Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Systems Analysis

U.S. Department of Transportation
Federal Highway Administration

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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research
and Development

NOTICE

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16. Abstract

The program described by this eight-volume report, a resource materials document type, identified the issues and risks associated with the potential design, development, and operation of an Automated Highway System (AHS), a highway system that utilizes limited access roadways and provides "hands off" driving. The AHS effort was conducted by a team formed and directed by the Calspan Advanced Technology Center. Primary Team members included Calspan, Parsons Brinckerhoff, Dunn Engineering Associates, and Princeton University. Supporting members of the team were BMW, New York State Thruway Authority, New York State Department of Transportation, Massachusetts Department of Transportation, the New Jersey Department of Transportation, Boston Research, Vitro Corporation, and Michael P. Walsh of Walsh Associates.

Calspan provided overall management and integration of the program and had lead responsibility for 5 of the 17 tasks. Parsons Brinckerhoff provided transportation planning and engineering expertise and had lead responsibility for 5 tasks. Dunn Engineering provided traffic engineering expertise and had lead responsibility on 2 tasks. Princeton supported the areas of transportation planning and automated control.

The 17 task reports (A through P plus Representative Systems Configurations) are organized into 8 volumes. This volume, which describes AHS systems analyses, covers 5 tasks. Automated Check-In Analysis (Task B) was supervised by Thomas F. Leney of Calspan. Automated Check-Out Analysis (Task C) was supervised by Douglas J. Funke of Calspan supported by consultant Caren Levine as well as Kimberly Witherow and Brenda Knight of Calspan. Lateral and Longitudinal Control Analysis (Task D) was supervised by Thomas F. Leney of Calspan and supported by Robert L. Gordon of Dunn Engineering for alternative system designs, infrastructure electronics reliability, and functional/cost analysis; consultant Ditmar Bock was a major contributor to sensor studies, and consultant Lorianne Ferger provided much of the review of the sensor state of the art. AHS Entry/Exit Implementation was supervised by Philip A. Reynolds of Calspan and supported by consultant Agamemnon L. Crassidis, and Robert Gordon and Egan Smith of Dunn Engineering for queing analyses. Vehicle Operations (Task L) was supervised by Farhad Pooran of Parsons Brinckerhoff/Farradyne Systems.

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VOLUME IV — AHS SYSTEMS ANALYSIS

CHAPTER 1: AUTOMATED CHECK-IN (TASK B)

1.0 EXECUTIVE SUMMARY

1.1 APPROACH

The objectives of the check-in studies were to (1) develop a preliminary definition of the functions and subsystems that should be tested before the vehicle enters the AHS; (2) study methods of performing these tests; and (3) study how the check-in process might be performed for various Representative System Configurations (RSCs). The various systems/functions to be tested were grouped into two categories: one includes all normal vehicle-related items, such as oil pressure and engine coolant temperature; the other involves all AHS-related equipment, such as the steering or longitudinal control system. For each group, rather extensive lists of functions were identified and examined. The lists were reduced by combining functions into more systems and eliminating items that were very unlikely to cause a breakdown or present a serious safety hazard. For each item, we determined the criticality, measurability, and frequency of tests.

Check-in scenarios were postulated for various RSCs to outline where and how the check-in process would occur.

1.2 CONCLUSIONS/KEY FINDINGS

Three major key findings resulted from this study, as discussed below:

- Check-in tests should be performed on the fly.

We believe all check-in tests can be made without stopping the vehicle. Status of all vehicle equipment can be tested with a series of dynamic tests. Upon receipt of a command to perform a check-in test, either generated by the roadside or by the vehicle computer, the various tests are performed. If certain tests determine that some vehicle equipment fails the test, the vehicle's computer would prevent the engagement of the automatic modes, and would also communicate to the roadside infrastructure that the vehicle is not fit to operate on the AHS.

- Actuators for steering, throttle, and brakes will require testing in a series of dynamic tests.

In order to test for the proper operation of the various actuators, it is necessary to command the actuator to move and measure its response to the test command. These dynamic tests, which will cause a steering maneuver and changes in the vehicle's longitudinal acceleration, need not be a large or long-duration displacement. Steering tests can be a series of short pulses that may result in displacing the vehicle only a few inches. These tasks can be made on an out-ramp or in a transition lane.

- Vehicle testing will be performed continuously during AHS operation.

The vehicle equipment test sensors and built-in test systems used during check-in will also be used as part of the malfunction management system to monitor vehicle health when engaged on the AHS. Tests of all the vehicle systems will be performed at various rates; e.g., the lateral control system will need to be monitored at a high rate. The check-in function can be considered a subset of the vehicle malfunction monitoring and management system.

With such an approach, the check-in/monitoring system must be tamper-proof, thereby preventing an unfit vehicle from operating on the AHS roadway.

1.3 RECOMMENDATIONSFOR FUTURE RESEARCH

- Studies should continue to address how various monitoring instrumentation could be implemented for functions not currently monitored on vehicles, such as coolant and transmission fluid levels.

- A study should be conducted of the various actuator technologies that could be employed to provide steering control and brake operation. Both of these areas are safety-critical (particularly the steering), and will most likely require redundant components to provide the required extremely low probability of failure. This study should address reliability, cost, and ease of implementation.

- A system architecture study of the vehicle equipment monitoring system should be performed. Issues such as how the various sensors are monitored, built-in-test commanded and performed, and dynamic test executed need to be addressed. Outputs of this study would include a plan for how all the vehicle health monitoring, malfunction detection, and management would be integrated.

- Future studies and analysis of check-in should be combined with the malfunction management efforts into a single area. Check-in testing is a subsection of the larger area of malfunction detection and management.

2.0 INTRODUCTION

The objective of this task was to develop a preliminary approach to testing the vehicle to verify that all vehicle and AHS systems are functioning properly and to define how these tests might be performed. The following discussions are divided into two major categories: first, those functions associated with the manned vehicle such as brakes, oil pressure, etc. The second category is the equipment associated with the AHS functions - control loops, sensors, etc. Also discussed is how the tests would be performed for the three primary representative system configurations..

3.0 TECHNICAL DISCUSSION

A discussion of the functions necessary to be tested during AHS check-in and operation is presented.

We believe that all of the check-in functions should be performed by the vehicle's computers. At check-in, the vehicle would report to the roadway system a go/no-go status. We do not believe it makes sense to have the roadway system querying each test item or the vehicle data bus. The vehicle monitoring system that provides a continuous check of the vehicle systems must be tamper-proof to prevent someone from setting the go/no-go output to a permanent go condition. We also feel that the check-in tests can all be performed on the fly without stopping the vehicle.

Based on our studies and thinking during this task, the most serious of the possible failures is the loss of lateral steering control. For other failures, even loss of longitudinal control, one can define safe management of the loss. Without steering control, there is little that can be done to control the vehicle. It appears that the best approach is to position the wheels at a neutral position and to brake the vehicle to an abrupt stop. Even with a neutral steering angle, the vehicle will not maintain lane following but may not depart the roadway in the braking distance (~150–175 feet). A full panic stop should not be employed, as it may result in a rear end collision, but the braking should be as aggressive as possible without causing a collision. In our view a loss of lateral control is unacceptable, and redundant systems including sensors must be employed.

A study was conducted to determine the items that should be tested as part of a check-in procedure. It is envisioned that a check of all vehicle systems, AHS equipment, and driver capability would be performed just prior to entering the AHS roadway.

A rather exhaustive list, not shown here, was developed of potential vehicle systems and components that lead to vehicle breakdown or an unsafe condition. This list was distilled down by combining individual components into more systems-level tests. For example, brake pad wear would be monitored during periodic vehicle inspections that might occur every six months, rather than attempting to measure the amount of brake pad remaining. It should be recognized that, as check-in tests become more numerous and detailed, the likelihood of a failure in the testing equipment increases, which can result in false failures; i.e., a condition where the testing system declares a failure when indeed there is none. While this condition is safe (not allowing the vehicle onto the AHS lane), it can become unacceptable if the overall false failure rate is significant.

Although the various systems will be tested at check-in, we believe the testing will continue during AHS operation, as part of malfunction management. The functions/systems to be tested are discussed in the following subsections. The discussions are divided into three categories; (a) normal vehicle functions, (b) those systems that are added to perform the AHS functions, and (c) the driver-related issues.

Section 3.4 discusses how the check-in procedure and engagement to automatic control might be implemented.

3.1 VEHICLE SYSTEMS

The vehicle systems/functions are shown in table 1-1. For each entry in the table, we have included three columns that estimate (1) the criticality of that function/system, (2) how readily the function can be measured, and (3) the frequency with which the function should be tested.

Table 1-1.Vehicle Systems Check-In Functions

ITEM	CRITICALITY	MEASURABILITY	FREQUENCY OF TESTS
Oil Pressure	2	A	S
Fuel Level	2	A	M
Battery Charging System	2	A	M
Tire Pressure	2	B	S
Coolant Temperature	2	A	S
Lights	4	B	CI
Periodic Inspection	—	B	CI
Brakes	1	B	PI
Coolant Level	2	B	M
Power Steering Fluid	2	B	C
Power Train	2	B	S

Legend

Criticality	Measurability	Frequency of Tests*
1 - Very serious; e.g. loss of lateral control 2 - Somewhat serious; e.g., overheating 3 - Somewhat serious, unlikely 4 - Less serious; e.g., tail light out	A - Available B - Possible at all times but not yet available	C - Continuously (several times per second) S - Every few seconds M - Every few minutes CI - Check-in PI - Periodic Inspection *All functions checked at Check-In

3.1.1 Oil Pressure

Currently, most automobiles utilize a pressure-operated switch, along with a low oil pressure light. When the oil pressure changes below a given level, the switch closes and completes the ground to light the light. Other vehicles utilize an oil pressure sensor that exhibits a varying resistance with pressure, which can be utilized with a current metering system to indicate the pressure. Either system can be used to provide a warning when the pressure falls below a given value, such as 34.5 kPa (5 lb/square inch). The pressure measuring system would require additional circuitry to provide a low-pressure warning.

Upon low oil pressure indication, it must be quickly recognized so that the vehicle can be shut down in the breakdown lane. An engine that has lost lubrication can only be expected to continue running for a few minutes; therefore, it should be monitored at least every few seconds.

3.1.2 Fuel Level

All modern vehicles are equipped with fuel level monitors that are electric. At the time of check-in, the built-in test (BIT) system would verify that the vehicle has a minimum amount of fuel. It seems reasonable that no vehicle be admitted with less than 20% of the full quantity. Most automobile tanks will provide for 5 to 8 hours of driving at 60 mph. For AHS roadways where roadway operations are controlled by a centralized system, it is expected that a vehicle entering the AHS roadway would identify itself and convey the intended exit. The on-board BIT system would compute the distance and verify that sufficient fuel remains, or inform the driver of the requirement to exit early to obtain fuel. While enroute, the test system should warn the driver and initiate exiting AHS whenever the fuel remaining is less than required to complete the next section of the AHS. We believe the fuel check should be performed at least every few minutes.

3.1.3 Battery Charging System

The battery charging system should be monitored every few minutes to ensure that the alternator system is functioning. This test would monitor the battery terminal voltage and the charging current or battery drain. If the battery voltage is below 13 to 14 volts and there is a drain on the battery (no charging current), a charging system failure would be declared. The vehicle would be directed to leave the AHS at the next exit. Even with a failure of the charging system, the battery should be able to supply the loads for at least an hour, which is sufficient time to exit the AHS. If the battery should be determined to be badly discharged (low terminal voltage for a given discharge load), it may not be possible to reach the next exit, which would require stopping in the breakdown lane. Standard systems now measure battery voltage and charge/discharge current on most vehicles.

3.1.4 Tire Pressure

Remote-sensing tire pressure systems have recently appeared on the market. Several companies are developing systems to monitor the tire pressure of all five tires (including the spare) while the vehicle is underway. As the cost of these units are reduced, more and more vehicles will incorporate them. The commercial truck market is likely to be the first to widely equip vehicles. Running a tire soft will cause excessive wear. Since large truck tires are expensive, tire pressure monitoring systems will be employed to protect the investment in tires. An underinflated tire can cause lateral control problems as well as reduced braking.

The tire pressure monitoring system would be continuously monitored by the AHS system. In the event of a low-pressure detection, the system would direct the vehicle to leave the AHS at the next exit.

3.1.5 Coolant Temperature

Thermistors are employed to provide a variable resistance with coolant temperature, which is utilized to provide a variable current with temperature for a meter movement. Some vehicles utilize a high-temperature switch to operate a temperature warning light. The BIT system should monitor the coolant temperature or the state of the temperature switch every few seconds while operating on the AHS roadway. In the event of a high-temperature condition, the vehicle would be steered to a breakdown lane. If an exit is within a mile or so, the vehicle could continue and exit the AHS roadway. Driving for more than a few minutes could result in the engine seizing.

3.1.6 Lights

Headlights

Because of redundancy, only testing at check-in seems necessary. A simple light sensor at each light could be employed. Alternatively, the current drawn by the lights can also be sensed to indicate an operating light. While headlight testing is not currently performed, the technology to implement these tests is straightforward.

Brake/Taillight/Turn Signal Lights

As in the case of headlights, these lights can be tested at check-in. Since signal lights and tail lights are of less utility in the AHS mode, acceptance of a vehicle with a failed turn signal light should be considered.

3.1.7 Periodic Inspection

It is expected that a periodic inspection would be made on all AHS-certified vehicles for safety purposes, as well as to prevent or greatly reduce the number of vehicle breakdowns. Currently, many states require an annual safety inspection designed to identify unsafe vehicles. Items that are covered include headlights, tail lights, brakes, tires, and steering systems. With AHS, these inspections should be required more frequently such as every six months. These inspections should include non-safety items, such as the engine cooling system, that can result in vehicle breakdown.

In addition, the AHS control equipment will need to be tested. These tests include automatic braking actuator and control systems, as well as the throttle control system and actuator. The steering control system would also be inspected for proper operation and condition of components.

It is envisioned that a BIT system would continuously check all systems. At the periodic inspection, the BIT system will also be tested to ensure that it is operating within specifications. In addition to the AHS control systems, the communication equipment will need to be tested to verify operations within specification; i.e., power output — receiver sensitivity, etc.

Once the inspection is completed, the licensed technician would update the inspection valid date that resides in the BIT computer. Details of test procedures must be carefully developed so as to fully evaluate AHS equipment and, at the same time, not result in excessive inspection costs.

3.1.8 Brakes

The basic vehicle braking system would be thoroughly inspected during the periodic inspection. Such things as brake pad wear, rotor condition, fluid line condition, etc., would be covered as part of the inspection. Brake system tests, while underway, are discussed in subsection 3.2.3.

3.1.9 Coolant Level

Currently, vehicles do not monitor the engine coolant level, but rather monitor only the temperature of the coolant. Since many of the breakdowns that occur today are engine overheating problems, a detector could be installed in the coolant recovery container that would indicate when the recovery unit is empty. Normally the recovery tank is partially full when the engine is at operating temperature. Therefore, if the engine is "warmed up" and the coolant level sensor detects a lack of coolant, the low coolant flag would be sent to the BIT system.

Alternatively, a level sensor could be located near the top of the radiator, that could detect a low coolant level condition when the engine is cold or warm. The problem that breakdowns will cause on the AHS, and the fact that many of the current vehicle breakdowns are caused by engine overheating, suggest that a coolant level sensor be considered for AHS vehicles.

3.1.10 Power Steering Fluid

Currently, vehicles do not monitor the power steering fluid level or the power steering pressure. Experience has shown that there are few vehicle breakdowns due to the loss of fluid. These systems are generally very reliable. If, however, the power steering system were to be incorporated into an AHS auto steering system (as opposed to a separate system), it would be prudent to monitor the fluid level as well as the pump output pressure. A level sensor could be installed in the power steering reservoir to detect a low level condition. The level should be monitored continuously to detect a sudden loss of fluid.

3.1.11 Power Train

In recent years, vehicles have begun to utilize electronic control of the engine timing and fuel injection. More recently, digital data buses are being employed to pass operating data from many systems to the computer(s) that control the engine. Although expertise in these systems is usually the province of manufacturers, it appears that the vehicle computer could determine when the performance of the engine is abnormal; i.e., engine missing or throttle position abnormal vs. speed for a given acceleration or constant cruise setting. Problems that are developing with the engine could be detected early, before a breakdown.

While automatic transmissions usually give some notice of impending problems such as abrupt shifting or slippage during acceleration, it would be wise to monitor the transmission fluid pressure. Low transmission fluid level usually shows up as shifting problems; i.e., the transmission does not shift from low gear, or hangs up in low for an unusually long time. It may be reasonable to monitor the fluid level as well as the pressure. Problems with fluid loss are due to leaking seals, which generally are detected by loss of fluid over a period of time and can usually be detected from a periodic visual inspection. If the sensing of the fluid level and pressure are relatively straightforward, such sensors should be considered.

Consideration was given to monitoring the rear-end gear box lubricant in vehicles with rear-wheel drive. Loss of this lubricant is due to leaky seals and generally is detected during routine servicing. Wear and damage to the gears creates a howling sound long before a failure occurs. Because of the low likelihood of sudden rear end failure and the difficulty of measuring a fluid level under such splashing conditions, it is not deemed worthwhile to measure the rear end fluid level.

3.2 AHS SYSTEMS

The previous section discussed normal vehicle systems; this section addresses those systems and functions that are added for AHS functions. The AHS systems are shown in table 1-2.

3.2.1 Longitudinal Control System

The longitudinal control system will consist of a sensor to measure the gap spacing and rate of change of the gap between the subject vehicle and the vehicle ahead. It also utilizes data received from the vehicles ahead as to their current actions; i.e., acceleration and deceleration rates. A control system then adjusts the throttle to accelerate or coast, and activates the brakes to decelerate if braking rates greater than the coast deceleration are required. The monitoring of the throttle and braking actuators is discussed in following sections.

The longitudinal control system receives the gap sensor data and inputs from other vehicles (via the communications links) and generates commands to the throttle actuator or the brake actuator. To verify that this control system is functioning properly, a self-test would be performed. At a fairly high rate, the output commands would be frozen at their current value, and the inputs would be disconnected or ignored. A sample command calculation would be made with a pre-determined set of inputs, and the resulting outputs would be noted. Once the test is completed, the control system would once again utilize the sensor inputs and generate new commands. It is envisioned that these tests would be made at a rate of at least ten times per second. The duration of the tests would be very short, such as a few milliseconds. Once a failure has occurred, there are several options. If the failure of the control system is deemed sufficiently serious, a redundant unit could be used, or the throttle could be commanded to close, resulting in a coast to a stop in a breakdown lane. It is unlikely that the vehicle would be returned to manual control while on an AHS roadway.

The headway sensor utilized to measure the spacing between a vehicle and the vehicle ahead will most likely be in the form of radar or lidar (laser based radar). A malfunction of the headway sensor could result in collision if it failed to detect the vehicle ahead. The outputs of multiple sensors could be compared; if the inputs agree within certain limits, all units are considered to be functioning normally. The outputs with the shortest range and highest closing range rate would be utilized by the control system. With this redundancy approach, care must be exercised to avoid common mode failures. That is, what failures can cause both units to give incorrect measurements?

Table 1-2.Vehicle Systems Check-In Functions

ITEM	CRITICALITY	MEASURABILITY	FREQUENCY OF TESTS
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Coolant Temperature	2	A	S
Lights	4	B	CI
Periodic Inspection	—	B	CI
Brakes	1	B	PI
Coolant Level	2	B	M
Power Steering Fluid	2	B	C
Power Train	2	B	S

Legend

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1 - Very serious; e.g. loss of lateral control 2 - Somewhat serious; e.g., overheating 3 - Somewhat serious, unlikely 4 - Less serious; e.g., tail light out	A - Available B - Possible at all times but not yet available	C - Continuously (several times per second) S - Every few seconds M - Every few minutes CI - Check-in PI - Periodic Inspection *All functions checked at Check-in

A second approach is to employ one sensor and very thorough BIT testing to verify that the signal sensor is functioning properly. This approach has been used with airborne terrain-following radars. The BIT testing is performed periodically at a high rate, such as several times per second. These tests include transmitter power measurements and receiver sensitivity tests. A test pulse is fed into the receiver at the antenna, and the resultant outputs of the system are monitored for the correct response. If these tests are designed properly, a complete end-to-end test can be performed. In the event of a detected failure, a malfunction management procedure must be followed. With no headway information, the vehicle would be slowed and parked in the breakdown lane.

Because of the criticality of the headway sensor, some form of a backup sensor should be considered, such as differential GPS. If each vehicle knew its position and the position of the vehicle ahead to a few feet, emergency headway could be maintained.

The BIT of the headway sensor would be performed at check-in. This BIT testing would also be performed at a high rate while operating on the AHS.

3.2.2 Throttle Accelerator Actuator

The throttle can be controlled with an electric motor or a piston driven by hydraulics or vacuum. The specific form of the actuator would be the subject of a design study. Regardless of the specific implementation, it is envisioned that, during the check-in test process, the throttle would be commanded to advance and retard in a pulse-like fashion, to check for proper operation of the throttle to a given command. Once the vehicle is on auto control, the longitudinal computer would maintain a comparison of the throttle command versus the response. This continued monitoring of the throttle response would detect failures in the actuator system. Once a failure is detected, the throttle would be allowed to close (absence of a command). The vehicle would then be parked in the breakdown lane. As in the case of the control system, a redundant actuator could be activated, which would allow the vehicle to exit the AHS and not result in a breakdown.

3.2.3 Brake and Brake Actuator

The auto braking system, including the actuator, must be failure-proof. Modern automobile braking systems are highly reliable. The introduction of dual braking, systems where the front and rear axle system are independent, has greatly reduced the chance of loss of all braking. It is expected that the brake actuator would be tested at check-in by a test that would apply the actuator for a short duration. The hydraulic pressure for both front and rear axle systems would be measured. Once the vehicle is operating on the AHS, there should be little or no braking required. Some braking may be required to create gaps or slots for merging vehicles. Each time the actuator is commanded to operate, the command versus the resultant hydraulic pressure can be compared to determine if the actuator and braking system are functioning properly.

A dual actuator should be considered that is coupled in such a way that the unit generating the greatest hydraulic pressure will control the brakes. If the two systems developed different hydraulic pressure (by more than a given value), a failure would be declared and the vehicle would be required to exit the AHS at the next available exit.

3.2.4 Lateral Control System

The lateral control system receives lateral position errors from the lateral guidance sensor. The control system computes the steering command and drives the steering actuator system. Control of the steering system is the most critical of the AHS functions. An improperly functioning lateral guidance system can result in a collision or road departure in a few seconds. It is our belief that redundancy will be required to ensure that loss of steering control cannot happen. That is, the probability is so low that a road departure or collision would not be a real concern. One occurrence per year for all vehicles operating on AHS highways might be reasonable.

In order to achieve this level of reliability, it appears that some form of redundancy of the lateral control system is required. This includes the lateral guidance sensor and actuators, as well as the control system computers. Very thorough BIT coupled with automatic selection of the currently functioning system will be required. These tests would be performed at check-in and continuously (many times per second) while operating on the AHS.

3.2.5 Steering Actuator

Automatic steering could be implemented in several ways. The currently employed power steering system could be retained with steering inputs being introduced through the rack and pinion steering gear, with an electrically operated (servo/ motor/stepper motor) or a hydraulic actuator. This approach is straightforward, with minimum interface. A second approach is to utilize a separate actuator tied directly to the steering linkage.

Because of the critical safety issues associated with auto steering, it is likely that redundant actuators will be employed. While BIT testing can be performed on the electric equipment that drives the actuator, the only way to know if the actuator is functioning is to issue a command and verify the proper response. During the check-in process, prior to closing the automatic loops, a test movement of the actuator could be made. The movement would cause small left-right steering inputs of only a short duration, so as to not disturb the trajectory of the vehicle. Once the vehicle is operating on the AHS, a running comparison can be made of the commands and resulting responses.

3.2.6 Lateral Guidance Sensor System

Several methods could be employed to sense the lateral position of the vehicle relative to the center of the driving lane. Methods of performing BIT will vary with the concept chosen. If, for example, the magnetic markers or nails were installed on the road and magnetic sensors were used on the vehicle to measure the lateral position of the vehicle, a test electromagnet could be pulsed to create a magnetic field near the sensor. The sensor would detect this test field and generate a left/right steering error. In this way, the complete magnetic sensor can be tested.

We also feel that a backup system might be employed. For instance, the magnetic nails may be the primary control technique, along with a vision-based system as a secondary or backup. Much consideration will need to be given to safety and malfunction management for any chosen lateral guidance system. The system simply cannot be allowed to fail in such a way that steering control is lost.

In summary, the check-in procedures for lateral control would involve BIT and dynamic steering movements to check the actuator. These dynamic tests would be performed at a speed close to the AHS operating speed.

3.2.7 High Speed Stability

A closed loop test should be performed at or near the AHS operating speed before the vehicle enters the AHS roadway. During check-in the various systems will be tested and verified to be operational. It seems prudent to engage the longitudinal and lateral control systems while the vehicle is still in the transition lane or on the AHS merge ramp. These tests verify that the system is operating normally, and check for any stability problems at high speed that might not be detected with the open loop BIT tests. If any roadway infrastructure additions are employed, such as magnetic nails, special optical or radar reflectors, these items would have to be installed on the transition lane as well as on AHS ranges.

3.2.8 Communications Systems

Several communication data links will be employed for AHS operation. For even the most simple representative system configurations (RSC) which might reflect early deployment, we expect a roadway-to-vehicle link to convey advisory information, such as roadway conditions, operating speed, and location of incidents. For more advanced RSCs, the roadway-to-vehicle link will pass much more detailed information such as vehicle spacing and commands to each vehicle.

Vehicle-to-vehicle communication will be utilized to pass vehicle state information such as speed, acceleration/deceleration, and possible vehicle position. These data are required to allow vehicles to run with short headway spacing.

Vehicle-to-roadway communication will be required to confirm receipt of commands, and to inform the roadway of intentions such as exiting requests.

These data links can be very critical to the operation and safety of the AHS roadway. It is envisioned that a BIT test would be employed to verify properly operating links. In addition, test messages are likely to be built into the message format to allow communicating parties to verify operation. Built-in tests could include monitoring one's own transmission through the normal receiver, which would check the transmitter power output and signal quality as well as the receiver chain. These tests would be performed at check-in and continuously, or at least several times per second, during AHS operation.

A strategy for managing the loss of a data link must be developed. The most critical is the vehicle-to-vehicle link, which is required for longitudinal control of short gap spacing. If a vehicle-to-vehicle link has failed, one might increase the headway spacing in a controlled non-abrupt fashion.

3.2.9 Navigation Sensors

AHS operation will most likely involve some form of navigation. Differential GPS and, in particular the use of carrier phase tracking, promise the capability to measure the position of a vehicle to within a few centimeters. There are several problems that must be overcome with this concept, which others are currently addressing. Even if a GPS based system is not chosen as the primary sensor for lateral and longitudinal control, it may well be used as a backup. Any GPS receiver that is to be used for precise position location must include a BIT that will verify that the outputs are correct. This BIT must be performed at a high rate, such as several times per second. During check-in the vehicle BIT would confirm that the GPS receiver system is reliable. It would also monitor the GPS BIT during operation or the AHS roadway.

It is also likely that an Inertial Measurement Unit (IMU) will be employed to augment the GPS system and to supplement the lateral control system. If lateral control is based upon magnetic or visual markers in the road, such as special optical tracking strips, it will be necessary to be able to change lanes utilizing a supplemental system such as an IMU. Even relatively low cost IMUs can provide accurate estimates of position changes for brief periods such as several seconds. The IMUs must include a BIT system to verify the system functionality. The update rate of any BIT must be at least several times per second. As with other critical sensors, confirmation at check-in would occur, as well as continuously while operating on the AHS roadway.

3.3 DRIVER CAPABILITES

Considerable thought was given to verifying the driver's capabilities during the check-in process. We considered requirements to verify that the driver is not under the influence of alcohol or drugs but quickly came to the conclusion that the problem of an impaired driver is not just an AHS problem. Impaired drivers are much more of a problem on the manual roadways. To saddle the AHS development with solving this problem did not seem realistic.

We do believe that a special license will be issued to drivers who have completed an AHS training course and are authorized to use the AHS. The check-in process would verify that the driver is certified. One verification approach involves the use of a magnetic card reader in the vehicle. Each certified driver would be issued a card with a magnetic strip that the driver would pass through the reader, thus confirming an AHS qualified driver is in the vehicle. We do not believe any further testing of the driver is necessary during check-in. Chapter 2 of this volume addresses the check-out procedure and verifying that the driver is alert during travel on the AHS roadway.

3.4 CHECK-IN CONFIGURATIONS FOR VARIOUS RSCs

There are three basic configurations for implementing check-in functions. All of the various RSCs utilize one of the three basic configurations. Each configuration is discussed below, along with how the check-in and transition to automatic is envisioned.

3.4.1 Mixed Traffic (I1C1)

The I1C1 RSC is defined as a mixed traffic system where manually driven vehicles are mixed with AHS vehicles in the same driving lanes. The headway would be greater than other AHS configurations, similar to spacing maintained by the manual drivers (1 to 1.5 seconds). While there would be little improvement in throughput, there are other benefits to be realized such as safety and driver convenience. Because the AHS vehicles could maintain spacings that are less than conservative drivers would allow, there would be some improvement in throughput.

For this type of configuration, one would expect the control to be autonomous, with the roadway communicating general advisory information such as incidents, speed, congestion, and general road conditions. The check-in would be performed by the vehicle system as previously discussed. The vehicle system computer would check all vehicle systems and AHS systems, including the dynamic tests of the actuators while under manual control. If all check-in tests are passed, a light would be actuated to notify the driver that the system is ready to engage automatic control. Once the driver actuates the engage button, the AHS control systems would "take control." The driver can tell that the systems are operating by the feedback he or she would feel. The longitudinal control would feel very much as if cruise control was engaged; i.e., the accelerator pedal pressure would be relieved and the driver would notice some steering activity. Once engaged, an auto light would be activated. To disengage the system, the driver would push a disengage button. The throttle control would be immediately returned to the driver, and the steering would disengage whenever the driver made a small steering input. In that way, the steering would not be relinquished until the driver "took control" to avoid a momentary loss of steering control.

If the check-in process determines that the vehicle is unfit for operation on the AHS roadway, the driver would not be allowed to engage any of the control loops.

3.4.2 Transition Lane Scenario (I2C2 or I2C3)

This configuration utilizes a transition lane between the manual lanes and the AHS lanes on a common highway. This configuration is most likely to be employed during the first few decades of AHS deployment. It is very unlikely that new freeways will be built for AHS only; nor is it likely that whole freeways will be switched to AHS-only use until the vast majority of vehicles are AHS equipped. We also expect the manual lanes to be separated from the AHS lanes with a barrier, except for the area where transition lanes occur, such as every four to five miles in an urban or suburban area. The transition lane would be instrumented, if necessary, for lateral control. The driver would steer the vehicle to the transition lane, where the check-in would be performed including dynamic tests to verify proper operation of steering, throttle, and brake loops.

Two different concepts could be employed to engage and enter the AHS flow. The first is for the driver to steer the car into the AHS and engage the automatic control as in subsection 3.4.1. The most likely method would involve engaging the lateral and longitudinal control loops in the transition lane, automatically controlling the vehicle into the AHS lane. The method of accomplishing the actual entry depends on the system design (RSC) as discussed in Chapter 4 of this volume under AHS Entry/Exit Implementation (Task J). To disengage the system, the driver could either disengage in the AHS lane and steer into the transition lane, or disengage in the transition lane after the auto-control system has placed the vehicle into the transition lane. The disengage process and resumption of manual control would be the same as discussed in subsection 3.4.1.

If the vehicle does not pass all the check-in test, engagement of the automatic control loops would not be allowed, and the driver would be directed to depart the transition lane and return to the manual traffic flow.

3.4.3 Dedicated AHS Roadway (I3C2 or I3C3)

In this configuration, all traffic on the roadway is under automatic control with no manual vehicles. In this configuration—the most mature AHS configuration—it may be that by the middle of the 21st century, all or nearly all freeways would be AHS only. In this configuration, the check-in would be performed on the on-ramp. It is envisioned that the on-ramp would be instrumented, if necessary, to provide lateral control. The check-in would be performed as described in the mixed traffic and transition lane scenarios, with the dynamic tests occurring on the ramp. Once it has been determined that the vehicle's systems are functioning properly, the driver would engage, as described in the previous discussions. Engagement could be automatic once the dynamic tests have been made. If the vehicle systems are determined to be improperly functioning, the vehicle would be directed to a return ramp, prior to merging with the traffic flow, which would return the vehicle to a parking area or surface streets. Once the automatic systems are engaged on the on-ramp, the vehicle would be under auto control during the merging process. Upon exit, the vehicle would be auto controlled onto the off-ramp and the driver would disengage the system and take control similar to that described in subsection 3.4.1.

4.0 CONCLUSIONS

4.1 KEY FINDINGS

Three major key findings resulted from this study, as discussed below:

- Check-in tests should be performed on the fly.

We believe all check-in tests can be made without stopping the vehicle. Status of all vehicle equipment can be tested with a series of dynamic tests. Upon receipt of a command to perform a check-in test, either generated by the roadside or by the vehicle computer, the various tests are performed. If certain tests determine that some vehicle equipment fails the test, the vehicle's computer would prevent the engagement of the automatic modes, and would also communicate to the roadside infrastructure that the vehicle is not fit to operate on the AHS.

- Actuators for steering, throttle, and brakes will require testing in a series of dynamic tests.

In order to test for the proper operation of the various actuators, it is necessary to command the actuator to move and measure its response to the test command. These dynamic tests, which will cause a steering maneuver and changes in the vehicle's longitudinal acceleration, need not be a large or long-duration displacement. Steering tests can be a series of short pulses that may result in displacing the vehicle only a few inches. These tasks can be made on an out-ramp or in a transition lane.

- Vehicle testing will be performed continuously during AHS operation.

The vehicle equipment test sensors and built-in test systems used during check-in will also be used as part of the malfunction management system to monitor vehicle health when engaged on the AHS. Tests of all the vehicle systems will be performed at various rates; e.g., the lateral control system will need to be monitored at a high rate. The check-in function can be considered a subset of the vehicle malfunction monitoring and management system.

With such an approach, the check-in/monitoring system must be tamper-proof, thereby preventing an unfit vehicle from operating on the AHS roadway.

4.2 ISSUES AND RISKS

Two issues resulting from this study are shown in table 1-3. The first issue, loss of steering control, became quite clear in considering how to accommodate system failures. For all other system failures postulated, there are management techniques to safely handle the failure. If the longitudinal control loop should fail, the vehicle can be brought to a stop in the breakdown lane. Special care will need to be given to the design of the lateral steering system, including redundant actuators and associated electronics, to reduce the probability of such a failure to extremely low values (similar to an aircraft that uses a fly-by-wire system with no mechanical linkage between the control column and the control surfaces).

We envision the check-in and vehicle health monitoring being performed by the vehicle itself instead of monitoring by a roadway system.

4.3 RECOMMENDATIONS FOR FUTURE RESEARCH

- Studies should continue to address how various monitoring instrumentation could be implemented for functions not currently monitored on vehicles, such as coolant and transmission fluid levels.

- A study should be conducted of the various actuator technologies that could be employed to provide steering control and brake operation. Both of these areas re safety-critical (particularly the steering), and will most likely require redundant components to provide the required extremely low probability of failure. This study should address reliability, cost, and ease of implementation.

- A system architecture study of the vehicle equipment monitoring system should be performed. Issues such as how the various sensors are monitored, built-in-test commanded and performed, and dynamic test executed need to be addressed. Outputs of this study would include a plan for how all the vehicle health monitoring, malfunction detection, and management would be integrated.

- Future studies and analysis of check-in should be combined with the malfunction management efforts into a single area. Check-in testing is a subsection of the larger area of malfunction detection and management.

Table 1-3.Issues And Risks

Issue No.	Issue/Risk Description Title	Description/ Recommendation	RSC Impact	Where Discussed
CI-1	Loss of lateral control cannot be allowed to occur.	The probability of a failure in the lateral control system that results in loss of lane-keeping must be extremely low; i.e., virtually never occurs. The design of the lateral control loop must include redundant systems — a malfunction management scheme will still be required even though a failure is extremely unlikely.	All RSCs	3.0 3.2.4 3.2.5 3.2.6
CI-2	Check-in test and system monitoring must be tamper-proof.	If the vehicle is to perform all system monitoring and issues, a go-no/go output to the roadway is important so that it cannot be bypassed or defeated.	All RSCs	3.0