Infrastructure Assisted Concept

Datta Godbole, Mark Miller, Jim Misener, Raja Sengupta, Jacob Tsao,
California PATH, Institute of Transportation Studies
University of California, Berkeley

January 23, 1996

Introduction

This document describes one of five Automated Highway System (AHS) concepts, namely *Infrastructure Assisted AHS,* developed for NAHSC Task C2. In its final deployment, the Infrastructure Assisted AHS concept (hereafter concept), supports *fully automated vehicles on dedicated lanes*. The concept description is organized into several state descriptions. These states correspond to different deployment stages in time, and options for different localities e.g., urban, rural, inter-urban etc. The aims of the concept design are to,

- achieve higher throughput by using platooning when necessary (free agent operation otherwise),
- achieve higher safety by guaranteeing co-operative vehicle behavior'
- achieve greater reliability by including infrastructural faclilities for system-wide flow control,
- achieve reduced emissions by smoothing acceleration and deceleration patterns,
- achieve better inter-modal and inter-jurisdictional co-ordination by system-wide flow control,
- achieve better control of local trip demand and congestion patterns by system-wide flow control.
- free the driver from the chores of driving, but nevertheless allow the driver to decide on matters of convenience.

The concept development is based on conservative technological assumptions with respect to vehicle sensing capabilities. Accordingly, vehicle and infrastructure communication systems are proposed to simplify sensor requirements. It is also assumed that AHS safety levels higher than present day levels can only be attained by guaranteeing co-operative vehicle behavior. This requires standardized inter-vehicle co-ordination protocols, that eliminate aggressive or drunk driving and reduce chance phenomenon such as pinch maneuvers in lane changing. Moreover, the co-operative vehicle assumption also mandates that the automated vehicles be isolated from vehicles that are may not behave in a co-operative manner, i.e., placing the automated vehicles in dedicated lanes. Non-cooperative vehicles and their associated hazards will be rarely present. Physical barriers and well designed check-in procedures can further reduce the probability of such presence. Such physical segregation could also reduce the presence of obstacles on the AHS.

This concept supports a variety of options representing different distributions of intelligence between vehicle and infrastructure. The appropriate option can be selected based on local factors, vehicle and infrastructure cost trade-offs, or infrastructure cost and social benefit trade-offs. The local tailorability section describes both local factors and local options in greater detail. In all options, the infrastructural intelligence is not safety critical. If the infrastructure fails the concept is designed to either operate safely with reduced service or have the system shut down safely. In other words, the system will degrade safely and gracefully. The degraded mode section describes this in detail.

The concept is designed to have several evolutionary deployment paths that are feasible in societal and institutional terms and in terms of technological maturity. The deployment paths envisage incremental growth in vehicle and infrastructure intelligence, and incremental conversion of existing manual highway facilities to automated highway facilities, in tandem with increasing market penetration. The deployment section describes one such deployment path.

The following summarizes the salient features and requirements of the concept.

1. *Standardized inter-vehicle co-ordination protocols to guarantee co-operative vehicle behavior.*
2. *Separation of automated vehicles into dedicated lanes for fully automated operation.*
3. *Short range, high data rate inter-vehicle communications for platooned operation.*
4. *Medium-range low data rate communications required for co-ordinated lane change in multi-lane operation.*
5. *Infrastructure to vehicle broadcast communications in entry and exit zones with long entry and exit lanes.*
6. *Infrastructure to vehicle two-way channel communications in entry and exit zones with short lanes and highway to highway merge zones.*
7. *Global infrastructure to vehicle broadcast communications for system-wide routing and flow control or static signage for speed limits, separation policy etc.*

These requirements may be partially met by ITS services such as in-vehicle signage or ATIS.

8. *Global infrastructure surveillance system to do data collection for system-wide flow control.*

Again, some of these requirements may be offset by ITS facilities such as probe vehicles, roadside data collection beacons, surveillance systems.

9. *Vehicle to infrastructure communications for emergency notification, incident reporting and emergency advice.*

These requirements may be supported by ITS services on non-AHS specific communication media such as CDPD.

This concept differs from the other four concepts in the following respects. The infrastructure supported concept assumes no two way vehicle to infrastructure communications anywhere. This concept assumes that such communication exists in entry, exit and merge zones. The free radical concept assumes there are no AHS specific inter-vehicle or infrastructure to vehicle communication requirements. The co-operative concept assumes that there are no AHS specific infrastructure to vehicle communications. This concept assumes that vehicle sensing must be supplemented by both inter-vehicle and infrastructure to vehicle communications.

The concept description is organized as a reference state and several other states. For descriptive convenience the reference state describes fully automated vehicles on dedicated lanes in an urban, high traffic volume environment, with benign weather and equipment conditions. This is expected to represent the most sophisticated state of the concept. We describe both normal and degraded mode operation. Other concept states are described by their differences from the reference state. Section 2 describes the reference state, section 3 deployment states, section 4 describes states for local tailorability, section 5 the degraded mode operation of the reference state, and section 6 discusses specific societal and institutional issues associated with this concept. Section 7 is a concluding comment.

Section 2: Concept Reference State Description

This state is requires the least driver support. The driver can make routing and exit choice decisions based on advice from the AHS infrastructure or other ITS sources. The decisions are then executed by the vehicle. The driver can also participate in obstacle and emergency detection through the driver interface. The vehicle system may fuse this information with that from other sources such as its own sensors, or infrastructure communications. Such driver participation is not safety critical.

The rest of this document concentrates on the operational functionality. AHS functionality for normal operations can be put in four major categories: recognition, movement/maneuver decision, movement/maneuver planning and coordination, and movement/maneuver control.

- Recognition functions include roadway geometry recognition, roadway and other conditions recognition (including obstacles), ambient environment recognition, traffic regulation recognition, and traffic condition recognition.
- Movement/maneuver decision includes those regarding speed, spacing, lane change timing and location.
- Movement/maneuver planning/coordination is needed for merging, lane-changing, entry, exit, platoon formation and dissipation.
- Movement/maneuver control implements the decisions.

In addition to normal operational events, vehicles must be alerted to nearby abnormal events, e.g., failures or collisions, either

1. through detection by on-board sensors or
2. through notification by the failed or collided vehicles directly or indirectly by the infrastructure.

The vehicle-system must be able to respond to such events safely.

This section focuses on normal operations; failure events & degraded modes will be the focus of Section 5.

Vehicle Classes: All

Assumptions: Fully automated vehicles on dedicated lanes, benign weather and equipment conditions.

Figure 1 represents a physical architecture diagram showing components of the automated vehicle and infrastructure control system. An automated vehicle consists of sensors, actuators, communication devices and controllers. Self state sensors sense the state of the vehicle such as velocity, acceleration, yaw rate, etc. Neighborhood sensors obtain information about roadway geometry and the state of the surrounding vehicles and obstacles. This information is used by the feedback control laws for different maneuvers. For operation in a platoon, the following vehicles require the acceleration information about the preceding and the lead vehicle which can not be sensed. This information is provided by the intra-platoon communication system. Without this communication, the vehicles can still operate as free agents. The planning and coordination system on the vehicle is responsible for taking strategic decisions such as lane change decision, speed &

inter-vehicle separation decision, platoon join-split decision. In making these decisions, the planning and coordination system uses the routing suggested by the driver or the infrastructure, incident, emergency and weather information broadcast by the infrastructure control system. The join, split, lane change maneuvers are coordinated with neighboring vehicles by exchanging a structured set of messages (protocol) using inter-vehicle communication systems. The structured maneuver execution results in increased throughput and safety. Coordination and execution of entry, exit and merge maneuvers involves communication with neighboring vehicles as well as the infrastructure.

The infrastructure control system is divided into sectional controllers and one central network controller called Automated Highway Management Center (AHMC). The adjacent sectional controllers are connected by a wireline nework with each other and with AHMC. The sectional controllers themselves contain stretch[1], entry, exit and merge controllers as subsystems. The stretch control system broadcasts suggested speed, separation and routing as well as incident, emergency and weather information to the automated vehicles in its range. It uses roadside flow sensors to obtain local flow information and the wireline communication network to obtain flow information of adjacent sections and highways. The roadside sensors are also used for obstacle detection. The entry, exit and merge controllers help vehicles execute entry, exit and merge maneuvers more efficiently. This can reduce physical highway size and alleviate capacity bottlenecks. These controllers detect and help create gaps in automated traffic and establish communication between the vehicles involved in the required maneuvers. The AHMC controller calculates global flow parameters such as estimated delays based on traffic information obtained from individual sectional controllers.

The hierarchical decomposition of the control system allows safe and efficient operation with lower sensing and control complexity and robust fault tolerant operation. The failure of infrastructure bases systems is tolerated by vehicle-borne systems and vice-versa. Refer to section 5 for further development.

We next describe the concept reference state with a physical architecture table and descriptions of several operational functions. The physical architecture table contains list of systems and brief description of their functionality. Each function description section has an information flow table showing the interconnections between different systems. Some of the detailed information flow requirements that are necessary for executing almost all vehicle control laws are not mentioned separately in each function description. For example, most of the control laws need to know vehicle parameters such as mass, rolling resistance, cornering stiffness of the tires, etc. to calculate the feedback control. These quantities are either sensed by sensors or are adaptively identified using available sensor readings.

[1] A *stretch* controller operates on a highway *link* without any decision nodes such as entry, exit and merge points.

Figure 1: Automated Highway System Architecture

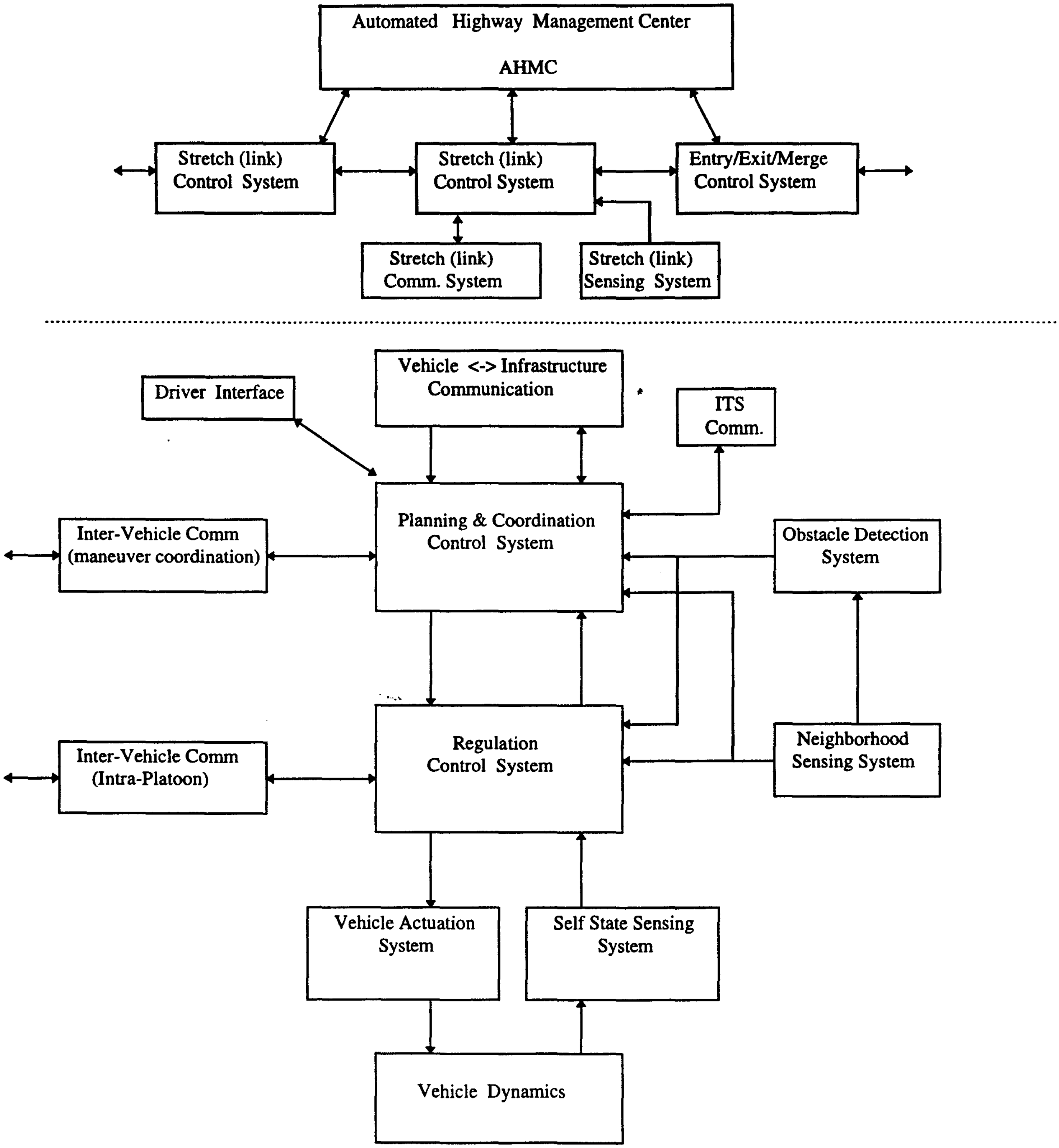

Table 2.1 Physical Architecture Table

Location	System Type	System Description	
Vehicle	Control System	Name	**Planning and Coordination System**
		Function	Execution of all Strategic Driving Functions
		Subsystems	Planning System, Co-ordination System
		Name	**Planning System**
			Speed decision, Entry decision, Exit decision, Inter-vehicle separation decision, Join decision, Split decision, Merge planning, Obstacle avoidance planning, Emergency Response Planning
		Name	**Coordination System**
		Function	Gap negotiation, Join negotiation, Split negotiation, Stop coordination , Entry coordination, Exit coordination
		Name Function	**Regulation Control System** Speed control, Longitudinal separation control, Intra-platoon separation control, Inter-platoon separation control, Join control, Split control, Lane keeping, Gap alignment, Move-over Note: Lane changing performed by gap alignment and move-over.
	Sensors	Name	**Vehicle Neighborhood Sensing System (VNSS)**
		Function Technology	To sense all roadways, vehicles and obstacles in the lane of the vehicle and in adjacent lanes (including entry and exit ramps if required by design). Thus the system does Obstacle detection, Lateral position sensing, longitudinal separation, and speed of neighboring vehicles sensing. Most probably a fused sensing system, including either radar or vision as the primary technology. Can include lidar or some other proximal sensing technology such as sonar or capacitance detectors.
		Name	**Vehicle Self-State Sensing System**
		Function	Sense speed, lateral accl., longitudinal accl. and other parameters of associated vehicle.
		Technology	Tachometer, Magnetic encoders, Accelerometer
	Communication Systems	Name	**Intra-platoon Communication System**
		Function	Communicate acceleration and speed of platoon lead vehicle, acceleration of vehicle in front.
		Technology	Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared

Location	System Type	System Description	
Vehicle		Name	**Inter-vehicle Communication System**
		Function	Communication for Gap negotiation, Join negotiation, Split negotiation, Stop co-ordination, Obstacle detection
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared
	Communication Systems	Name	**Vehicle to Roadside Communication System**
		Function	Communication for Speed decision, Lane change decision, Exit decision, Entry decision, Maximum platoon size, Obstacle detection, Gap negotiation for Entry and Merging, Hand-off for Entry, Hand-on for Exit .
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared Include: tag (on vehicle) and beacon (@ roadside)
		Name	**ITS Communication System**
		Function	Communication for Routing, Emergency response, Emergency detection and other ITS services.
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared FM subsidiary communications authorization (SCA) FM radio broadcast data system (RBDS) TV secondary audio programming (SAP) Highway advisory radio (HAR) Global positioning satellite (GPS) For infrastructure-to-infrastructure: Spread spectrum systems operating in unlicensed bands Microwave radio Twisted pair fiber optic cable

Location	System Type	System Description	
Vehicle	Actuators	Name	**Throttle Actuator System**
		Function	Throttle control
		Name	**Brake Actuator System**
		Function	Braking control
		Name	**Steering Actuator System**
		Function	Steering control
	Other Systems	Name	**Driver Interface**
		Function	Communication with driver for Emergency monitoring and response, Obstacle detection, recognition and avoidance, Exit decision, Entry decision, Routing, Hand-off, Hand-on.
		Technology	Motion sensing Absolute position systems Vehicle system
		Name	**Driver Monitoring System**
		Function	Monitor the alertness of the driver for Hand-on.
		Name	**Obstacle Recognition System.**
		Function	Data fusion for obstacle recognition
		Name	**Emergency Detection System**
		Function	Data fusion for emergency detection
	Driver	Function	Obstacle recognition, Emergency detection and response, Exit decision, Entry Decision, Hand-off, Hand-on

Location	System Type	System Description	
Roadside	Control System	Name	**Section Control System**
		Function	Speed Decision, Inter-Vehicle Separation Decision, Lane Change Decision, AHS Flow Control, AHS Admission Control, Emergency Detection & Monitoring, Emergency Response & Incident Clearing
		Subsystems	Stretch Control System, Entry Control System, Exit Control System, Merge Control System
		Name	**Stretch Control System**
		Function	Speed Decision, Inter-Vehicle Separation Decision, Lane Change Decision, AHS Flow Control, AHS Admission Control, Emergency Detection & Monitoring, Emergency Response & Incident Clearing
		Subsystems	Stretch Sensing System, Stretch Communication System

Location	System Type	System Description	
Roadside	Sensors	Name	**Stretch Sensing System**
		Function	Sensing of average speed, flow, road image for obstacle recognition and emergency detection.
	Communication Systems	Name	**Stretch Communication System**
		Function	Broadcasting from roadside to vehicle, two-way emergency communication from roadside to specific vehicle.
	Control Systems	Name	**Entry Control System**
		Function	Entry metering, gap creation, gap negotiation, gap alignment, check-in, hand-off
		Subsystems	Entry Rate Controller, Entry Sensing System, Entry Communication System, Entry Co-ordination Controller, Entry Check-in Controller
		Name	**Entry Rate Controller**
		Function	AHS admission control (entry rate metering)
	Sensors	Name	**Entry Sensing System**
		Function	Sense entry queue length, entering vehicle location, speed and communication-id on on-ramp, vehicle location, speed and communication-id in entry zone of automated highway, road image for obstacle recognition and emergency detection.
	Communication Systems	Name	**Entry Communication System**
		Function	Two way message based communication with vehicles in the on-ramp and the entry zone of the automated highway. Broadcast communications to all vehicles in the entry zone of the highway.
	Control Systems	Name	**Entry Co-ordination Controller**
		Function	Gap negotiation between vehicles in highway entry zone and entering vehicle. Speed, separation decision and lane change decision for vehicles in entry-zone of highway.
		Name	**Entry Check-in Controller**
		Function	Vehicle and driver status monitoring, hand-off

Location	System Type	System Description	
Roadside		Name	**Exit Control System**
		Function	Exit Rate metering, check-out, hand-on
		Subsystems	Exit Sensing System, Exit Co-ordination Controller, Exit Communication System, Check-out Controller, Exit Rate Controller
	Sensors	Name	**Exit Sensing System**
		Function	Sense exit queue length, exiting vehicle location, speed and communication-id on off-ramp, road image for obstacle recognition and emergency detection.
	Control Systems	Name	**Exit Co-ordination Controller**
		Function	Speed of exiting vehicle. Speed, separation decision and lane change decision for vehicles in exit-zone of highway.
	Communication Systems	Name	**Exit Communication System**
		Function	Two way communication with vehicles on the off-ramp and the exit zone of the automated highway. Broadcast communications to vehicles in the exit zone of the highway.
	Control Systems	Name	**Check-out Controller**
		Function	Vehicle check-out, driver status checking, hand-off
		Name	**Exit Rate Controller**
		Function	Exit queue control, To control rate of vehicles entering the local traffic
		Name	**Merge Control System**
		Function	Highway to highway merging, gap creation, gap negotiation, gap alignment, speed decision, separation decision and lane change decision in merge zone
		Subsystems	Merge Sensing System, Merge Communication System
	Sensors	Name	**Merge Sensing System**
		Function	Sense speed, distance of vehicles in the merge zone, road image for obstacle recognition and emergency detection
	Communication Systems	Name	**Merge Communication System**
		Function	Two way message based communication with vehicles in the merge zone of the automated highway. Broadcast communications to all vehicles in the merge zone of the highway.

Location	System Type	System Description	
AHMC	Control System	Name	**Network Control System**
		Function	AHS Routing, AHS Flow Control, AHS Admission Control, Obstacle Recognition, Emergency & Incident Detection, Emergency Response & Incident Clearing
		Subsystems	Network Routing Controller, Emergency Detection & Monitoring System, Obstacle Recognition System, Roadside Communication System.
		Name	**Network Routing Controller**
		Function	Highway to highway routing, Dynamic O-D demand estimation, Desired entry rate computation, current and predicted link travel time estimation
	Communication Systems	Name	**Roadside Communication System**
		Function	Two way communication between roadside control systems and AHMC and roadside control systems.
		Technology	Wireline Network
	Other Systems	Name	**Emergency Detection & Monitoring System**
		Function	Process road images to detect and recognize emergencies, process messages from section control systems to detect and recognize emergencies
		Name	**Obstacle Recognition System**
		Function	Process road images to recognize obstacles and process messages from vehicles, section control systems and other external agencies for the same.

2.1: AHS Function Descriptions

2.1.1: Speed Tracking

General Description: This function is provided by the *regulation control system* in conjunction with the inter-vehicle separation tracking function. For this purpose, the *regulation control system* receives desired reference speed and desired inter-vehicle separation from the *planning system*. Based on the actual and reference speed, an actuator command (throttle or brake) is calculated. The reference speed is tracked only if the vehicle in front is farther than the desired inter-vehicle separation and moving at least as fast. The speed tracking controller maintains passenger comfort standards for acceleration and jerk. The *regulation control system* needs information about vehicle speed and acceleration from the *self state sensing system* as well as front vehicle distance and relative velocity from the *neighborhood sensing system.*

Information Flow

Description	From System	To System
Desired reference speed	Planning system	Regulation control system
Desired inter-vehicle separation	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Front vehicle distance	Neighborhood sensing system	Regulation control system
Front vehicle speed (relative)	Neighborhood sensing system	Regulation control system
Throttle command	Regulation control system	Throttle actuator system
Brake Command	Regulation control system	Brake actuator system

Highway Geometry Modification: None

2.1.2: Inter-vehicle Separation Tracking

General Description: This function is provided by the *regulation control system* in conjunction with the speed tracking function. For this purpose, the *regulation control system* receives desired inter-vehicle separation (either as distance or time headway) and desired reference speed from the *planning system*. Based on the actual and desired separation, an actuator command (throttle or brake) is calculated.

- In case of the platoon leader and free agent, the inter-vehicle gap is given by a constant-time or constant safety factor separation. If the vehicle in front is farther than the desired inter-vehicle separation and moving at the same speed or faster, the desired speed is tracked instead of the desired separation. Actual vehicle speed never exceeds reference speed during separation tracking.

- The followers of the platoon typically maintain a constant intra-platoon distance from the preceding vehicle. To avoid slinky (accordion type) effect, the controller needs values of acceleration of the preceding vehicle as well as velocity and acceleration of the lead vehicle of the platoon. This information is provided by short-range high data rate vehicle-vehicle communication.

The separation tracking controller also requires acceleration and jerk measurements to maintain passenger comfort.

Information Flow

Description	From System	To System
Desired inter-vehicle separation	Planning system	Regulation control system
Desired reference speed	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Front vehicle distance	Neighborhood sensing system	Regulation control system
Front vehicle speed (relative)	Neighborhood sensing system	Regulation control system
Front vehicle acceleration, lead vehicle velocity/acceleration	Inter-vehicle communication (platoon follower operation)	Regulation control system
Throttle command	Regulation control system	Throttle actuator system
Brake Command	Regulation control system	Brake actuator system

Highway Geometry Modification: None

2.1.3: Lane Keeping

General Description: This function is performed by *regulation control system.* The objective is to maintain the vehicle in the center of the highway lane. The controller receives sensor readings from the *neighborhood sensing system* that describes the deviation of the vehicle from the center of the lane[2] and the lane geometry preview. The lane keeping controller sends a steering command to the *steering actuator system.* The calculation of steering command requires the knowledge of the state variables of the lateral dynamical system such as lateral velocity, lateral acceleration and yaw rate.

[2] In case of magnetic marker/magnetometer system, the sensors directly provide deviation from the center of the lane. In case of cameras, one has to calculate it using the information about the lane markers in the image.

Information Flow

Description	From System	To System
Deviation from the lane center	Neighborhood sensing system	Regulation control system
Road geometry preview	Neighborhood sensing system	Regulation control system
Lateral velocity	Self state sensing system	Regulation control system
Lateral acceleration	Self state sensing system	Regulation control system
Yaw rate	Self state sensing system	Regulation control system
Longitudinal velocity	Self state sensing system	Regulation control system
Steering command	Regulation control system	Steering actuation system

Highway Geometry Modification: Depending on the neighborhood sensing system, the highway should be modified so that the deviation from the lane center as well as lane preview can be easily obtained. Thus, for a magnetic marker/magnetometer system, magnetic markers/tape should be installed in the center of each automated lane. For vision system, lane markers should be appropriately marked/painted.

2.1.4: Lane Changing

General Description: This function is performed by *regulation control system.* The decision to change lane (either to the left or right) is taken by the *coordination system.* The function is split into two elemental functions, namely, gap alignment and move over.

Once the lane change decision is taken, the coordination system checks (using the *Neighborhood sensing system)* for the appropriate gap in the target lane. If the gap exists, the coordination system commands the regulation system to move over. If the gap does not exist, the coordination system uses the communication capabilities to coordinate with the neighboring vehicles so as to create the appropriate gap. The coordination protocol is described in Section 2.1.11. If the coordination is successful, the coordination system commands the regulation system to execute gap alignment. Gap alignment involves acceleration/deceleration so as to align with a gap in the target lane. The gap alignment can take place due to joint movement of vehicles in both lanes.

The move over function involves planning a path for lateral movement to the target lane and commanding the steering actuator system to execute the path. Thus the complete lane change functions involves both longitudinal and lateral movements.

Information Flow

Description	From System	To System
Lane change commands	Planning system	Regulation control system
Desired gap (in adjacent lane)	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Lateral velocity	Self state sensing system	Regulation control system
Lateral acceleration	Self state sensing system	Regulation control system
Yaw rate	Self state sensing system	Regulation control system
Road geometry preview	Neighborhood sensing system	Regulation control system
Front vehicle distance & velocity	Neighborhood sensing system	Regulation control system
Relative distance & velocity of vehicles in target lane on either side of the gap	Neighborhood sensing system	Regulation control system

Steering command	Regulation control system	Steering actuator system
Acceleration command	Regulation control system	Acceleration actuator system
Braking command	Regulation control system	Brake actuator system

Highway Geometry Modification: Necessary modification depending on lateral sensing technology.

2.1.5: Road Geometry Recognition

General Description: The neighborhood sensing system on each vehicle is responsible for road geometry recognition. This information is mainly used by the regulation layer controller for maintaining lateral position along the center of the lane, lane changing and tracking of speed and inter-vehicle separation. A certain amount of road geometry preview is also needed for lateral control. The information can either be obtained by using *vision sensors* (cameras) mounted on vehicles that detect the *lane markers* on the road or by installing *magnetic markers/ magnetic tape* in the center of the lane and using *magnetometers* on the vehicle to sense the lane center. The *preview* information can either be encoded in the *magnets*, broadcast by *roadside beacons* or displayed on roadside *message signs* that can be sensed by the vehicle sensors.

2.1.6: Obstacle Recognition

General Description: Several systems perform the function of obstacle detection. In the reference state, it is not essential that the driver participate in obstacle detection. This concept requires minimal obstacle detection functions, as the infrastructure physical restrictions will exclude many obstacles. The *vehicle neighborhood sensing system* and the *roadside sensing systems* (which consists of *stretch sensing system, entry sensing system, exit sensing system,* and, *merge sensing system*) both have (multiple) sensors for obstacle detection. Obstacle detection includes detection moving and fixed obstacles (including vehicles). If the roadside sensing system detects an obstacle (other than a normal moving vehicle), it sends communication messages (broadcast) to all vehicles in the appropriate geographical location. The information from multiple on-board sensors and roadside communications is fused in the vehicle obstacle recognition system in order to perform the obstacle recognition function. The obstacle recognition information is communicated back to the roadside.

Information Flow

Description	From System	To System
Obstacle detection information	Neighborhood sensing system	Obstacle recognition system
Obstacle detection information	Roadside sensing system	Obstacle recognition system of all vehicles in range (broadcast communication)
Obstacle detection information	Roadside sensing system	(other) Roadside control systems (wireline communication)
Obstacle recognition information	(vehicle) Obstacle recognition system	Roadside control systems

Highway Geometry Modification: Necessary changes to aid obstacle detection sensors on vehicles and roadside.

2.1.7: Obstacle Avoidance

General Description: Obstacle avoidance is performed by the vehicle on-board controllers. Driver assistance is not required in the reference state implementation. The *vehicle planning and coordination system* contains special obstacle avoidance maneuvers, such as following the moving obstacle at a safe distance, stopping behind a stationary obstacle or changing lanes to avoid an obstacle. It also contains the logic to select the appropriate maneuver. The *coordination control system* has the responsibility to coordinate the obstacle avoidance maneuver with the neighbors, communicating the maneuver decision to neighboring vehicles and roadside, as well as, asking the *regulation control system* to execute the obstacle avoidance maneuver.

Information Flow

All the information flow represented by the tables in Sections 2.1.1, 2.1.2, 2.1.4, 2.1.8, 2.1.9, 2.1.10, and 2.1.11 is essential. Additional information flow is given by the following table.

Description	From System	To System
Obstacle recognition information	Obstacle recognition system	Planning & coordination system

Highway Geometry Modification: None

2.1.8: Speed Decision

General Description: The *planning system* on the vehicle receives reference speed command from the
appropriate *roadside control system.* This message transfer can be achieved either by broadcast communication, roadside beacon, or by variable message signs that are read by the vehicle sensors.

The planning system uses this as an advisory information to calculate the desired reference speed for the *regulation control system* to track. Depending on the local conditions (road surface conditions or environmental disturbances to sensing and communications) and the vehicle state, the planning system may ask the regulation controller to track a lower speed than the reference speed command it received from the roadside. This speed reflects the local safety requirements.

The roadside control system calculates the reference speed for the entire section taking into account safety and flow optimization. Refer to Section 2.1.20 for AHS flow control description and the corresponding information flow table.

We now present the additional information flow table.

Information Flow

Description	From System	To System
Reference speed command	Roadside control system	Vehicle planning system
Vehicle self state information (e.g., Brake pressure, Cornering stiffness)	Self state sensing system	Vehicle planning system
Environmental disturbance info	Neighborhood sensing system	Vehicle planning system
Desired reference speed	Vehicle planning system	Regulation control system

Highway Geometry Modification: None

2.1.9: Inter-vehicle Separation Decision

General Description: Similar to the speed decision, the *planning system* on the vehicle receives reference inter-vehicle separation command (for both leader and follower operation) from the appropriate *roadside control system.* The separation policy is provided for all vehicle classes and it can be either fixed distance or time headway command. This message transfer can be achieved either by broadcast communication, roadside beacon, or by variable message signs that are read by the vehicle sensors.

Based on this information, the planning system calculates the desired reference inter-vehicle separation for the *regulation control system* to track depending on the local safety requirements.

The roadside control system calculates the reference inter-vehicle separation (for all vehicle classes) for the entire section taking into account safety and flow optimization. Refer to Section 2.1.20 for AHS flow control description and the corresponding information flow table.
We now present the additional information flow table.

Information Flow

Description	From System	To System
Reference separation command	Roadside control system	Vehicle planning system
Vehicle self state information (e.g., Brake pressure, Cornering stiffness)	Self state sensing system	Vehicle planning system
Environmental disturbance info	Neighborhood sensing system	Vehicle planning system
Desired reference separation	Vehicle planning system	Regulation control system

Highway Geometry Modification: None

2.1.10: Lane Change Decision

General Description: Vehicle *planning system* decides when to change lane. There are two main reasons to change lane; to equalize the flow across AHS lanes, and to be able to exit. The *roadside control system* calculates the lateral flow requirements between lanes so as to balance the flow. It broadcasts this information along with the exit information to the vehicles in range. This functionality of the roadway control system proves to be very important in order to dissipate the resulting congestion after an incident. The vehicle planning system interprets this information to decide whether to change lane. Of course, close to the intended exit and during emergencies (e.g., obstacle avoidance), the vehicle planning system decides to change lane on its own. The change lane decision is passed to the vehicle *coordination control system.*

Information Flow

Description	From System	To System
Lane change proportions	Roadside control system	Planning system
Exit Information (distance to exit)	Roadside control system	Planning system
Obstacle information	Obstacle recognition system	Planning system
Lane change command	Planning system	Coordination system

Highway Geometry Modification: None

2.1.11: Lane Change Coordination

General Description: Once the lane change decision is takerf by the *planning system*, the *coordination system* coordinates the lane change maneuver with the neighbors. The coordination involves finding appropriate gap in the target lane. If the gap exists, the vehicles next to adjacent lane are notified of the lane change intent (so as to avoid two vehicles changing lane into the same gap, i.e., the pinch maneuver). If the gap does not exist, communication is established with the neighboring vehicles in the adjacent lane in order to create a gap. The gap negotiations are successful if the other vehicle/platoon is not engaged in another maneuver. During the gap creation process, one or both vehicles decelerate/accelerate to align the gap with the vehicle that wants to change lane. After the gap alignment, the *regulation control system* is asked to execute the lateral move over maneuver. If any time during the gap creation or alignment maneuver, safety of the vehicles in either lane is threatened, the maneuver is aborted.

Information Flow

Description	From System	To System
Lane change decision	Planning system	Coordination system
Relative positions and velocities of vehicles in two adjacent lanes (target & adjacent to target lanes)	Neighborhood sensing system	Coordination system
Relative position and velocity of vehicle in front	Neighborhood sensing system	Coordination system
Gap creation negotiation	Coordination system	Coordination system of neighboring vehicle in target lane
Lane change negotiation	Coordination system	Coordination system of neighboring vehicle in target lane
Lane change negotiation	Coordination system	Neighboring vehicle in next to target lane
Move over command	Coordination system	Regulation control system
Gap alignment command	Coordination system	Regulation control system

Highway Geometry Modification: None

2.1.12: Platoon Formation and Dissipation

General Description: This function is only applicable to platooning. The above function can be decomposed further into elemental functions such as planning, coordination and execution of platoon formation and dissipation.

Planning: Depending on the traffic flow, the roadside control system decides a maximum platoon size that is communicated to the *planning system.* As platooning helps increase capacity, the planning system attempts to join with the platoon ahead whenever the *neighborhood sensing system* senses a vehicle in front as long as the combined platoon size does not exceed the maximum size. Platoons are separated so as to facilitate vehicles within the platoon change lanes and exit. Platoon splits may also occur due to reduction of maximum platoon size by the roadside control system. Depending on the lane change technology, a platoon may be split into up to three platoons with safe inter-platoon gap between them, or a small break-up allowing a vehicle to change lane/exit and then rejoin. The request for change lane from the planning system of one of the vehicles in a platoon initiates platoon separation.

Information Flow

Description	From System	To System
Maximum platoon size	Roadside control system	Planning system
Front vehicle distance	Neighborhood sensing system	Planning system
Platoon join or split command	Planning system	Coordination system

Coordination: Platoon leaders engage in structured exchange of messages to coordinate joining of two platoons or splitting of a platoon into two. The platoons check that their combined size will not be above the maximum platoon size and that they are not involved in any other maneuver at that time. Once the coordination is complete, the coordination system of the appropriate vehicle asks its *regulation control system* to execute the maneuver.

Information Flow

Description	From System	To System
Platoon join/split command	Planning system	Coordination system
Join/split negotiations	Coordination system	Coordination system of the vehicle in front/behind
Platoon join/split execution command	Coordination system	Regulation control system

Execution: The *regulation control system* executes the platoon join/split command. In the join maneuver, the platoon behind accelerates to catch up with the platoon in front. During the platoon split maneuver, the platoon splits at the designated location and the rear part of the platoon (which is now a separate platoon) decelerates to safe inter-platoon separation. Both maneuvers are executed as feedback control laws based on sensor readings of relative velocity and position of the vehicle in front. The maneuver may involve planning reference trajectory and then tracking it using feedback.

Information Flow

Description	From System	To System
Platoon join/split execution command	Coordination system	Regulation control system
Front vehicle relative velocity and position	Neighborhood sensing system	Regulation control system
Vehicle velocity and acceleration	Self state sensing system	Regulation control system
Throttle command	Regulation control system	Throttle actuation system
Brake command	Regulation control system	Brake actuation system

Highway Geometry Modification: None

2.1.13: Vehicle Operation Status Monitoring

General Description: This function is performed by the *vehicle self state sensing system.* The purpose is to monitor all subsystems of the sensing, communication, actuation and control system to determine if they are functioning at their full capability. If a loss of capability is detected, the *vehicle planning system* is notified. The planning system switches to a degraded mode of operation so as to ensure safety. The self state sensing system contains *fault detection and diagnosis subsystem* for performing sensor data fusion. The *emergency detection system* works in a similar fashion except it is also responsible for emergency situations developing in the surrounding.

During entry, the vehicle operation status monitoring system is used to determine the capabilities of the vehicle to operate on the AHS. Vehicles that do not have the required capability are denied access to the AHS.

Information Flow

Description	From System	To System
Self state sensory data	Vehicle self state sensor system	fault detection/diagnosis system
Self state sensory data	Vehicle self state sensor system	Emergency detection system
Vehicle operation status info	fault detection/diagnosis system	Entry control system
Vehicle operation status info	fault detection/diagnosis system	Vehicle planning system
Emergency detection information	Emergency detection system	Vehicle planning system

Highway geometry Modification: None

2.1.14: Driver Status Monitoring

General Description: As the reference state does not require driver involvement for driving on the AHS, the driver status monitoring is used before hand-on to the driver takes place during exit. The objective of this function is to determine that the driver is alert (physically and mentally awake) and is ready to take over control. The vehicle has sensors to monitor the physical state of the driver and the mental awareness and readiness is signaled by the driver by taking partial control of the steering wheel. The sensors are also used to check if the driver is having physical problems (e.g., heart attack) during AHS operation. If any problem is detected, the vehicle planning system is notified which then takes vehicle out of the highway at the nearest exit. The overall task of driver status monitoring is performed by the *driver monitoring system.*

Information Flow

Description	From System	To System
Sensor readings about driver alertness	Driver sensing system	Driver monitoring system
Driver readiness to take over	Driver sensing system	Driver monitoring system
Driver alertness information	Driver monitoring system	Hand off control system
Driver physical alertness info.	Driver monitoring system	Vehicle planning system

Highway Geometry Modification: None

2.1.15: Vehicle Entry

General Description: This function is the entry of the vehicle into AHS from the non-AHS environment. Both the transition lane and dedicated entry/exit facilities are supported in this concept. The entry functionality is similar for both options. The differences are mainly in terms of the effects on safety, throughput and cost. The transition lane entry/exit affects the throughput of both the AHS and non-AHS highway lanes as both the traffic flows affect each other. The transition lane also requires gaps in the barriers that may enable a non-AHS vehicle to enter the AHS.

The entry function can be broadly categorized into check-in , hand-off, and vehicle entry.

Check-in: The driver drives the vehicle to the check-in station (which is at the beginning of the dedicated entry ramp or the transition lane). The vehicle status monitoring system (or the operator at check-in) certifies that the vehicle is capable of AHS operations. The check-in control system on the roadside check-in station allows the vehicle to proceed. Vehicles that fail check-in are routed back to the manual highway. The check in can be performed by many ways, such as on-the-fly, or while stopped at the check-in station, etc.

Hand-off: After check-in, the driver initiates the hand-off to the automatic control system on the vehicle (e.g., by pushing a button). After the hand-off, the vehicle is controlled by the vehicle control system.

Vehicle-entry: The automated vehicle is assisted by the roadside control system. The *entry control system* determines the available space upstream of the entry point on the automated lane using its *entry sensing system.* If the space does not exist, it creates the space by communicating with the vehicles on the automated lane. The entry control system then informs the entering vehicle of the gap and assists in establishing communication between the entering vehicle and the vehicles on either side of the gap on the automated lane. The entering vehicle then accelerates and aligns itself with the gap on the automated lane and changes lane (or merges) with the AHS traffic. The gap negotiation is carried out by the *coordination system* and the gap alignment and move over executed by the *regulation control system.* The gap has its own dynamics depending on the downstream flow on the AHS. Therefore, the vehicles on either side of the gap communicate the speed and size of the gap to the entering vehicle so that it can adjust its motion in order to align itself with the gap at the entry point.

Information Flow

Description	From System	To System
Vehicle operation status info	Vehicle self state sensing system	Check-in control system
Vehicle check-in / reject	Check-in control system	Vehicle planning system
Hand-off control	Driver	Vehicle control system
Entry request	Vehicle planning system	Entry control system
Traffic flow information (AHS and non-AHS)	Roadside control systems, AHMC and ITS service providers	Entry control system
Gap determination on AHS	Entry sensing system	Entry control system
Gap negotiation on AHS	Entry control system	Vehicle planning systems of vehicles on the automated lane
Communication ID information	Entry control system	Vehicle coordination systems of vehicles on AHS and entry ramp
Available gap information	Entry control system	Entering vehicle planning system
Gap dynamic information : speed, size	Neighborhood sensing system or coordination from AHS vehicles	Entering vehicle regulation control system
Lateral velocity, acceleration, yaw rate	Self state sensing system	Entering vehicle regulation control system
Road geometry preview	Neighborhood sensing system	Entering vehicle regulation control system
Front vehicle distance and speed	Neighborhood sensing system or communication system	Entering vehicle regulation control system
Vehicle velocity & acceleration	Self state sensing system	Entering vehicle regulation control system
Vehicle actuation commands	Entering vehicle regulation control system	Entering vehicle actuation systems (steering, brake, throttle)

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by entry sensing system.

2.1.16: Vehicle Exit

General Description: This function is the exit of the vehicle from AHS to non-AHS environment. Again, there are two configurations that are supported, dedicated exit and transition lane exit. Both of them are very similar in functionality. The exit consists of three functions, <u>vehicle exit</u>, <u>hand-off</u> and <u>check-out.</u>

<u>Vehicle-exit:</u> This function involves taking the vehicle from the automated lane to the exit ramp/transition lane. It is executed either as a regular lane change or as a highway split. The *vehicle planning system* gets the information about available gap on the transition lane/exit ramp from the *exit control system* on the road. The exit control system creates a gap (on the transition

lane) if it does not exist and is possible to do so. Otherwise, either the vehicle is routed to the next exit or joins the queue on the ramp/transition lane which ultimately slows down the traffic on the automated lanes.
Check-out: The vehicle passes the check-out station where the driver status monitoring system checks that the driver is ready to take over control. If the driver is not ready an attempt is made to alert him/her, otherwise the vehicle is automatically parked at the parking lot where assistance is provided. The check-out can be done either on-the fly or while the vehicle is stopped. Many other functions such as toll collection can be performed at the check-out.
Hand-off: If the driver is alert, the vehicle control is turned over to the driver. The driver has to follow a certain procedure to take over control. If he/she fails to do so, the control is returned to the automated system and the vehicle is taken to the parking lot. After taking over control, the driver drives onto the non-AHS street/highway. An exit-metering light is provided for flow control onto manual highway.

Information Flow

As in the case of entry, the vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

Description	From System	To System
Information about gaps/space on the exit ramp/transition lane	Exit control system	Exiting vehicle planning system
Traffic flow information (AHS & non-AHS)	Roadside controllers & AHMC and ITS providers	Exit control system
Exit gap information	Exit sensing system	Exit control system
Exit gap negotiation	Exit control system	Coordination system of vehicles on exit ramp/transition lane
Driver alertness report	Driver status monitoring system	Check-out control system
Wake up call	Driver status monitoring system	Driver
Hand-off control signal	Driver	Vehicle control system
Exit metering signal	Exit control system	Driver

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by exit sensing system.

2.1.17: Automated Highway Merging

General Description: This function is the movement of automated vehicles from one automated highway to another. As the neighborhood sensing system of the vehicles may not be able to detect gaps in the merging traffic because of difference in curvature, banking, elevation of the merging highway lanes, the *merge control system* on the roadside uses *merge sensing system* to sense the gap and communicate it to the vehicles on both highways. The system supports merging two streams of platoons. If the appropriate gaps do not exist, the merge control systems coordinates