper is on the level of functional specification and it is intended that the functions supported by any major operating scenario be a subset of the functions captured by the architecture.

1.6 The Organization of the Paper

Section 2 describes the criteria for architectural robustness. Major traffic planning functions for capacity optimization are organized in an architecture in Section 3. Section 4 concludes this paper.

2 CRITERIA FOR ARCHITECTURAL FLEXIBILITY

Traffic planning tasks associated with different possible operating scenarios exhibit a considerable degree of commonality. This commonality enables the design of a ***flexible*** architecture for the task of traffic planning that possesses the following attributes:

(i) *Modularity:* The task of overall traffic planning is decomposed into a number of functions (sub-tasks) each of which contributes to the efficiency of the traffic flow and can be implemented with different control algorithms.

(ii) *Hierarchy:* Functions are organized in a multi-layered tree-structured hierarchy. This structure can be easily translated into software structure, where subroutine calling sequences usually follow a tree structure. The selection of this structure is also motivated by its simplicity, which is desirable in designing complicated systems.

(iii) *Completeness:* The set of capacity-optimizing traffic planning functions associated with any possible major operating scenario is a subset of the functions captured in the architecture.

(iv) *Expandability: New* functions can be added and/or old functions can be replaced by new ones to improve capacity.

(v) ***Integrability***: Functions, some or all, belonging to a subtree (branch) can be collapsed into one and can be implemented with an integrated algorithm for capacity improvement. Note that different functions at the same level in a subtree may overlap with one another and each of them could be desirable enough to be selected alone.

3 TRAFFIC PLANNING FUNCTIONS AND AN ARCHITECTURE

AHS capacity-optimizing traffic planning functions can be put in three broad categories: system flow planning functions, vehicle movement planning functions and vehicle movement execution functions. System flow planning functions seek to optimize the *macroscopic* traffic flow in the system and do not concern themselves with the movement of *individual* vehicles. Based on the system flow plans, vehicle movement planning functions plan for the *microscopic* movements of individual vehicles. Vehicle movement execution functions implement the planned route, trajectory and maneuvers for each individual vehicle while resolving potential conflicts among different maneuvers (pending or currently being executed) for safety. These three categories of functions match the three decision categories of in the Anthony's decision-making framework, namely strategic planning, tactical planning and operations control. The distinction between the two types of planning functions matches the well-accepted way of distinguishing detail level of traffic study, namely macroscopic vs. microscopic.

3.1 The Architecture

The architecture for the capacity-optimizing traffic planning functions is shown in Figure 1, 2 and 3. We define the various functions in the context of full-automation with multiple lane dedicated to the automated traffic. We assume that AHS roadway is partitioned into a number of sections.

We now describe the two categories of planning functions. System flow planning functions and vehicle movement planning functions are labeled with prefixes SF and **VM** respectively. The numerical label of a function reflects its level in the hierarchy. Functional contents may depend heavily on the design options and the detail level of traffic planning. To maintain robustness, we describe the general purposes of individual functions without specifying the exact input data, output, planning detail and functional contents.

3.2 System Flow Planning Functions

This group of functions (i) regulates the AHS traffic inflow and (ii) monitors and optimizes AHS traffic throughput by metering and intelligent traffic assignment subject to the constraint that all or nearly all vehicles reach their desired exits. The input data to these functions tend to be aggregate, approximate and predictive. The performance of this function hinges upon the quality of input data. The task of approximating the microscopic characteristics of vehicle movement, particularly those of the vehicle movement planning functions, by some appropriate macroscopic (flow) representations is pivotal and is expected to be mathematically challenging. These functions need to be invoked periodically and plans need to be updated accordingly. They may need to assign traffic not only to a section of a highway but also to different lanes of a section, which is different from the conventional traffic assignment task.

Input to these functions may include the physical configuration of the AHS and the adjoining arterials/city streets, vehicle self-control rules, traffic demand (known and/or forecast), current traffic conditions, macroscopic representations of the microscopic characteristics of vehicle movement, and driving conditions. The demand estimates may be point-to-point aggregates, e.g. the total number of vehicles that go from an entrance to an exit in a time period. They could also be grouped according to vehicle types and driver requirements/ preferences. Although the demand may be aggregate in nature, the physical configuration needs to be represented in detail. For example, to enable lane assignment, different lanes in one AHS section should be treated as distinct identities. Also, in some scenarios, a vehicle's entry/exit point may be on either side of the highway. For example, a vehicle may enter from an automated ramp on the *left-hand-side* of the highway and exit from the transition lane on the right-hand-side of the automated lanes. To ensure successful exiting, precise knowledge about the side of an entrance or exit is necessary.

Output from these functions depend on the detail level of planning. The detail level could vary considerably. Major dimensions contributing to level of detail include highway, section, lane, time (interval), trip O-D, vehicle type, and driver preferences. The former three pertain to highway configuration while the latter three relate to the vehicle. Note that driver preferences can be used to group trips, e.g. trips that should be routed onto fastest routes or least-toll routes. A possible output from this function may include AHS inflow rates, assignment of traffic onto different highway/lane/section/time-interval combinations, assignment of traffic speed and density to highway/lane/section/time-interval, assignment of traffic according to trip O-D, vehicle type, and driver preferences.

These functions can be put in three subcategories: system flow monitoring, entry flow planning and system flow optimization.

(SF1) System Flow Monitoring

This function monitors the current system traffic flow, which is used as an input to the other system flow planning functions.

(SF2) Entry Flow Planning

This function regulates the intake of traffic. This function consists of four subfunctions: two metering functions and two preplatooning functions.

(SF2.1) Transition Lane Preplatooning Planning

A preplatoon is a group of closely-spaced automated vehicles ready to enter the automated lanes. A preplatoon is different from a platoon in that it has not joined the automated traffic on the automated lanes yet and that its maximum size is expected to be smaller than that of a regular platoon. This function determines if preplatooning at particular locations on the transition lane is needed and, if so, determines how arriving vehicles should be organized into preplatoons. Possible decisions made in this function include the maximum size of the preplatoon and the maximum amount of waiting time, for any vehicle, for the formation of a preplatoon. In heavy traffic, preplatooning could increase AHS inflow.

(SF2.2) Transition Lane Metering Planning

On an AHS with a transition lane, especially an AHS in which the only way to access the automated lanes is through the transition lane, the transition lane may become a bottleneck. During congestion, regulating automated traffic entering the automated lanes may become crucial. Metering may involve both limiting the amount of traffic entering the transition lane (and then the automated lanes) and evening out the incoming traffic spatially and temporally. The object of metering may be a platoon or a vehicle.

One way to meter traffic on the transition lane is as follows: An automation-equipped vehicle that wishes to use the automated lanes has to make a request to the roadside control system while driven on the manual lanes. Upon receiving the permission, it is driven manually into the transition lane. The roadside control system may provide instructions about the time and place to make the manual lane change. Factors influencing roadside's metering decisions include traffic conditions and vehicles' trip lengths/destinations. The roadside control system may deny a vehicle's entry because of its short trip length.

Other activities on the transition lane may further exacerbate the traffic conditions on the transition lane. For example, if vehicles have to be inspected on the transition lane before entering the automated lanes and the inspection cannot be performed instantaneously, the transition lane may limit the amount of traffic able to enter and use the automated lanes. Similarly, the need to verify driver readiness to take over manual control (after the vehicle leaves the automated lanes) may cause vehicles to spend more time on the transition lane.

(SF2.3) Automated On-Ramp Preplatooning

This function is identical to the transition lane preplatooning function except that it takes place on an automated on-ramp.

(SF2.4) Automated On-Ramp Metering

This function resembles its conventional counterpart. However, it may meter the entry of platoons too. (Since driving has been automated at this point, facilities needed for conventional metering, e.g. metering lights, are no longer needed.) Similar to Transition Lane Metering Planning, factors influencing roadside's metering decisions include traffic conditions and vehicles' trip lengths/destinations.

(SF3) System Flow Optimization Function

This is the main function that optimizes the system flow based on the inflow. It consists of platoon size (maximum and average) planning, target speed/density/spacing planning, traffic assignment, and flow balancing planning.

(SF3.1) Platoon Size Planning

Given the traffic demand and taking into consideration the safety requirements, this function determines the maximum platoon size and the target platoon size. Note that the sizes may vary with respect to section, lane and time.

(SF3.2) Target Speed/Density/Spacing Planning

This function determines the target speed, density and longitudinal spacing for throughput optimization. (Under platooning, two types of spacing, inter-platoon spacing and intra-platoon spacing, need to be determined.) Note that the speed, density and spacing may vary with respect to section, lane and time. For AHS with lane merges (where a lane is dropped) and lane divisions (where a new lane is added), this function also plans for the merging and diverging of traffic flow. This covers the cases of highway-to-highway intersection, highway-to-street intersection, and regular lane addition and lane drop on AHS.

(SF3.3) Traffic Assignment

Given the inflow (metered or not), demand estimates, the current traffic conditions, physical configuration of the AHS and the adjoining arterials/city streets, and regulated vehicle self-control rules, this function assigns AHS traffic (aggregate traffic, not an individual vehicle). Possible objectives include maximization of longitudinal traffic flow, minimization of travel time, etc. The stringency of the exiting requirement may vary. The assignment may be at the detail level of highway/section/lane/time-interval. Traffic may be grouped according to O-D, vehicle type and driver preferences. This is the core of the system flow planning function and requires intensive mathematical treatment. If assignment includes the detail of time, speed/density/spacing plans may be inferable. Actual traffic flow may deviate from the planned flow due to over-aggregation or inaccuracy of the input data, inaccuracy of the macroscopic representations of the microscopic characteristics of the vehicle movement planning functions or the inability of the vehicle movement planning functions to achieve the planned flow. Traffic assignment needs to be performed periodically.

(SF3.4) Flow Balancing Planning

Flows on different lanes may be so imbalanced that highway capacity is not fully utilized. This function seeks to correct the imbalance.

3.3 Vehicle Movement Planning Functions

These functions plan for the movement of *individual vehicles.* Input to these functions may include: output of the system flow planning functions, configuration of AHS and the adjoining arterials/city streets, traffic conditions on AHS and the adjoining arterials and city streets, driving conditions on AHS, trip destination, type of vehicle and driver preferences, etc. Output from this function may include vehicle trajectory plans. These plans imply route assignment and also reflect planned maneuvers to “condition” (lengthed, create, shorten or close) gaps between vehicles for more efficient lane-changing activities. The contents of these plans may encompass lane selection, lane-change timing, lane-change location and lane-change coordination, e.g., the assignment of the receiving gap for a lane change. Some component of the movement plans for a particular vehicle, e.g. timing of lane changes, may be developed gradually as the vehicle proceeds on the automated lanes towards it destination. The performance of traffic planning hinges on how well these functions are integrated with the system flow planning functions.

(VM1) Route Planning

Given the destination of a particular trip, the configuration of the AHS network and the current and forecast traffic conditions, this function determines a route or suggests multiple routes that meet certain selection criteria. (This function deals with one trip (vehicle) at a time.) Various driver preferences may need to be accommodated. If the traffic assignment function is also available, an additional input to this function is the output of that function. Particularly useful are the route(s) assigned to the trips with the same origin/destination and perhaps the same vehicle type and driver preferences. If driver choices or preferences are not accommodated in the system flow planning process, they may be satisfied in this function. Doing so may cause deviation of the actual flow from the flow planned by the traffic assignment function. On the other hand, considering such driver choices in the system flow planning process introduces an additional dimension of demand uncertainty.

(VM1 .l) Initial Route Selection

This function is requested by vehicle at the time of its entry into the AHS.

(VM 1.2) Route Change

This function re-selects the route for a trip. It may be invoked by the driver after a change of destination or after a change of mind about the earlier selection. It can also be invoked by the vehicle or the roadside control system after a change in traffic condition. The routing algorithm and the user interface are similar to the function of Initial Route Selection.

(VM2) Path Planning

The path of a trip is the vehicle's trajectory from the entry point to the departing point, possibly across lanes. This function determines the path the vehicle should traverse. If the Route Planning function is also available, this function determines the path on the selected route. Note that a path is different from a route in that the former specifies (i) the lane identification and (ii) the time/location of a lane change. This function could build the planned path gradually as the vehicle proceeds towards its desired destination. If the traffic assignment function is also available, the highway/section/lane/time-interval combination assigned to the trips with the same origin and destination (and perhaps the same vehicle type and driver preferences) should be useful. This function consists of two subfunctions: lane selection planning and lane change planning.

(VM2.1) Lane Selection Planning

For each trip, this function assigns a particular highway/section/lane/time combination for the vehicle throughout the trip. (The exact time and location at which to initiate a lane change are determined by the function of lane change planning.) Possible differences between this function and Traffic Assignment include: (i) The former deals with the specific trip needs of one vehicle while the latter considers demand for the whole system and seeks to optimize the system throughput; (ii) The former is likely to be invoked more often than the latter. This decision is based on the vehicle's destination, current and forecasted traffic conditions. If the Traffic Assignment function is also available, this function could use the assigned highway/section/lane/time-interval unless it can improve the system throughput determined by Traffic Assignment by using up-to-date data.

(VM2.1.1) Initial Lane Selection

This function is invoked upon vehicle's entry to the AHS.

(VM2.1.2) New Selection

This function is similar to Initial Lane Selection except that it is invoked after a change of route.

(VM2.1.3) Re-selection (Flow-Balancing)

If the flow-balancing function is available, this function is invoked by the roadside control system (not by the driver) to balance the flow on different lanes. The initial lane selection was done based on, among other things, the forecast traffic conditions. Deviation from the forecast demand may require re-selection of lane for throughput optimization and successful exiting.

(VM2.2) Lane Change Planning

This function plans for the exact time/location and gap identification/creation for a lane change. This function could be completely decentralized so that each vehicle is responsible for timing, locating and negotiating for its lane changes. A possible completely decentralized scheme would be to let the driver make the lane change request and let the vehicles themselves negotiate the exact time and location of the lateral movement. In this case, this function is beyond traffic planning and is effectively non-existent. This function could also be completely centralized. For example, the roadside control system could determine the exact vehicle trajectories that culminate in a successful lane change. A less centralized scheme is to have the roadside control system (collectively) determine only the timing of initiating individual lane changes and then let the vehicles themselves negotiate the exact timing and location of the lateral movement. In such a case, the lane change planning function could do nothing but scatter out the lane change initiations spatially and temporally. Note that priority may be given to some vehicles, e.g. those vehicles that are closer to their desired exits. No matter how centralized this planning process is, coordination among the involved vehicles is necessary for safety. This function consists of two subfunctions: lane-change scheduling and lane-change receiving gap assignment.

(V M 2 . 2 . 1)

This function determines the exact timing (and hence location) of the initiation of the lane change preparation. Timing may be influenced by the position of the vehicle and the surrounding traffic conditions.

(VM2.2.2) Lane-Change Receiving Gap Assignment

This function determines the gap, existing or to be created, into which the lane-changing vehicle enters upon entering the destination lane. As a part of gap determination, this function identifies the vehicles involved. For AHS with lane barriers, this function also determines the opening through which the lane-changing vehicle is to pass.

(VM3) Vehicle/Gap Distribution Planning

The physical distribution of vehicles and gaps has a great impact on the ability of vehicles to change lane and the time needed to complete a lane change. Proper distribution can improve the lateral and hence the overall AHS capacity. This function plans for the proper distribution of vehicles (platoons, if applicable) and gaps. This function consists of the following two subfunctions.

(VM3.1) Gap Management

This function monitors and manages the position and the length of individual gaps between the traffic units. (The traffic unit may be a platoon or an individual vehicle.) Independent of the gap creation for individual lane change maneuvers, this function manages the gaps to maximize the lateral capacity. The output of Target Speed/Density/Spacing Planning, if present in the scenario, can be used to guide gap management.

(VM3.2) Platoon Merge/Split

This function determines and plans (i) whether and when to split one platoon into two or more and (ii) whether and when to merge two or more platoons into one. It also determines where the split(s) should occur within a platoon. If the platoon size planning function is also available, then the output of that function can be a useful input.

3.4 Discussion

Selection of particular design options could not only incur special functions but also impact the functional contents and data requirements. Detail level of a planning function and the actual planning algorithm would obviously impact the functional contents and data requirements. We now briefly discuss the relationship of this architecture to some individual design options. Note that combining design options could incur compounding effects.

Assume that different types of vehicles are accommodated on an AHS. Although this does not entail any functions applicable only to such accommodation, it will have significant impacts the functional contents. It is obvious that, under the platooning strategies, since no heavy duty vehicles should be mixed with light-duty ones in the same platoon, system flow optimization algorithms, the lane selection and lane change algorithms should contain more intelligence than otherwise.

The presence of the transition lane, entailed by sharing the highway between the automated and manual traffic, plays an important role. It entails those functions related to transition lane operation and also makes the contents of the common functions potentially very different, e.g. lane change planning function accommodating manually-driven vehicles on the transition lane.

The adoption of platooning has a fundamental impact on many functions. The effects come not only from the necessity of those functions applicable only to the platooning scenarios, e.g., preplatooning and platoon size planning, but also from the more complicated implementation of the common functions, e.g., lane-change planning and target speed/density/spacing planning.

Although there are no functions peculiar to the barrier scenarios, the presence of barriers has tremendous implications on the functional contents, e.g. lane-changing through opening between barriers. Note that adopting the barrier option may require more advanced AHS enabling technologies.

As the current highway system evolves towards AI-IS, new functions can be added and old function can be replaced by new ones. For example, path planning may be needed and can be added after two or more lanes are dedicated to automated traffic (and lane changes are fully automated); route planning may be needed and can be added when a network of automated highways becomes operational. When or where ultra-high capacity is needed, platooning may be required. Consequently, functions like platoon size planning could be added and those like lane-change planning can be replaced.

4 CONCLUSION

An architecture for AHS capacity-optimizing traffic planning functions has been defined. These functions can be used to specify not only fully automated AHS scenarios but also associated evolutionary paths to them. It can be used to define the functional requirements for a collection of computer simulation tools. In addition, it can guide the efforts on analytical modeling for evaluation, optimization and comparison of capacity of various AHS operating scenarios. Since this architecture analyzes and organizes the overall task of traffic planning, it can be used as a basis for designing the physical AHS traffic planning system. Finally, from the view-point of technology development, this architecture can help identify the vehicle and roadside control system functions necessary for supporting any particular AHS scenario.

All vehicle movement planning functions are executed through a collection of vehicle maneuvers. These maneuvers will be constantly invoked by various controllers. To ensure safe vehicle movement, potential conflicts among different maneuvers must be identified and resolved. This requires rigorous definition for the concept of maneuver and that of conflict among different maneuvers. In addition to specifying maneuver protocols, a complete definition of maneuver should also specify, for example, the conditions for maneuver initiation and continuation (or abort). Also required is the specification of a conflict recognition/resolution method that ensures safety. This line of research is underway by the author and the findings will be reported separately.

In the conventional highway system, the definition of a maneuver conflict is simple. For example, when two drivers plan to use a common time-space for their maneuvers, e.g., both intending to change lanes into a common gap at the same time, a conflict occurs. Although fully automated AHS with advanced traffic planning functions for efficiency have the potential of maximizing the capacity, conflict recognition and control coordination can potentially be very complex and susceptible to design errors 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 AHS design objectives should be sought.

The functional architecture proposed in this paper will be used by the author to develop an analytical approach to the evaluation, optimization and comparison of the capacity of various AHS operating scenarios. To minimize the complexity of functional interface, two groups of analytical models are expected, one for the macroscopic system flow planning functions and the other for the microscopic vehicle movement planning functions. To further minimize the functional interface within the system flow planning functions, it is desirable to have a unified model for all of the system flow planning functions. In fact, the approach of dynamic traffic assignment seems particularly suitable for the problem of overall AHS system flow optimization. However, computational complexity could be an issue and the problem may need to be decomposed. Due to the fact that microscopic traffic modeling often hinges upon the operational details associated with individual AHS scenarios, separate but coupled models are likely to be required. The major interface task will be between the system flow optimization model(s) and the vehicle movement models and the nature of the task will be to approximate the microscopic characteristics of vehicle movements, particularly those characteristics dictated by the vehicle movement planning functions, by some appropriate macroscopic (flow) representations.

Dynamic traffic assignment through analytical modeling and optimization has been widely accepted by the IVHS R&D community as a promising traffic control tool for relieving traffic congestion on conventional highways and city streets. Due to the completely controlled nature of AHS traffic, dynamic assignment of AHS traffic is even more promising. One added dimension of complexity associated with AHS dynamic traffic assignment is lane assignment. Lane changes, for fully utilizing AHS capacity or for exiting, incur disturbances to and hence reduction of longitudinal flow. The amount of such disturbances depends on the operating scenario. If a lane change incurs significant amount of such disturbances or a large amount of lane changing is required, then traffic assignment at the additional detail level of lane assignment becomes necessary. Although trip lengths may be long, trip lengths on a particular highway could be significantly shorter. Although missing the desired exit and exiting at the next exit once in a while may be acceptable, missing a highway-to-highway connector ramp may incur unacceptable inconvenience. Therefore, intelligent lane assignment is necessary to ensure a high rate of successful exiting, to another highway or to city streets, while minimizing the resulting disturbances to and reduction of longitudinal flow. For robustness of the system flow optimization model(s), a general class of equations/inequalities that can represent the impact of lane changes on AHS longitudinal flow under various operating scenario should be identified. However, to achieve this requires a detailed study of the lane change rules under all major operating scenarios. With this general class of equations and inequalities, the AHS dynamic traffic assignment model can then be precisely formulated. Therefore, a microscopic study of lane-changing under different operating scenarios should be the focus of the early stages of AHS capacity evaluation and optimization.

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