Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Commercial and Transit AHS Analysis

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-142
November 1994

PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Activity Area F

Commercial and Transit AHS Analysis

Results of Research

Conducted By

Delco Systems Operations

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.

Original signed by:

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

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
PRECURSOR SYSTEMS ANALYSES OF AUTOMATED HIGHWAY SYSTEMS Activity Area F Commercial and Transit AHS Analysis	6. Performing Organization Code
7. Author(s) E. Crowe*, R. Schulze*, J. Pluta*	8. Performing Organization Report No.
9. Performing Organization Name and Address Delco Electronics Corporation Delco Systems Operations 6767 Hollister Avenue Goleta, CA 93117-3000	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-93-C-00194
12. Sponsoring Agency Name and Address IVHS Research Division Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296	13. Type of Report and Period Covered Final Report September 1993–November 1994 14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer’s Technical Representative (COTR)–J. Richard Bishop HSR 10
* Daniel, Mann, Johnson, and Mendenhall, Phoenix, AZ

16. Abstract
When an Automated Highway System (AHS) is deployed, its design and operational attributes will differ considerably depending on whether or not commercial and transit vehicles are accounted for. This activity analyzes the implications of commercial and transit operations on an AHS. The physical characteristics of large vehicles are analyzed with regard to differences they may cause in AHS design and operation. The influence of operational issues, such as differences in acceleration and braking, on facility design are considered. Human issues, such as acceptance by passenger car occupants, safety, comfort, and actual versus perceived risks, are examined. Issues related to the expected number of heavy vehicles which would use AHS are addressed.

Social and political issues related to transit use of AHS are addressed. It is recommended that these issues be weighed along with technical issues as AHS planning proceeds.

17. Key Words	18. Distribution Statement
automated highway systems, commercial vehicles, transit vehicles, truck performance, transit vehicle operations, heavy vehicles, AHS infrastructure design, entry facility design, social issues, political issues, AHS safety	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)Reproduction of completed page authorized

(PF V2.1, 6/30/92)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Commercial and transit operations on Automated Highway Systems (AHS) differ significantly from passenger cars due to differing operational and physical characteristics between the two types of vehicles. Task one of the report focuses on the physical and operational characteristics of heavy vehicles that potentially could affect the development of the AHS provided that these types of vehicles are permitted onto the facility. Operational characteristics that may affect infrastructure include; acceleration, deceleration, speed differentials, operations on downgrades, capacity, comfort and safety, off-tracking, trailer sway, load shifting, use of automatic transmissions and pavement design. In addition, the physical size and related dimensions are summarized for a comparison between various types of vehicles including passenger vehicles and various commercial and transit vehicles. These operational and physical characteristics are used in the determination of whether separate AHS facilities are required for heavy vehicles or whether different vehicle types can use the same AHS lane.

Separate lanes for heavy vehicles on all AHS facilities may be cost prohibitive. However, provision of separate lanes under certain circumstances may provide the operational improvement required while preserving costs concerns. Issues are presented that indicate when and /or where provision of separate lanes would be practical from not only a cost standpoint but also for operational aspects. Some issues are related to primarily rural situations , while others are concerned with urban operations. Rural issues are primarily associated with situations where rolling to mountainous terrain hinders the operation of heavy vehicles which affects passenger vehicles whose operations are not affected by grades. Urban issues involve allowing transit vehicles on AHS and how passenger throughput can be significantly improved at the expense of passenger vehicle capacity. Inclusion of heavy vehicles within the same lane requires discussion of safety issues associated with mixed use AHS lanes.

Inclusion of heavy vehicles on AHS requires a policy regarding how these vehicles are going to be operated on AHS. The significant aspects of this issue are the spacing between heavy vehicles, and whether a platoon operation is utilized. Task three discusses issues associated with development of a policy that addresses heavy vehicles headway. These issues include multiple vehicle operation modes, exclusive passenger vehicle headway policy, actual and perceived risks associated with headway spacing, variations in vehicle performances, human factors, relationships to AHS subsections (entry/exit), interface to intelligent transportation systems and institutional factors. Each of these issues are discussed in detail with respect to establishing a headway policy regarding not only heavy vehicles but also mixed heavy and light vehicles.

Task four discusses the issues associated with forecasting demand for heavy vehicle use on both urban and rural AHS. This analysis is a purely subjective discussion based on benefits for AHS use compared with the additional costs associated only with passenger car use. In the urban area, trip characteristics of different vehicles are compared to expected trip

characteristics associated with AHS use. As a result of this exercise it is concluded that demand for AHS use will be high for transit vehicles and in some cases large trucks. However, it is imperative that this type of analysis be performed for each individual corridor as different corridors have different trip and/or demand characteristics. Rural issues relating to demand are given including; travel time savings, safety, fuel consumption, maintenance cost, comfort and convenience, arrival predictability, initial cost and usage cost. The benefits associated with demand issues in both rural and urban situations are used in a benefit cost analysis discussed in task five.

Finally, a discussion is given on the interface requirements for heavy vehicles on AHS. This discussion raises the various issues associated with various types of vehicles in both the urban and rural areas. It is concluded that trucks will need to be processed without delay if the time advantage of using AHS is to maximized. Issues related to testing these vehicles at off site facilities include safety, frequency of testing required and verification of truck and trailer compatibility. In addition, the infrastructure requirements for interfacing heavy vehicles is discussed. Acceleration lane length requirements are the biggest issue. Research indicates that acceleration lane length requirements of heavy vehicles corresponds to common urban interchange spacing. This means that a separate lane will be required along the entire length of the corridor if present interchange spacing is maintained on AHS. Solutions developed that would minimize this problem include exclusion of heavy vehicles from AHS, limiting access points to AHS, or limiting access to only the terminus points on AHS.

Interfacing requirements for rural areas are different from urban areas in that access to the AHS is obtained through the normal freeway lanes. This type of interface eliminates the problem of long acceleration lane length as acceleration will take place on the conventional freeway lanes. Testing issues associated with rural interfacing are similar to urban testing and are therefore discussed as they apply to rural testing. Exit requirements for both urban and rural corridors are similar to the entrance requirements.

INTRODUCTION

Treatment of an AHS which includes commercial and transit vehicles raises a separate set of issues related to these vehicles. The issues can be categorized as follows.

- Physical – These are issues related to the height, width, length and weight differentials between commercial/transit vehicles and passenger vehicles.
- Operational – These are issues related to the acceleration, deceleration, and turning characteristics of the truck/transit vehicles compared to passenger vehicles.
- Institutional – These issues relate to the real and perceived costs and benefits to the users when commercial/transit users are compared to passenger car users.

This research approach is infrastructure-based. The intent is to identify infrastructure-based differentials between a passenger car only AHS and an AHS containing both passenger cars and larger vehicles, and the issues and risks associated with such an accommodation.

REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC's) were generated very early in this Precursor Systems Analyses of AHS program. These RSC's are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC's identify specific alternatives for 20 AHS attributes within the context of three general RSC groups.

Since the RSC's have such general applicability to these precursor systems analyses, they are documented in the Contract Overview Report.

TECHNICAL DISCUSSION

Task 1. Define Differences In Characteristics

Two specific categories for defining the differences between passenger cars and commercial/transit vehicles are discussed in this task. These are:

- Physical characteristics.
- Operational characteristics.

Differences as they; relate to demand are discussed in task 4.

Physical Characteristics

There is a wide variety in the physical characteristics of different passenger cars, trucks and buses. For purposes of this study, and for a measure of comparison, we will use the American Association of State Highway and Transportation Officials (AASHTO) Green Book design vehicles as shown in tables 1 and 2.

Lane width criteria for trucks, transit, and passenger vehicles are discussed in the Activity H – AHS Roadway Deployment Analysis report.

Based on AASHTO, the design passenger vehicle has a height of 1300 mm. Conceivably, vertical clearances for AHS passenger car only use could be as low as 1.5 m. Cost savings could be significant, particularly in the case of tunnels or long bridges (2 deck bridges).

Such low ceilings may have human factor impacts, maintenance impacts (need for specially designed maintenance vehicles), and even special ventilation and aerodynamic impacts.

In areas with limited right of way (urban) the increased width of heavy vehicles could limit construction options. For example, an AHS lane may need to be constructed between two fixed objects (bridge piers) which has a limited width. The extra width required for heavy vehicles (greater than 0.5 m per lane) may preclude this opportunity for an alignment.

In addition to the increase in lane width, the pavement depth will have to be increased in order to handle the heavier trucks and buses. Pavement thickness will be greater and pavement life could be shorter.

The biggest effect of mixing cars with trucks and buses will be in the area of operational characteristics.

Operational Characteristics

There are a number of parameters to be looked at with respect to operational characteristics. These are acceleration, deceleration, effect of grades, capacity, comfort and safety.

Table 1. AASHTO Design Vehicle Dimensions

		DIMENSION (m)						
		Overall						
Design Vehicle Type	Symbol	Height	Width	Length	WB_1	WB_2	WB_3	WB_4
Passenger Car	P	1.3	2.1	5.8	3.4			
Single Unit Truck	SU	4.1	2.6	9.1	6.1			
Single Unit Bus	BUS	4.1	2.6	12.2	7.6			
Articulated Bus	A-BUS	3.2	2.6	18.3	5.5			
Combination Trucks								
Intermediate Semitrailer	WB-40	4.1	2.6	15.2	4.0	8.2		
Large Semitrailer	WB-50	4.1	2.6	16.8	6.1	9.1		
"Double Bottom" Semi-trailer - Full Trailer	WB-60	4.1	2.6	19.8	3.0	6.1	20.9	
Interstate Semitrailer	WB-62[1]	4.1	2.6	21.0	6.1	12.2-12.8		
Interstate Semitrailer	WB-67[2]	4.1	2.6	22.6	6.1	13.7-14.3		
Triple Semitrailer	WB-96	4.1	2.6	31.1	4.1	6.3	21.7	21.7
Turnpike Double Semitrailer	WB-114	4.1	2.6	36.0	6.7	12.2	44.0	
Recreation Vehicle								
Motor Home	MH		2.4	9.1	6.1			
Car and Camper Trailer	P/T		2.4	14.9	3.4	5.5		
Car and Boat Trailer	P/B		2.4	12.8	3.4	4.6		
Motorhome and Boat Trailer	MH/B		2.4	16.2	6.1	6.4		

[1] = Design Vehicle with 14.6 m trailer as adopted in 1982 STAA (Surface Transportation Assistance Act)
[2] = Design Vehicle with 16.2 m trailer as grandfathered in 1982 STAA (Surface Transportation Assistance Act)
WB_1, WB_2, WB_3, WB_4, are effective vehicle wheelbases.

Table 2. AASHTO Minimum Turning Radii Of Design Vehicles

Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Bus	Articulated Bus	Semi-Trailer Intermediate	Semi-Trailer Combination Large	Semi-Trailer Full Trailer Combination
Symbol	P	SU	BUS	A-BUS	WB-40	WB-50	WB-60
Minimum Design Turning Radius (m)	7.3	12.8	12.8	11.6	12.2	13.7	13.7
Minimum Inside Radius (m)	4.2	8.5	7.4	4.3	5.8	5.9	6.8

Design Vehicle Type	Interstate Semi-Trailer	Interstate Semi-Trailer	Triple Semi-Trailer	Turn-pike Double Semi-Trailer	Motor Home	Passenger Car w/Travel Trailer	Passenger Car w/Boat Trailer	Motor Home and Boat Trailer
Symbol	WB-62[1]	WB-67[2]	WB-96	WB-114	MH	P/T	P/B	MH/B
Minimum Design Turning Radius (m)	13.7	13.7	15.2	18.3	12.2	7.3	7.3	15.2
Minimum Inside Radius (m)	2.8	2.8	6.3	5.2	7.9	0.6	2.0	10.7

[1] = Design Vehicle with 14.6 m Trailer as Adopted in 1982 STAA (Surface Transportation Assistance Act)
[2] = Design Vehicle with 16.2 m Trailer as Grandfathered in 1982 STAA (Surface Transportation Assistance Act)

Acceleration

According to Homburg and Kell’s, “Fundamentals of Traffic Engineering,” acceleration rates for passenger cars on level roads are approximately 5–6 km/h/sec up to 40 km/h. Heavy trucks can accelerate at no more than 3 km/h/sec on level roads. Based on this, it will take trucks longer to reach operating speeds on a AHS lane. This would have an impact on the entry/exit scenarios. Further discussion of this issue is in task 6. Figure 1 illustrates the acceleration differences of passenger cars and heavy trucks. The specific truck category used has a mass per engine power rating of 180 grams per watt.

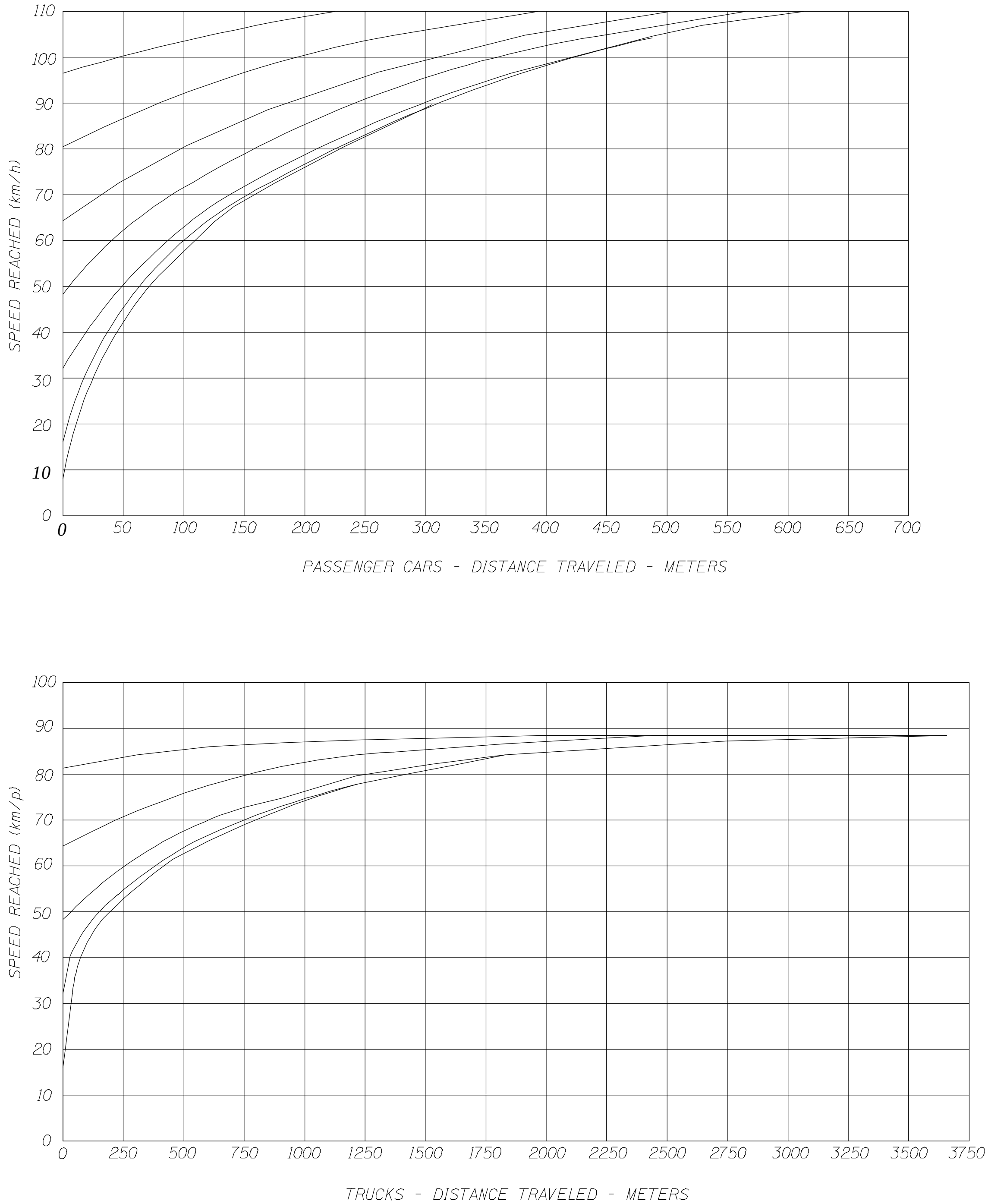


Figure 1. Typical Passenger Vehicle and Truck Acceleration Curves

Formula 1 shows the relationship between velocity and distance traveled to come to a stop assuming the worst case condition of locking brakes. This formula takes into account the effect of grade on stopping distance. Depending on the percentage of grade and design speed, the effect of either positive or negative grades on stopping distance can increase stopping distance by as much as 25 percent on down grades and decrease the upgrade stopping distance by as much as 20 percent.

$$d = \frac{v^2}{245(f \pm g)} \qquad (1)$$

Where d = skidding distance (m)
v = speed of vehicle (km/h)
f = average coefficient of friction during skid
g = percent of grade divided by 100

It is noted that although a locked wheel condition generally produces close to minimal braking distances, on vehicles equipped with a traditional braking system, this type of stop produces unsafe operations with certain types of heavy vehicles. For example, if the rear wheels lock up on a tractor trailer unit, a jack knife situation may occur in which the tractor unit spins. Therefore controlled safe stopping distances require much longer braking distances than those given by the above formula. On traditional trucks controlled braking distance is dependent on how well the driver can modulate the brakes. Modulating of the brakes refers to the application/release operation of the braking system. There is a point between a rolling wheel and totally locked wheel where the optimum braking efficiency occurs. By correctly modulating the brakes optimum braking efficiency can occur. However, modulating too much can cause a reduction in braking efficiencies.

A recent trend in automobiles is to equip vehicles with anti-lock brakes. This technology basically decelerates the vehicle at the optimum efficiency as discussed above. This trend has started to infiltrate the trucking industry. Studies have shown that trucks equipped with anti-lock brakes can safely stop in the same distance calculated by the AASHTO braking distance formula given above.

Braking efficiency is not only a function of modulation techniques, but also of the surface type/ tire interface, i.e., friction. Coefficients of friction vary widely, and because of this deceleration rates and distances will also vary widely. Some conditions that cause variations in friction coefficients include:

Road surface factors:
- Surface condition–dry, wet, snow, and ice.
- Surface construction–type, method, material, and texture.
- Surface scouring, weathering, time, and age effects.
- Temperature.
- Effects of traffic.
- Geometric design features.

Vehicle operating factors:
- Speed.
- Size and weight.
- Type of braking.

Tire factors:

- Size, tread pattern, plies, and cord angle.
- Load, contact area, and inflation area.

Effect Of Grade

Table 3 illustrates the wide variation of coefficient of friction for various surfaces and tire conditions as a function of speed. It is noted that this table only illustrates variation of coefficient of friction due to road surface during locked wheel stop.

Table 3. Comparison Of Coefficient Of Friction For Various Conditions

Speed (km/h)	**Good Tread Dry**	**Good Tread Wet**	**Worn Tread Wet**	**Dry Concrete**	**Wet Concrete**	**Dry Asphalt**	**Wet Asphalt**	**AASHTO Wet Pavement**
30	.76	.63	.52	.67	.38	.66	.28	.40
45	.78	.60	.46	.64	.35	.64	.34	.35
60	.76	.58	.38	.63	.33	.63	.31	.32
75	.72	.57	.35	.62	.32	.62	.28	.31
90	.66	.55	.31	.62	.29	.62	.26	.30
105	.58	.53	.30	.61	.28	.62	.25	.29

Speed Differential

On level ground the difference in speed between trucks and passenger vehicles is negligible once running speed is achieved. However the slightest change in grade can cause significant variations in speed between heavy vehicles and passenger vehicles. Figure 2 shows expected speed reduction of a typical interstate truck (180 grams/watt) for grades of zero to nine percent. It is interesting to note that even on a sustained grade of 1 percent (which is possible in urban areas) there is an expected speed reduction of up to 12 km/h. In rural areas where grades tend to be larger the speed reduction is much greater.

AASHTO indicates that passenger vehicles can negotiate grades as steep as five percent without any appreciable loss in speed indicating that on grades up to five percent, speed differential between heavy vehicles and passenger cars is due mainly to speed reduction of heavy vehicles.

Effect Of Downgrades

Long steep downgrades (usually found in rural areas) result in heavy vehicles dynamically converting a large amount of potential energy into kinetic energy. In order to prevent an increase in speed, this kinetic energy must be absorbed by the braking system of the heavy vehicle. Absorption of this energy generates excess heat which causes braking components to lose their efficiency or even fail depending on the amount of heat generated. Total brake failure results in an out-of-control or "runaway" truck which poses serious safety implications to the other vehicles on the facility.

To prevent this type of situation from occurring, truck drivers generally proceed down grades at a slow rate of speed using the truck's gears to control speed and hence decreasing the amount of energy that must be converted to heat. This slow speed of heavy vehicles produces similar speed variations between light and heavy vehicles as that of upgrade sections.

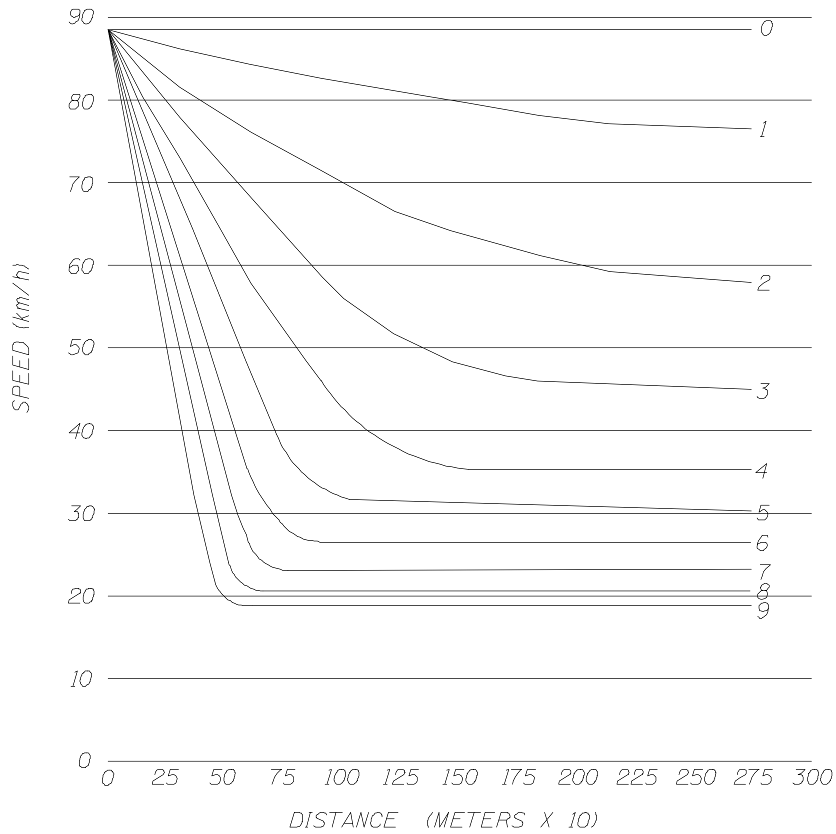


Figure 2. Speed–Distance Curves For A Typical Heavy Truck On Upgrades

Capacity

In a normal operating parameter, the effect on capacity of mixing trucks and buses with passenger cars is pronounced. Capacity is reduced as much as 83 percent depending on percentage of trucks/buses and grade, according to the Highway Capacity Manual (HCM).[1]

Reduction of capacity due to the presence of heavy vehicles in a mixed traffic stream is primarily due to three factors:

- Heavy vehicles are physically up to four times longer than passenger vehicles.
- Acceleration and deceleration rates are much lower than passenger vehicles.
- Speed differential between passenger vehicles and heavy vehicles is pronounced, especially on steep grades.

These factors affect either one or both of the elements (speed and density) that determine capacity. Physical size differences between heavy vehicles and passenger cars lower the density of a given lane and hence reduces capacity of the lane. Acceleration, deceleration, and speed differential characteristics of larger vehicles create large gaps in mixed traffic flow which, under no passing situations, lowers both density and speed of the lane causing a negative effect on capacity.

Comfort And Safety

With respect to operational characteristics, comfort and safety of trucks and buses in comparison to cars is hard to measure. People have varying degrees of comfort levels and it is difficult to define these measures. General issues related to mixing light and heavy vehicles within platoons are discussed in task 2.

Off-Tracking

When vehicles with large wheelbases or vehicles with trailers proceed around a tight curve the rear wheels do not follow the same path as the front wheels. This deviation in tire tracking is referred to as off-tracking. Off-tracking is a function of the degree of curvature where the larger the degree of curvature the more pronounced off-tracking is. Generally, off-tracking will not be a concern on AHS lanes as the degree of curvature will be small enough to support high speed operations negating off-tracking effects. However, entrance and exit facilities that will handle heavy vehicles will have to be designed sufficiently large enough to account for the effects of off-tracking.

Trailer Sway

In areas of severe wind, the phenomenon of trailer sway is an issue in determining lane widths. The minimum lane width of 3.2 m given in Activity H – AHS Roadway Deployment Analysis allows for the width of the vehicle plus 600 mm for tracking purposes. This width does not take into account trailer sway. Wind against the side of trailers can cause the trailer to wander because of the lack of driving control on the trailer wheels. In order to minimize the effects of trailer sway, constant adjustment of speed and lateral position of the driving vehicle is required. Depending on the amount of lateral adjustment required, extra lane width may be required for AHS lanes.

In certain driving conditions sudden changes in environmental conditions may pose sudden problems for heavier vehicles using the AHS system. One example of this is sudden wind gusts occurring naturally or from adjacent high speed trucks, which can cause truck trailers to wander or lose control. In these situations the driver has to maintain control by a combination of acceleration and steering operations. This phenomenon is an important safety issue in development of system control and infrastructure. Control systems must be able to immediately sense these types of situations and make adjustments to speed and lateral position appropriately. It is imperative under these types of situations that adjustments are made immediately or the possibility of an out of control vehicle may exist.

It is important to note that this phenomenon is not an exclusive heavy vehicle issue. In addition, cars or light trucks towing trailers may also be affected. As the vehicle dynamics are much different for these lighter vehicles compared to tractor trailer units, control systems developed for this phenomenon must account for a wide range of vehicle/trailer combinations.

Wider lanes may need to be provided to accommodate adjusting the lateral position of a vehicle. The amount of pavement widening required is difficult to determine as there are many factors affecting trailer sway including:

- Wind speed.
- Frequency of wind gusts.
- Surface area of trailer facing wind.
- Type of hitch.
- Weight of trailer.

Traditionally, freeway lanes are much wider than may be needed for ideal driving conditions. This extra width accounts for driver comfort, varying driving characteristics and items such as trailer sway. In order to determine width requirements for only the trailer sway element, a simulation model needs to be developed to predict the magnitude of trailer sway under varying conditions.

Load Shifting

Some accidents involving heavy vehicles result from significant shifts in cargo causing the driver of the truck to lose control of the vehicle. Load shifts cause a change in the center of gravity producing a change in the overall vehicle dynamic system. If this is not accounted for in driving control, an out of control vehicle situation may occur. Load shifts can be caused by many things, but most common would be human error in the way the vehicle was loaded. It is assumed that AHS trucks will be loaded in a similar manner as present day trucks, which means the phenomena of load shifting must be accounted for in the control systems. Adjustments in control of the vehicle, for load shifting will be similar to the control required for wind sway.

Future Operational Characteristics

An important issue for the modeling effort and results is the performance characteristics of heavy vehicles which will be on the road in the future. This is of primary importance with regard to acceleration and braking and to a lesser extent for cornering performance. Our discussions with industry indicate that no significant change (positive or negative) are expected in the foreseeable future.(2) Consequently, all work conducted under this activity is based on the aforementioned AASHTO design values.

Automatic Transmissions

Lane keeping could be applied to trucks with manual transmissions; however, it is difficult to imagine any automated longitudinal control for vehicles (except perhaps for constant or near constant speed cruising on flat terrain) that would not require automatic transmissions.

It is a widely accepted belief (among the researchers with whom we have discussed the subject) that cross country truckers (drivers) don't want automatic transmissions. One reason given for this opinion is that margins in the trucking business are so small that the additional first cost and perceived poorer fuel economy of automatics would not be tolerated.

For these reasons the following assumption is used in our research:

- AHS is assumed to add sufficient value to trucking so that any added purchase cost and/or operating cost associated with automatic transmissions are offset.

Pavement Design

Presently, highway pavements are designed for the number of equivalent 80 kn axle loads expected over the design life of the pavement. The forecasted vehicle mix expected to use the facility is converted to 80 kn equivalent axle loading (EAL) for design purposes. Pavement design procedures do not account for the fact that wheel loads are distributed laterally over the travel lanes. Figure 3 shows, conceptually, the EAL distribution on a travel lane for both conventional and AHS highways.

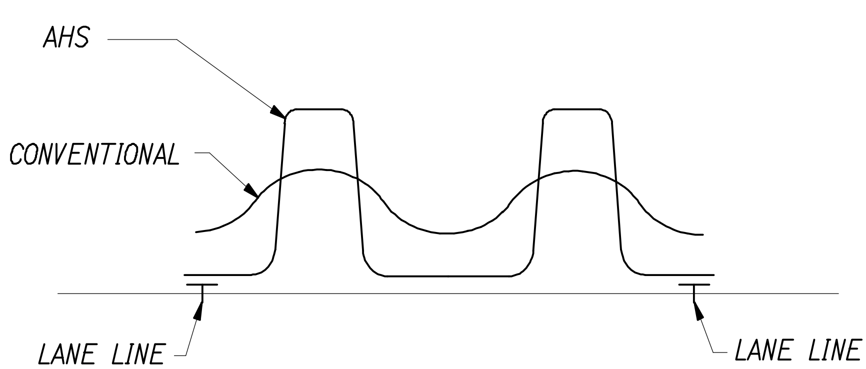


Figure 3. Axle Load Lateral Distribution–Conventional And AHS Lane.

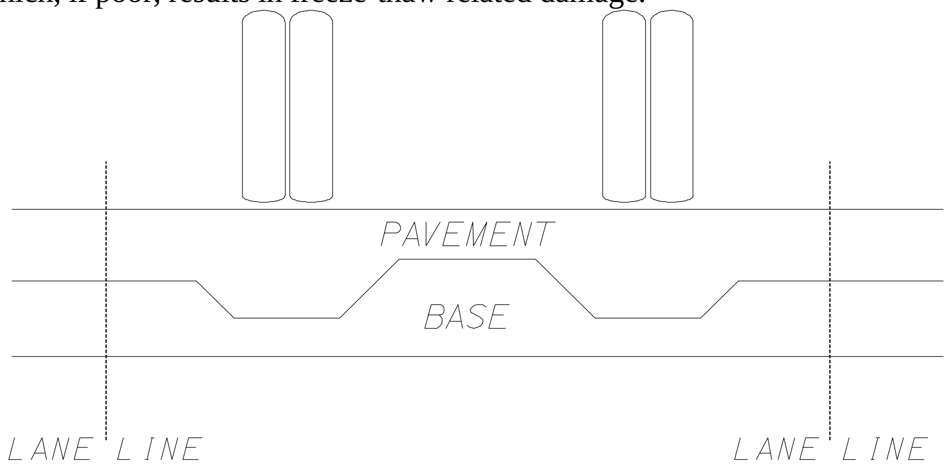
Because pavement design is largely empirical, it is not possible to determine the differential affect the AHS lateral lane axle distribution would have. The discussion below covers several issues to be addressed in developing a design procedure for a heavy vehicle AHS pavement design.

A literature search should be conducted to find data on existing lateral wheel distributions. The difference, if any, between urban and rural areas also needs to be determined. Other factors which may require different pavements designs are high and low traffic volumes, the influence of ramps, differences among vehicle classes, etc. Depending on the amount of data available in this area, additional research and data collection may be needed to proceed with design.

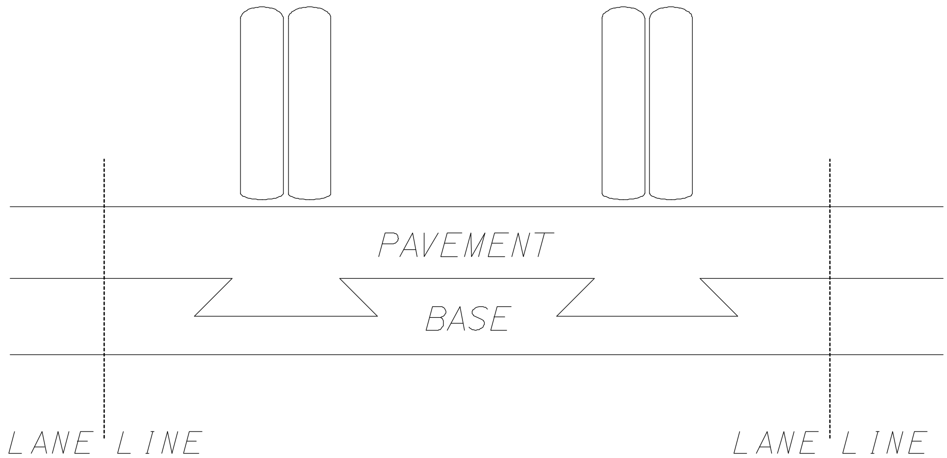
It may be possible to adapt a conventional design procedure to account for the AHS lateral wheel distribution. (In other words, can factors, curves, equations, etc. be established to convert AHS loading to a larger number of conventional EALs?) It may be found that new design procedures are needed due to the radically different lateral wheel load distributions.

Pavement Construction Techniques

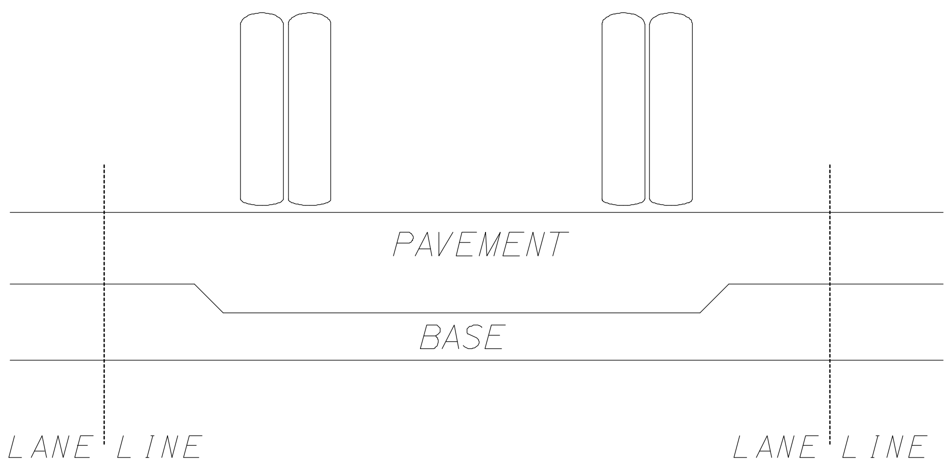
In the past, pavement construction techniques have not allowed any economical methods to provide a thicker section where it is needed the most (i.e. in wheel paths). The much narrower concentration of loads expected under AHS may economically justify a “keyed” pavement section. Figure 4 illustrates possible alternatives that could result in economy of construction, depending on the structural section differential between the wheel paths and the remainder of the pavement. Note that Alternative 3 could be a viable design concept in the case of a narrow truck configuration. The load concentrations and potential daily volumes of an AHS highway justify close attention to all details of pavement construction. This is especially true of pavement drainage, which, if poor, results in freeze-thaw related damage.



Alternative 1



Alternative 2



Alternative 3

Figure 4. Alternate Heavy Vehicle AHS Pavement Design Concepts

Task 2. Determine Feasibility Of Separate Lanes

Separate truck/transit lanes can be considered in cases where the car plus heavy vehicle demand exceeds the capacity of a single lane AHS. In such cases, segregation may offer benefits (separate pavement design is the most obvious reason to segregate). As mentioned above, pavement design requirements for passenger cars are significantly less severe than those for heavy vehicles.

Another justification for segregation by lane is on highway sections where terrain causes large speed differentials between cars and heavy vehicles. In such cases (long steep upgrades for example) separate lanes can be provided to keep low truck operating speeds from influencing travel times of passenger cars. Table 4 is a matrix of separate lane issues with indications of tendencies in favor of or against separate lanes. Several of the more important issues will now be discussed.

Cost Of Separate Lanes

A most important issue related to separate AHS lanes for truck/transit vehicles is their cost. In areas where demand for such lanes may be the highest (congested urbanized areas) the right-of-way and construction costs for both passenger car and truck/transit AHS would invariably be extremely expensive.

On the other hand, there may be rural scenarios where the costs of added lanes for truck/transit vehicles would be relatively modest, especially in areas with infrequent interchanges and adequate right-of-way.

Implications Of Mixing Light And Heavy Vehicles

In the opinion of the principal investigator, mixing of light and heavy vehicles within platoons is not desirable for the following reasons:

- Performance characteristics are incompatible.
- Such mixing would not be tolerated by passenger car drivers for comfort reasons alone.
- Bumper heights are incompatible especially during braking and acceleration.
- Diesel trucks/buses without vertical exhaust stacks would be unpleasant to follow at close proximity.

For these reasons, mixing of heavy vehicles with passenger vehicles within the same platoon is given no further consideration in this research project.

Since the focus of this report is to accommodate heavy vehicles on AHS lanes (dedicated or non dedicated) built adjacent to traditional highway lanes, where right of way and constructability constraints may exclude the possibility of separate lanes, issues relating to inclusion of heavy vehicles on a passenger vehicle AHS lane are discussed in detail.

Table 4. Matrix Of Separate Truck/Transit Lane Issues

Variable	**Measure**	**Justification for Separate Lanes**	
		For	**Against**
% Heavy Vehicles	Low		X
	High	X	
Total AHS Demand	> 1 Lane	X	
	< 1 Lane		X
Heavy Vehicle Demand	High	X	
	Low		X
Terrain	Flat to Rolling		X
	Rolling to Mountainous	X	
Sustained Grade	Long	X	
	Short		X
Exit-Entry Point Spacing	Short		X
	Long	X	
AHS Deployment Stage	Early Deployment		X
	Mature Deployment	X	
Pavement Cost Differential	Great	X	
	Small		X
Highway Configuration	Retrofit Existing		X
	New Alignment	X	
Safety	Potential Implications	X	
	Non-Potential Implications		X

Impact Of Grades On Service Volume And Travel Speed

Mixing vehicle types within the same lane may present undesirable societal issues relating to the perceived safety risk of inclusion of certain types of heavy vehicles. However the possibility of allowing certain types of heavy vehicles on a predominately passenger vehicle AHS lane may be acceptable. For example, in an urban situation inclusion of transit vehicles, either individually or in platoons, may be acceptable due to their present day acceptance on traditional roadways. On a rural AHS facility with no platoons the headways required due to stopping distance requirements may provide a comfort zone where inclusion of heavy vehicles may be acceptable providing terrain does not hinder the performance of the vehicles.

Figures 5 to figure 7 illustrate the effect mixing trucks with passenger vehicles has on service volume with respect to travel speed on traditional (non AHS) highways. These figures were derived from highway capacity manual (HCM) procedures for two lane highways which determines service volumes from average travel speed and percent time delay. In order to determine single lane service volumes, the following assumptions were used with the two lane HCM procedures:

- 100 percent traffic on uphill, 0 percent on downhill.
- No passing opportunities exist.
- No adjustments made for lane width.
- 20 percent trucks in traffic stream.

It is noted that this procedure is used only to illustrate the effect mixing trucks in a traffic stream on upgrades would have on potential service volumes of a traditional facility with similar characteristics as an RSC 3 AHS facility.

From these figures it is evident that on level terrain and short sustained upgrades that the decrease in service volumes with the inclusion of trucks in the traffic stream is due mainly to the physical size differences between trucks and light vehicles. As the length and severity of grade increases, difference in service volumes between mixed traffic and light vehicle only traffic becomes much greater. This indicates that as severity of grade increases service volumes of mixed traffic flows are primarily affected by the operational differences between trucks and light vehicles and to a lesser degree by the physical size differential of these two types of vehicles. It is noted that similar results for service volumes on downgrades could be expected on long severe downgrades due to the slow downgrade operation of trucks.

Passing Lanes

As a result of the preceding discussion, it is evident that in areas where terrain adversely affects the operational characteristics of heavy vehicles, a separate AHS lane would be required to prevent degradation of passenger vehicle operations. Strategic placement of this extra passing lane would allow for the most cost effective solution of allowing heavy vehicles on AHS while preserving travel time benefits for passenger vehicle users. Placement of passing lanes would start at a point before heavy vehicle operations begin to affect passenger vehicle speed, and end where the operations of the two vehicles again become compatible.

As previously stated, the cost of additional lanes including passing lanes would be extremely expensive in urban areas. However, significant grades are generally found in rural areas where the cost of the passing lane may be modest providing the additional width is readily available (rock faces do not constrain).

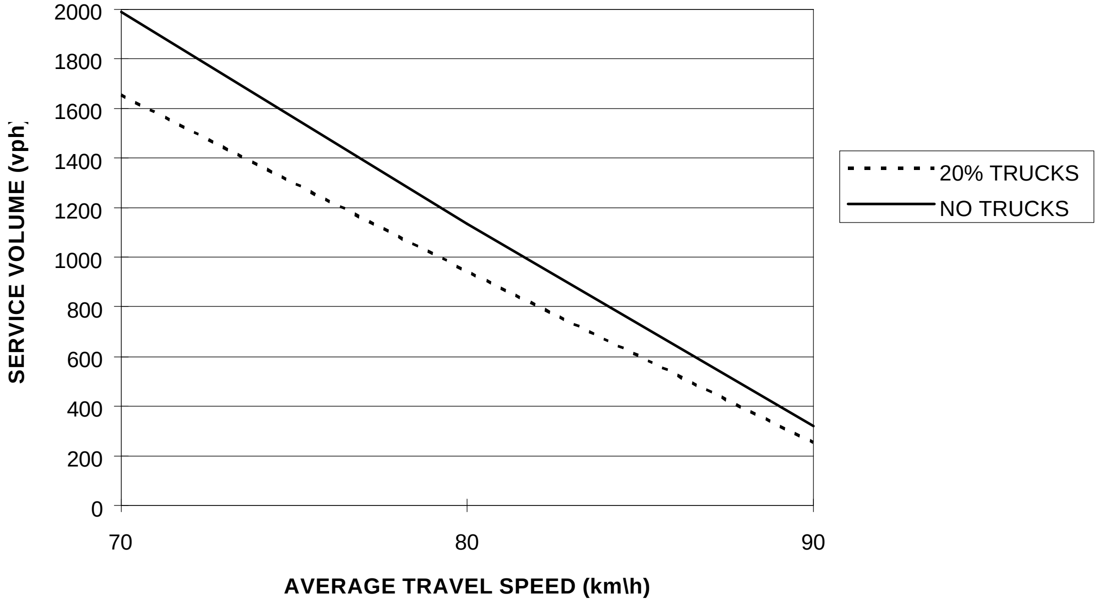


Figure 5. Traditional Highway Service Volume On Level Terrain

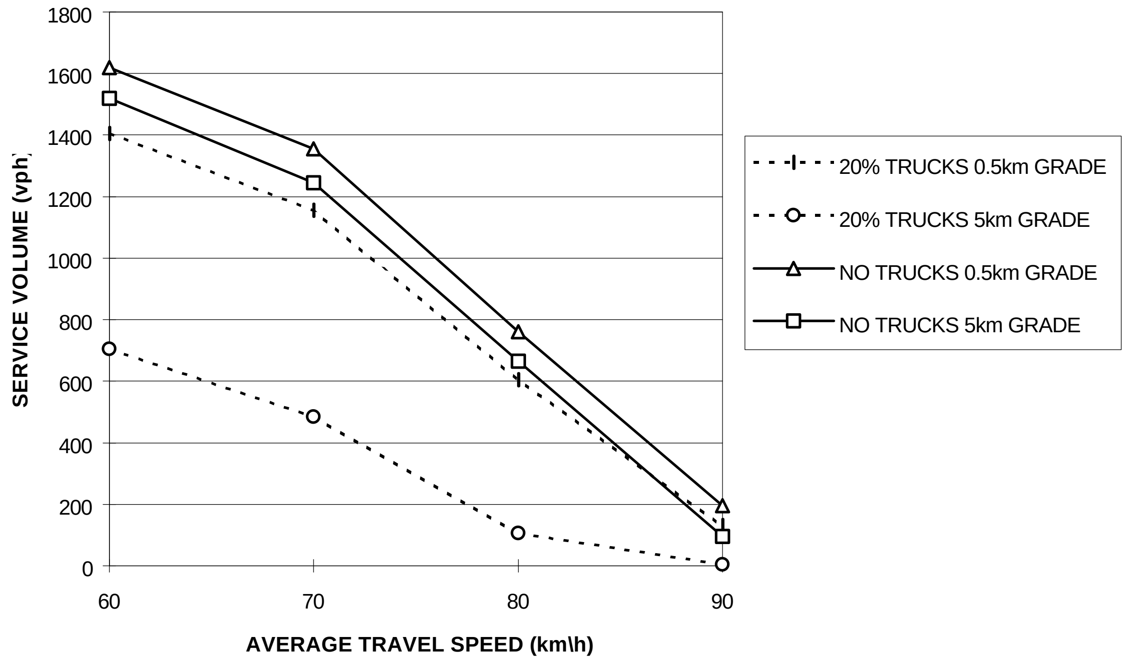


Figure 6. Traditional Highway Service Volume On Three Percent Grade

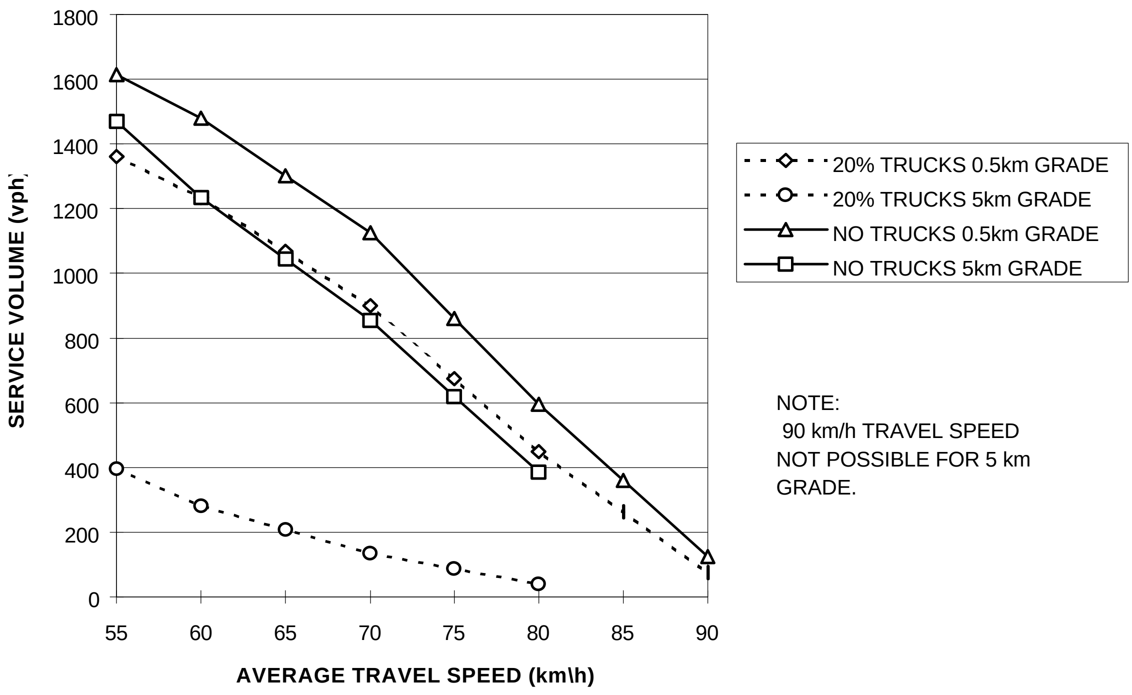


Figure 7. Traditional Highway Service Volume On Five Percent Grade

Safety

It is the opinion of some researches that separate lanes are required for heavy vehicle AHS use as the potential for safety related incidents is greater between vehicles with significantly different operational characteristics. Although the safety issue of combining heavy and light vehicles exists, there may be ways of addressing these issues without the use of separate lanes.

It is believed that the two general areas of safety concerns of heavy vehicle operation on AHS are the consequences of deceleration malfunctions and sudden unique situations affecting control. Both of these consequences could be accommodated on a single AHS mixed use lane. Rapid deceleration of a truck under controlled situations (ABS) could be accounted for in headway distances between light and heavy vehicles. Total brake failure is generally associated with long steep downgrades in which a separate lane would be required as per discussion on passing lanes. Situations may arise where sudden lateral adjustments may be required to maintain control of the vehicle. Provision of extra pavement width coupled with adjustments in headway spacing could provide a level of safety similar to separate lanes. It is noted here that consequences of malfunctions as discussed above may produce safety implications even if separate lanes were provided. For this reason further research could be undertaken to determine whether safety benefits of separate AHS lanes for heavy and light vehicles exist and to what extent.

Demand For Separate Lanes

Depending on the demand of heavy vehicles, loss in passenger vehicle capacity, due to inclusion of heavy vehicles on a mixed use AHS lane, may justify a separate lane for heavy vehicles. However, inclusion of transit vehicles may in fact increase the overall person throughput. Calculations are shown here to illustrate what passenger throughput could be expected for various bus / passenger vehicle combinations. The following assumptions are used:

- Speed – A range of speeds from 40–130 km/h.
- Coefficient of friction – The values used for coefficient of friction are from AASHTO Green Book for Wet Pavement. No adjustments to coefficient of friction are used for transit vehicles as it is assumed heavy vehicles are equipped with anti-lock brakes.
- Initial speed of the object to be avoided – Brick wall failure is assumed.
- Reaction time – 0.3 seconds used for both types of vehicles.
- Terrain – Level (no acceleration/speed loss concerns).
- Spacing within platoons – 1 m between cars and 4 m between buses.
- Vehicle length – Cars 6 m and buses 12 m.
- Vehicle occupancy – 1.5 persons per passenger vehicle and 40 passengers per bus.

Table 5 shows the braking distances used for capacity calculations.

Table 5. Braking Distances Used In Capacity Calculations

Velocity (km/h)	Wet Pavement Braking Distance (m)	Delay Distance (m)	Total Braking Distance (m)
40	16.6	3.3	19.9
50	28.1	4.2	32.3
60	44.3	5.0	49.3
70	62.2	5.8	68.0
80	84.0	6.7	90.7
90	110.0	7.5	117.5
100	135.8	8.3	144.1
110	170.1	9.2	179.3
120	202.5	10.0	212.5
130	246.4	10.8	257.2

Four bus flow rates were assumed 0, 50, 200 and 500 buses/h. These flow rates represent a range of values observed presently in cities with exclusive bus lanes.

Figures 8 to 11 show the passenger throughput for a mixed use AHS lane associated with the various bus flow rates discussed above. These figures represent both RSC 1 and RSC 2 combined with single and three bus platoons. It is interesting to observe that even though the inclusion of transit does decrease the capacity of passenger vehicles on a single lane AHS, the overall person throughput is increased at least four times over an exclusive passenger vehicle system. If passenger vehicle capacity loss is the sole criteria for measuring the need for separate lanes for transit vehicles, then depending on the acceptable passenger vehicle capacity and the demand of buses, a separate AHS lane for transit and heavy vehicles may be required.

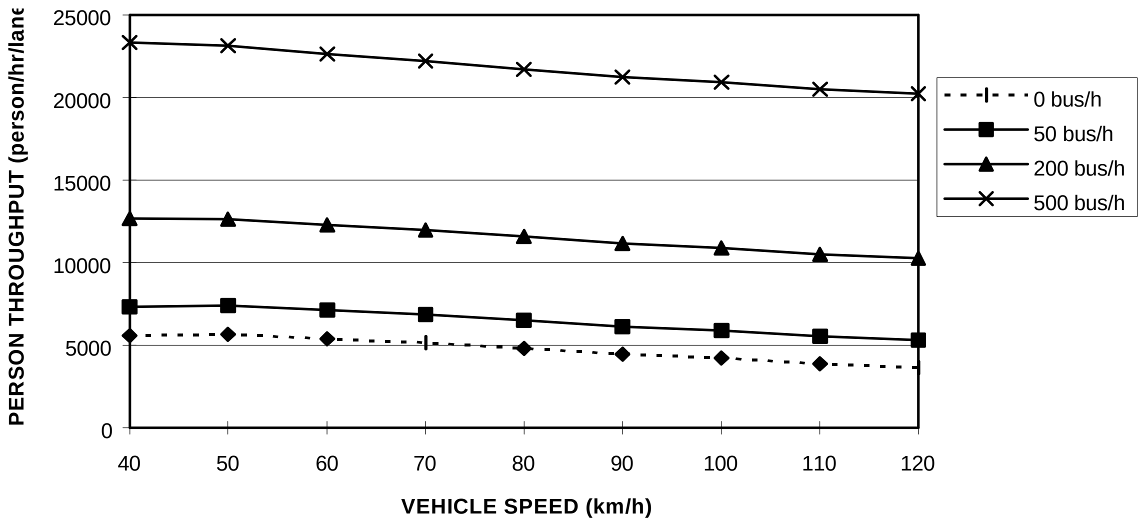


Figure 8. AHS Throughput For Five Car Platoon And One Bus Platoon

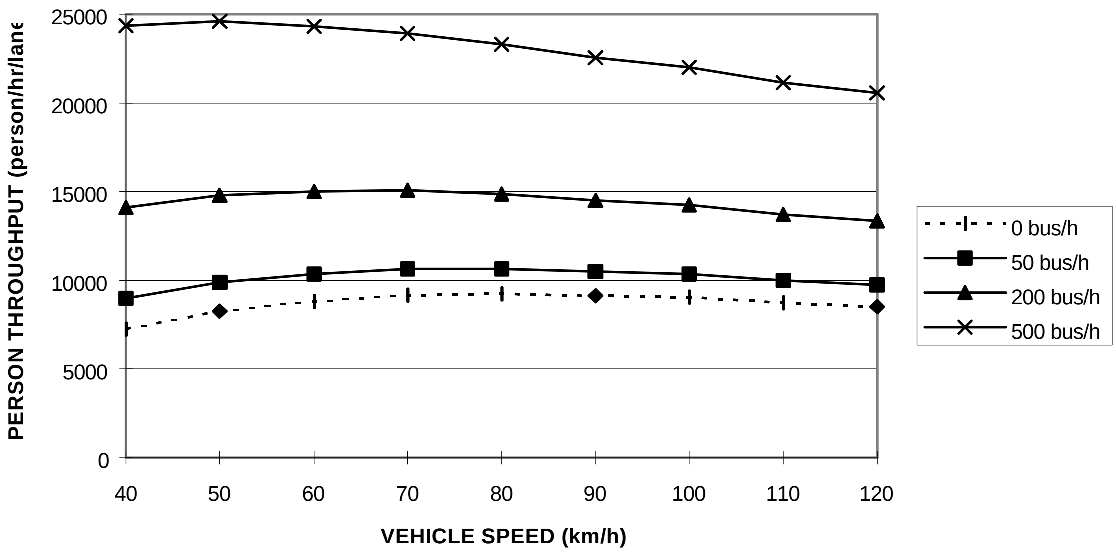


Figure 9. AHS Throughput For Fifteen Car Platoon And One Bus Platoon

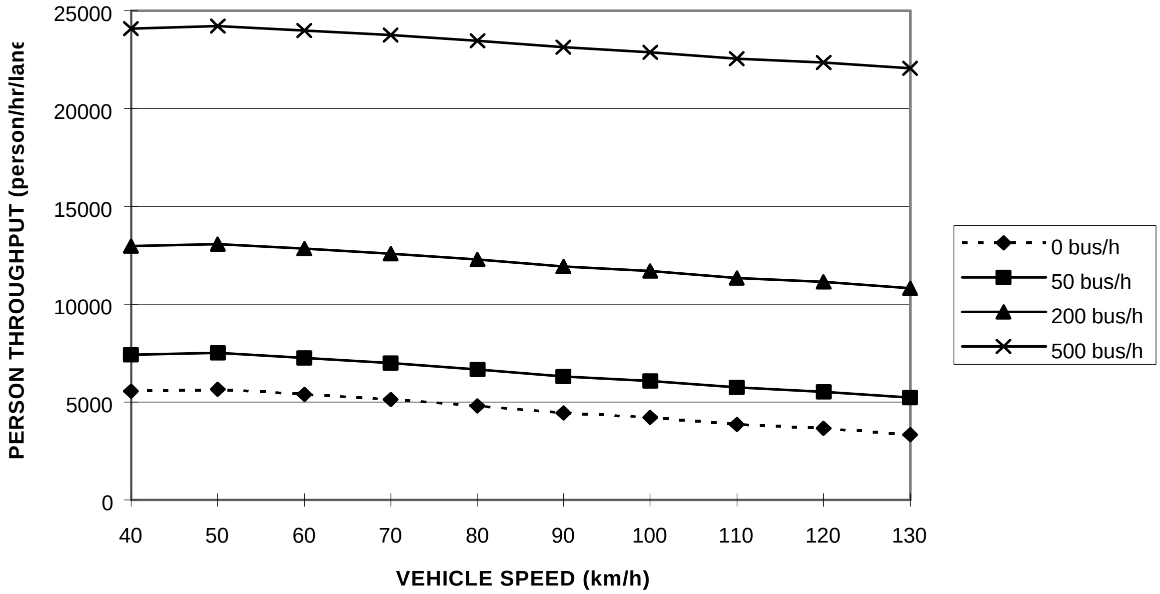


Figure 10. AHS Throughput For Five Car Platoon And Three Bus Platoon

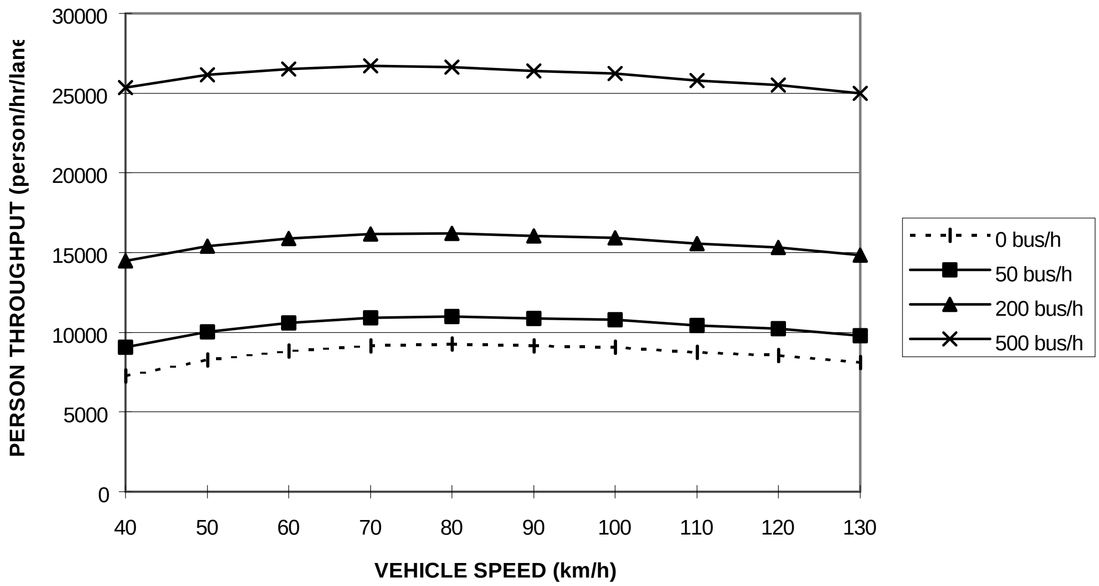


Figure 11. AHS Throughput For Fifteen Car Platoon And Three Bus Platoon

Task 3. Heavy Motor Vehicle Headway Policy

This section introduces some of the issues to be considered in developing a policy regarding the spacing of heavy motor vehicles (HMV) on automated highway lanes (AHL). This issues analysis is based on the following definitions and assumptions:

Definitions:

- Heavy motor vehicle – A bus or large truck.
- Bus – A large motor vehicle used to carry more than ten passengers, including school buses, inter-city buses, and transit buses.
- Large truck – A truck with a gross vehicle weight rating greater than 4354 kg.
- Passenger car – A motor vehicle used primarily for carrying passengers, including convertibles, sedans, and station wagons.
- Light truck – A truck with a gross vehicle weight rating less than or equal to 4354 kg, including pickups, vans, truck-based station wagons, and utility vehicles.

Assumptions:

- In urban areas, heavy motor vehicles are permitted to travel on an AHL on which passenger cars, light trucks, or transit vehicles are present.
- Only fully automated motor vehicles are permitted to enter an AHL.
- The headway between heavy motor vehicles and between heavy motor vehicles and all other types of vehicles traveling on an automated highway shall be defined such that the risks associated with operation of an AHS are mitigated.
- Heavy motor vehicles are not permitted to join platoons of non-heavy motor vehicles.

The following are issues identified for a heavy motor vehicle AHS headway policy.

Multiple Vehicle Operation Modes

At a minimum, an AHS HMV headway policy will address the following three modes of vehicle operation:

- Overtaking.
- Emergency braking and acceleration.
- Following.

In addition, the headway policy must address the entire spectrum of light and heavy motor vehicles in order to accommodate differences in vehicle performance characteristics (e.g., length, height, weight, engine size, number of trailers), types of cargo transported by the vehicle, and so on. For instance, bus and truck headway policy can differ for vehicle following involving steep AHL downgrades; a bus typically requires less distance to come to a complete stop on a downgrade than a single- or multi-unit truck.

However, the use of multiple HMV headway policies, each addressing the system state of an HMV and some portion of its environment, raises safety policy and technology investment issues.

Safety Policy Issue

It is necessary to test for gaps (e.g., logical consistencies, unsoundness, and incompleteness) in HMV headway policies. For example, conflicting headway policies can introduce system hazards, such as one class of HMV (fully loaded semi-trailer) following a different class of HMV (e.g., tandem tractor-trailer) at an unsafe distance. An increase in the number of HMV headway policies or an increase in the complexity of the relationships among these policies can lead to a corresponding increase in the level of difficulty of detecting gaps and updating headway policy.

Technology Investment Issue

Heavy motor vehicle headway policy will be translated into AHS requirements, which in turn will be implemented in software, hardware, driver and operator training programs, and so on. Hence, the cost to develop and maintain an AHS will be influenced by the HMV headway policy.

One strategy for minimizing the size and complexity of HMV headway policy is to base headway policy on worst case HMV performance characteristics. The third definition given previously and the sum of the weights in column two of table 6 (36,287 kg) define the lower and upper bounds on HMV weight, respectively. Since we know that the largest of buses weighs less than 36,287 kg and that in general the tractor-trailer is the most difficult HMV to control during emergency braking on dry or wet pavement, we can use the acceleration and deceleration characteristics of triple tractor-trailers under poor driving conditions as an integral constraint on HMV-wide (i.e., including all classes of trucks and buses) headway policy.

Table 6. Federal Limits On Truck Loading

Truck Component	Maximum Allowable Loading (kg)
Steer Axle	5,443
Drive Tires	15,422
Trailer	15,422

Passenger Vehicle Headway Policy

Suppose, for instance, that we assume a linear relationship between passenger vehicle and HMV performance and that we know the recommended following distances for these two types of vehicles on manual highway lanes. Given the 4 m vehicle spacing used in recent California PATH Program longitudinal control experiments, we can then derive, via interpolation, minimum spacing requirements for vehicle following by heavy motor vehicles on automated highway lanes. The results of this interpolation are presented in table 7.(3)

Table 7. Minimum Headway For Passenger And Heavy Motor Vehicles

Minimum Spacing Given a Speed of 105 km/h				
Vehicle Type	Manual Mode		Automated Mode	
	State	Industry(4)	PATH Program(3)	Interpolated
Passenger	3 s (87.5 m)	—	0.14 s (4m)	—
Heavy	5 s (146 m)	—	—	0.23 s (6.7 m)
Heavy	—	8 s (233 m)	—	0.37 s (10.8 m)

However, these derived values are not realistic because a linear relationship between vehicle performance does not hold; that is, minimum safe headways for passenger vehicles is not a good basis for determining the minimum safe headways for heavy motor vehicles. For instance, large trucks tend to be much more under powered than passenger vehicles for ascending steep grades and braking on downgrades. Also, braking by a heavy motor vehicle is a complex operation involving the brake system, vehicle tires, dimensions, loading characteristics, and pavement surface characteristics.

The redesign of heavy motor vehicles or the incorporation of anti-lock brakes, automatic transmissions, and other vehicle control technology into trucks and buses can reduce the performance gap between passenger and heavy motor vehicles, but how much they will reduce the gap is yet to be determined.

Actual And Perceived Risks

The actual or perceived risks associated with headway policy can differ. The risks can vary in terms of the:

- Likelihood of a system hazard occurring.
- Likelihood that a hazard will lead to an accident.

- Worst possible potential loss resulting from an accident.

For instance, it is not uncommon for truck air brakes to fail, especially if the air brake components are not properly maintained.[5] A loss of air brakes poses a hazard if the truck is in motion. This particular hazard, coupled with a fault in the jake (i.e., compression) brake and a descent on a wet, steep AHL grade (i.e., unfavorable environmental conditions) can result in an accident. This scenario is depicted in figure 12. The worst potential loss resulting from such a crash can be couched in terms of the death of one or more AHS users (i.e., one or more crashes) or bystanders (e.g., poisoning of the public or the environment by the release of hazardous cargo). Even with high barriers between the automated highway lanes and the manual highway, actual or perceived risks can result in the promulgation of conservative headway rules. That is, although it may turn out to be technically possible and economically feasible to operate tractor-trailers at a spacing of 6.7 m at 105 km/hr, the public may balk at such a proposal and argue for headways that are greater than 6.7 m or speed limits less than 105 km/hr. This is especially true for the spacing between passenger vehicles and heavy motor vehicles. There may be a general perception that it is dangerous for trucks and buses to follow passenger vehicles at less than, say 15m.

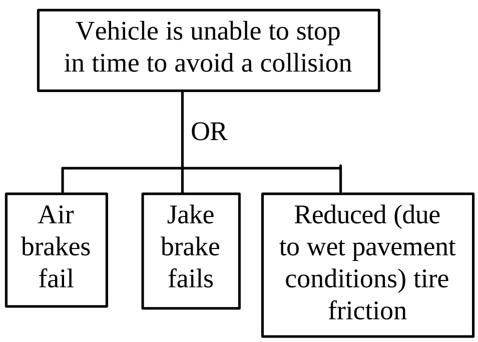


Figure 12. Fault-Tree Depiction Of Accident Scenario On A Downgrade

From an engineering perspective, AHS safety needs to be couched in terms of system hazards, not in terms of accidents and catastrophic system failures. That is, hazards which are within the engineering design space, and are thus controllable to some extent should be the focus of safety. Hence, identification of AHS hazards is a prerequisite to developing HMV safety headway policy. Based on the identified hazards, tradeoffs in AHS headway policy and AHS design can be made with respect to perceived and actual risks, system development resources (i.e., engineering economy considerations), and traffic congestion reduction goals.

Variations In Vehicle Performance

As discussed in the introduction of this report, performance characteristics, such as vehicle acceleration and stability, vary across the wide spectrum of heavy motor vehicles. For example, the vehicle acceleration of a single-unit truck is different from that of a bus, both of which differ in performance from that of a tractor-trailer. An abrupt maneuver performed by a tractor-trailer (especially twins and triples) can result in oversteering, which in turn can contribute to hazards such as exaggerated side-to-side motion (e.g., rearward amplification) or offtracking (i.e., rear wheels deviating from the path of the front wheels).

In addition, performance characteristics vary among types of buses, and among types of trucks. For instance, a tractor-trailer has a different stability profile from that of a truck-tractor. A tractor-trailer generally has more axles than a bus, and therefore tends to be more prone to experiencing locked-wheel stopping during emergency braking. Locked-wheel braking refers to the brakes gripping the wheels tightly enough to cause the wheels to stop rotating before the vehicle comes to a full stop. The cause-effect relationship for locked-wheel braking conditions are given in table 8. Each of these results constitutes a loss of vehicle control.

Table 8. Cause-Effect Relationships For Locked-Wheel Braking

Type of Locked-Wheel Condition	**Result**
Steering Wheels	Plow out; Loss of steering control
Tractor Rear Wheels	Jackknife; Tractor spins
Trailer Wheels	Trailer wing; Trailer spins

Hence, to accommodate tractor-trailers on an AHS, an HMV headway policy must provide an adequate distance for a controlled, low rate of deceleration under normal and emergency conditions. The policy must also take into account the inherent delay of approximately 0.5 sec in truck brake actuation; braking distance refers to the distance required to stop a vehicle from the instant brake application begins.

In addition, an HMV headway policy must be congruent with vehicle- and infrastructure-based collision avoidance technology. For instance, the existence of a runaway vehicle escape ramp on an downgrade or a passing lane on a upgrade, both of which are examples of infrastructure-based collision avoidance technology, will have an affect on the type of hazards introduced by headway policy and vehicle system behavior. Theoretically, on a section of an AHL equipped with an escape ramp, trucks and buses can be separated at shorter distances than if no escape ramp is present, all other things being equal. Alternatively, vehicle control algorithms can be tailored to adjust the speed of trucks and buses prior to their entering a downgrade, taking into consideration such factors as the percent of grade, weight of the vehicle, vehicle performance characteristics, and roadway and weather conditions.

The presence of a passing or turnout lane on an upgrade can permit lighter vehicles (e.g. passenger cars or high performance trucks) to pass slower moving (e.g., partially disabled or fully loaded) vehicles. Similarly, a lane dedicated to entering or exiting an AHL can mitigate the risk of collisions (i.e., during the maneuvers conducted to join or leave a platoon or slot) and thus provide the potential for implementing relatively short headways. Likewise, a shoulder for accommodating out-of-lane excursions can reduce risk and possibly the required headway, such as when the tire-pavement friction available for truck and bus braking is reduced by the portion of the available tire-pavement friction that is required for cornering.

Similarly, vehicle-based collision-avoidance technology will affect the setting of headway policy. The accuracy and dependability of sensors, wireless communications, and other collision-avoidance system components will determine the upper bounds on achievable safe headway distances. Likewise, any computer software that directly or indirectly controls vehicle actuators or provides actual or desired headway information to the driver, assuming the driver can retake control to provide for manual actuation of steering, braking, and acceleration, will have an affect on system safety. Due to the exponential explosion of possible system states that must be tested as the number of inputs (i.e., degrees of freedom) to a computer program increase, it is impractical and expensive to demonstrate software correctness in the region of 10^9 or greater executions without failure.

Human Factors

Automation of the vehicle overtaking, emergency braking and acceleration, and following tasks can potentially improve AHS safety. However, a driver cannot be expected to always regain control of his or her vehicle when the vehicle experiences a failure and he or she is required to take manual control of the vehicle. For example, in the case of a truck hauling twin or triple trailers, it is difficult if not impossible for the driver to sense impending trailer instability in time to take measures to compensate for vehicle instability. Thus, the ability to sense impending instability is another limiting factor on minimum headway distances. Similarly, bus and truck drivers, if required to retake manual control of their vehicles, must be able to compensate for physical forces such as aerodynamic buffeting and load shifting. In addition, splash and spray can affect the roadway visibility, affecting the usability of vehicle- and roadway-based sensor and other instrumentation, lighting systems (e.g., trailer marker and brake lights), as well as the vehicle windshield and mirrors.

Furthermore, drivers of passenger vehicles and light trucks may not be able to compensate to avoid collisions with heavy motor vehicles in either the case where the light vehicle experiences a failure or the case in which a heavy motor vehicle experiences a failure. A passenger vehicle driver may panic if it appears that he or she is going to collide with the rear or front end of a heavy motor vehicle.

Moreover, travel speeds and vehicle spacing on an AHS will be characterized by high-performance driving conditions. Driver reaction time can be inadequate under nominal and extraordinary AHS conditions to take the necessary and sufficient actions to manually maintain the spacing in a platoon or slot, or to prevent or lessen the severity of a collision, due to the complexity of HMV control. Even if the driver can physically react in time, he or she may not be able to adequately assess the state of the vehicle and the environment to react to changes in headway and other factors in an optimal or correct manner, such as correctly modulating the brakes so as to avoid locking one or more of the wheels.

Relationship To AHS Subsystems

Heavy motor vehicle headway policy will have an impact on AHS safety in terms of AHS subsystem functionality. For example, the risks posed by a high-speed, close following distance headway policy can necessitate very thorough HMV AHL check-in and check-out procedures. There can be a requirement that the fifth wheel be checked to verify that it has been adequately lubricated, that the trailers are in good condition, and that the load is securely stored (e.g., doors are locked shut and tarps are properly fastened); these items can be checked at a remote location. Air and compression brakes can be checked at the on-ramp, while tire tread and pressure can be monitored via continuous in-vehicle testing using in-tire computer chips.[6]

Another view of the relationship between headway policy and AHS subsystems can be obtained by considering each of the representative system configurations. Table 9 summarizes the technology, as defined in Activity D – Lateral and Longitudinal Control Analysis, for realizing longitudinal control of passenger vehicles.

Table 9. Longitudinal Control Technology For Passenger Vehicles

Representative System Configuration	Technology
Infrastructure Platoon Control	Wayside sensing; Cooperative ranging to roadside controllers
Autonomous Vehicle Platoon Control	Vehicle-based communication and ranging
Space/Time Slot Control	Wayside controllers; Wheel speed sensors and accelerometers provide control input

Note that the technologies associated with each RSC type may not be adequate for heavy motor vehicles. For example, for high-speed, close distance HMV following, it may be necessary to use brake gripping, load shifting, and other input data for algorithms to perform space/time slot control. In infrastructure platoon control, wayside sensing or cooperative ranging to roadside, may not be sufficient to allow for the on-vehicle control systems to adjust for noisy data values. Vehicle-based communication and ranging is subject to single points of failure, which can make autonomous vehicle platoon control unacceptable in the eye of the public, especially if trucks carrying hazardous materials are permitted access to the automated highway lanes.

Interface To ITS Services

Heavy motor vehicle safe headway policy will also be affected by planned (i.e., future) and operational intelligent transportation system (ITS) services. For example, one of the planned ITS services affecting truck and buses is weigh-in-motion. The separation of heavy motor vehicles will need to be sufficient for the weighing mechanism to perform its function (e.g., sensing, reporting, and enforcement). Other ITS services, such as automatic payment of roadway use fees, are already being implemented and fielded. Headways or vehicle speed may need to be adjusted at automated toll stations so as to mitigate the risk of high-speed collisions.

Institutional Issues

Finally, institutional issues will need to be considered. For instance, drivers of trucks carrying hazardous materials are required by Federal law to stop their vehicles and check their vehicles' tire pressure and wear the lesser of two hours driving time or 161 km. All other things being equal, very close vehicle following can potentially result in a truck being unable to safely exit from an AHL in time to satisfy laws regarding the carrying of hazardous materials, providing existing regulations are not modified for AHS use.

An AHS can be designed so as to continuously monitor truck tire pressure and tread wear, thus making some hazardous materials laws based on manual checking obsolete or redundant. Similarly, issues such as how to handle hazardous carriers on an AHL may be avoided all together if it is deemed that their presence on an AHL constitutes too great a risk or economic burden. As discussed above in Actual and Perceived Risks, actual and perceived risks will play a role in the determination of headway policy for both passenger and heavy motor vehicles, where perceived and actual risk are implemented as public policy.

Task 4. Forecast Demand

Because many of the issues associated with demand are site specific, it is difficult to quantify demand forecasts for commercial and transit vehicles. The approach used in this task is to highlight the basic issues that will affect demand of these types of vehicles both in a rural and urban setting. Wherever possible, national statistics are used to backup any conclusions about demand of specific types of commercial and transit vehicles. It is however reiterated that further studies will need to be done on a site specific basis to provide true demand forecasting for the particular locale that is being studied.

Urban Demand

Capacity conditions generally occur on traditional highway during two distinct periods of the day; morning and evening. During these peak periods the greatest benefits for all AHS users will be realized. In order to determine demand of heavy vehicles on AHS the various possibilities for heavy vehicle composition on AHS need to be analyzed with respect to decrease in congested travel as well as other benefits or disbenefits. For discussion purposes, three heavy vehicle compositions will be dealt with to identify heavy vehicle demand issues. These compositions are:

- Transit vehicles only.
- Transit and single unit trucks.
- All heavy vehicles (including interstate tractor trailer trucks).

Transit Vehicles

Unlike commercial vehicles, demand for transit use on a AHS facility will primarily be governed by the level of comfort and convenience of the passengers. Secondary issues affecting demand may result from the operating cost savings associated with AHS use.

It has been observed in some cities with efficient public transit systems, that passenger comfort and convenience on transit, results in high ridership percentages. Inclusion of transit on AHS corridors will provide the operation flexibility that is a characteristic of present day high occupancy vehicle lanes (HOV) in addition to the speed and travel predictability of a rapid transit type operation. This type of operation, coupled with efficient non AHS collector service using the same vehicle, potentially could provide the comfort and convenience required to increase overall transit ridership.

The idea of increased ridership corresponds to more revenue for the transit authority making transit operation more cost efficient. In addition to the possibility of increased revenues, other benefits for AHS also exist for the transit authority. Inclusion of transit vehicles in AHS may require platooning of transit vehicles. Depending on spacing within platoons, the aerodynamic drag may be reduced for the vehicles following the lead vehicle, hence reducing fuel consumption. In addition, frequent checks of automated transit vehicle components would be a requirement for AHS use. Maintenance costs could potentially be reduced as problems may be detected early reducing repair costs and down time.

In addition to the demand associated with ridership and operations, social and/or political demands for inclusion of transit vehicles could potentially be the most important demand issue. Campaigns throughout the country are presently underway to reduce the amount of single occupant vehicles on the urban roadway system. Development of AHS for only passenger vehicles would contradict this campaign. For this reason, political pressures to include transit on AHS will likely be high.

With respect to all of the user, operator and political issues associated with transit use on AHS, it is reasonable to conclude that demand for transit use on AHS will be very high within most urban areas.

Single Unit Trucks

In order to estimate demand of single unit truck use of AHS, characteristics of single unit truck travel patterns must be analyzed for compatibility with travel patterns expected with AHS use. In addition, this compatibility of systems must produce benefits which overcome any disbenefits associated with AHS use.

According to the Transportation and Traffic Engineering Handbook (1982), single unit trucks (light to medium commercial trucks) make an average of 10.1 trips each weekday. Typically these trips are short in length (5–8 km) and are usually confined to the arterial street system. It is assumed that operational characteristics of the AHS will discourage short trips and as a result it is unlikely that AHS will provide benefits for trucks making short trips. However, there may be longer suburban trips within the average, which may be long enough for AHS to provide benefits. However, since the majority of urban truck trips occur during non-congested periods of the day, travel time benefits associated with AHS use would only be realized by the portion of trucks traveling during congested periods. Limited benefits combined with disbenefits, such as cost of equipment, make it unlikely that sufficient demand would exist to justify inclusion of these types of trucks on AHS.

Heavy Trucks

Similar to light trucks, travel patterns for heavy vehicles must be determined, in order to identify demand issues for heavy trucks use of AHS. For the purpose of this report, the following three scenarios relating to heavy vehicle presence within an urban area are discussed:

- Inter-city/Interstate trucks at terminus point of trip.

- Inter-city/Interstate trucks passing through to a different destination.
- Local deliveries.

Each of these scenarios represent different trip characteristics, and hence affect heavy vehicle demand issues in different ways. It is noted that it is difficult to provide general issues that apply to all cities, as not all of the above scenarios occur to the same degree in all locations.

Terminal Trips

Some major cities are terminus points for a number of different transportation modes; namely rail, ship and truck. As a result, large volumes of trucks originate or terminate in these cities. Due to the nature of intermodal movement of goods, many of these intermodal depots are located at distinct areas of the city. As a result, travel times of heavy commercial vehicles categorized under this scenario generally involve the quickest most direct route from the outer limits of the city to this location.

Inclusion of heavy trucks on AHS under this scenario may be beneficial to the trucking industry as travel times and safety benefits would exist especially during congested periods. However, due to the potential large heavy truck volumes associated with this scenario, it is unlikely that sufficient capacity would exist with one mixed AHS lane and therefore a second AHS truck lane would have to be considered. Planning is currently underway in some cities with similar characteristics as this scenario to manage trucks during traditional peak hours by the use of separate truck lanes or even excluding trucks from freeways during peak hours. If these plans are realized before AHS implementation, benefits for these types of trucks using AHS may diminish.

Through Trucks

Many interstate/inter-city trucks must pass through cities en route to their final destination. Congestion during peak hours of the day causes delays for these types of trucks. Some cities have constructed outer loop freeways so congested urban areas can be avoided by vehicles passing through the city.

Inclusion of trucks on urban AHS in this scenario would be beneficial to the trucking industry providing alternate by-pass routes were not available and/or congestion on the traditional highway system was such that AHS would provide significant travel time savings. It is difficult to determine what net benefits would be realized by the trucking industry if inclusion of trucks on AHS was permitted under this scenario, as benefits would be dependent on the congestion and configuration of the traditional freeway system. For example, net benefits for using AHS in this scenario may only exist in a percentage of the cities that a particular truck passes through and therefore the overall benefits for all the cities may not provide enough benefits to balance the disbenefits such as initial cost outlay.

Local Deliveries

Heavy trucks that are involved with local deliveries within a city have similar travel characteristics to single unit trucks discussed previously. However, trip lengths are generally longer than the smaller trucks (6–11 km), and utilize both arterial street and freeway systems. Trucks under this scenario could potentially realize benefits through using AHS but as with the discussion of single unit trucks on suburban trips, benefits would only be significant during trips occurring during peak hours when congestion of traditional lanes exists. This reasoning coupled with the fact that large trucks account for only five to ten percent of local urban truck trips make it unlikely that a high demand for truck inclusion on AHS will occur under this scenario.

It is reiterated here that the three scenarios presented here are only to identify the issues associated with heavy vehicle demand on AHS. As every urban area has different freeway configurations and hence different heavy truck travel characteristics demand for inclusion of trucks on AHS may be high in some areas while non-existent in others. This leads to the conclusion that although issues regarding demand are identified, further study is required on a site specific basis.

Rural Demand

Traffic volumes and characteristics on rural freeways are such that capacity is rarely met except in localized areas where terrain hinders the operation of certain types of vehicles. For this reason it is conceivable that capacity constraints will not cause a shift from traditional lanes to AHS lanes in a rural setting.

As a result of this discussion, demand for trucks to use AHS will be dependent on other benefits associated with AHS travel. These may include:

- Directness of route.
- Travel time savings.
- Safety.
- Comfort/convenience.
- Predictable travel time.

Each of these possible benefits associated with AHS travel must provide an adequate advantage over traditional freeways in order for a significant number of commercial vehicles to convert to this mode.

Demand Issues

As many of the issues relating to demand of commercial vehicles using AHS are difficult to quantify, only issues relating to forecasting demand are presented here. Table 10 illustrates how issues relating to demand may be perceived by commercial vehicle operators.

As discussed in task 1 – Define Differences in Characteristics, margins in the trucking industry are such that truckers are reluctant to make equipment modifications to their trucks unless a significant market advantage exists for doing so. For this reason any positive items listed in table 10 must significantly outweigh the negative issues also listed in the table in order for significant demand of heavy vehicles to exist.

Of all the positive issues listed in table 10 perhaps the most important relating to commercial vehicle demand of AHS would be travel time savings. If travel time was substantially reduced more productivity could be realized from the equipment which means more revenue for the equipment owner. Obviously, if the additional revenue was substantial enough to outweigh the apparent negative items, demand for commercial vehicle use on AHS would exist. However, in order to estimate travel time benefits and hence demand, all factors affecting travel time must be analyzed.

Table 10. Matrix Of Issues Affecting Demand For Heavy Vehicle Rural AHS

	Perceived Reaction	
Issue	**For**	**Against**
Travel Time Savings	X	
Safety	X	
Fuel Consumption		X
Maintenance Cost		X
Comfort & Convenience	X	
Arrival Predictability	X	
Initial Cost		X
Usage Cost		X

Travel time savings may not be available in all corridors. Corridors with relatively level terrain could potentially support higher speeds necessary for travel time reductions. Level terrain and straight sections of road do not have the geometric limitations on speed that a mountainous section may have. Travel time reduction would be much more difficult to obtain with commercial vehicles in mountainous terrain as operational characteristics of the vehicles would govern the travel speed and hence no improvement over traditional lanes would be expected.

Travel time savings are not only a function of terrain and operations, but also a function of available infrastructures. If AHS is not continuous throughout a corridor, travel time benefits may not exist. Also, if demand is limited or controlled, certain trips may require use of traditional lanes due to excess vehicle (whether passenger vehicle or commercial vehicle) demand. Depending on the frequency of these occurrences overall travel time benefits may diminish.

In order to demonstrate what type of travel time reduction could be expected for heavy vehicle use of AHS, an analysis was performed for a segment of rural freeway (same section as was analyzed in Activity I – Impact of AHS on Surrounding Non-AHS Roadways) for various scenarios. This analysis used the FRESYS model (also described in Activity I) to compare travel speeds on non-AHS lanes to speeds on the AHS lane (determined from capacity curves from Activity I). In order to get useful numbers from this analysis the following assumptions are used:

- Limited access AHS (access at start, end, and one point in between).
- Utilization volumes derived in Activity H – AHS Roadway Deployment Analysis for hypothetical rural corridor assuming limited access.
- Corridor traffic composition: 22 percent heavy vehicles and 78 percent cars.
- Heavy vehicles are equivalent to 1.5 cars on level terrain.
- Use only the level portions of the hypothetical section (assume truck speed is the same for mountainous sections whether on AHS or traditional lanes), length = 54 km.
- Maximum speed on AHS lane = 120 km/h (governed by design speed of the roadway).
- Input to the FRESYS model to determine travel speed of the non-AHS lane as per rural modeling in Activity I.
- No platoons.

Table 11 shows the ten scenarios that were modeled to determine how traffic composition and increased volume on the AHS affects the travel times for trucks.

Table 11. Scenarios Used In Modeling

Scenario	Percentage of Cars *	Percentage of Trucks *
1	10	10
2	40	10
3	60	10
4	10	40
5	40	40
6	60	40
7	10	60
8	40	60
9	60	60
10	N/A	N/A

N/A - Scenario #10 is the base case (no AHS)
* Percentages given are the percentage of total corridor (AHS and non AHS) cars and trucks using the AHS facility.

Results

Figure 13 illustrates the results from this analysis. One of the apparent observations from this analysis is that travel time savings are greater at lower market penetrations. As the market penetration increases, the operation of non-AHS improves thereby decreasing the travel time savings advantage between vehicles on the two different modes.

This trend continues until volume on the AHS increases to a point where AHS speed decreases. At this point the travel time advantage vanishes and operations along the AHS are worse than the non-AHS lanes.

Another result is that at high truck market penetrations (60 percent) travel time savings exist if passenger vehicle penetration is low. As the passenger vehicle penetration increases the travel speed for trucks decreases.

As shown through this rural model, fairly significant travel time savings are shown for trucks at low market penetration; however, as the market penetration increases, these savings diminish. This raises an interesting issue in that advantages for trucks will be the greatest at early stages of development and will be eliminated as use increases to the point that speed on the rural non platooned AHS diminishes.

This analysis also reiterates that demand for trucks on AHS needs to be evaluated for each corridor. The percentage time savings shown here could only be evaluated for a totally level corridor. If the corridor contained mountainous sections, these percentages would be much lower.

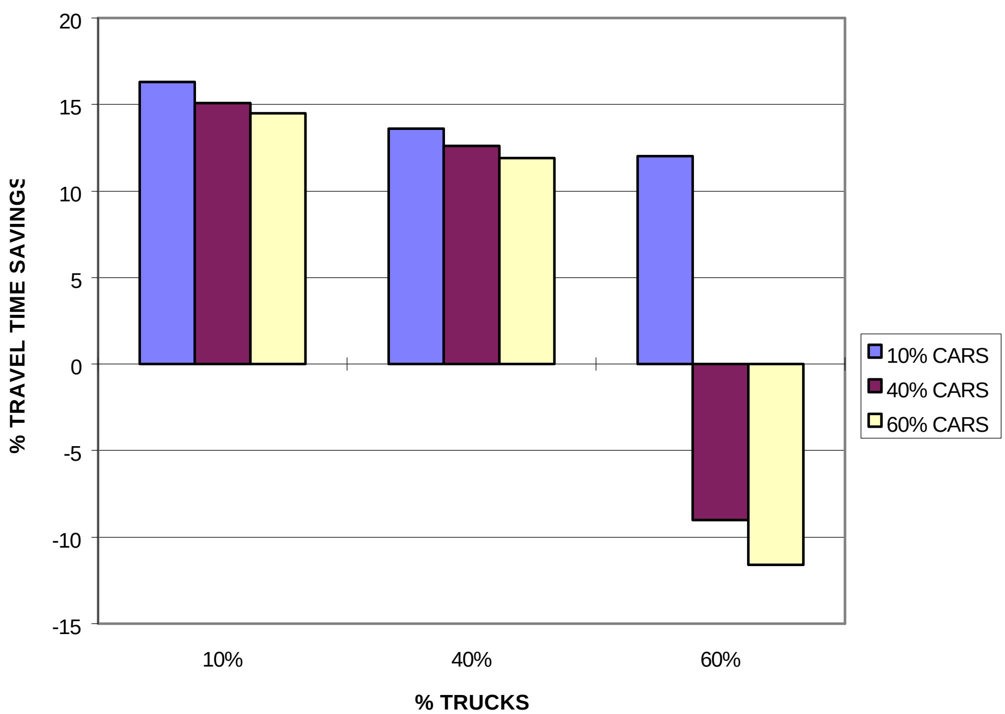


Figure 13. Percentage Travel Time Savings From Non-AHS Lanes

This analysis assumed a speed flow diagram that predicted the speed of the non-AHS lanes. Actual driving characteristics in a rural situation may differ from what the analysis shows. For example, on a level rural road the average speed on the non-AHS road may be above the legal speed limit, which would limit the amount of travel time savings of the AHS lane.

As shown from this model it is evident that positive elements of AHS use for commercial vehicles are dependent on site specific conditions. Corridors with high truck usage and limited passenger vehicle usage may provide the benefits required in order for commercial vehicle demand to exist. Operations in other corridors may provide disbenefits for commercial vehicle usage and demand for heavy vehicle use may not exist. Major factors such as travel time savings relating to commercial vehicle demand on AHS needs to be analyzed for each site.

Other positive benefits such as comfort and convenience, safety, and travel time predictability are benefits which could be analyzed for AHS in general. These items are not site specific but may still provide benefits for commercial vehicle demand to exist.

Comfort and convenience issues could potentially increase productivity of the truck. With the system performing driving functions, the intense concentration required for traditional truck drivers of the driver will be significantly reduced or eliminated. For this reason it may be possible to increase the amount of time a driver could spend on the highway without a rest. This would allow more operating time for the truck, creating higher profitability.

Another potential benefit achievable for trucks through AHS is safety. Some references state that accident rates for large trucks on rural freeways are 1.12 accidents per million miles.(7) According to the Transportation and Traffic Engineering Handbook, of rural area truck accidents in selected areas, 86.3 percent were related to improper driving. With AHS performing driving functions it is conceivable that improper driving could be eliminated. This type of reduction in accident rates should lower overall operating cost for the trucking industry through lower insurance premiums, decreased liability, downtime reduction, and equipment replacement cost.

Benefits such as travel time predictability may not directly increase the productivity of commercial vehicles but may provide benefits in the market place. Travel predictability may allow more efficient use of warehouse space at distribution centers as arrival times could be matched with departure times. Providing customers with this type of service may provide the commercial vehicle operator a market advantage, potentially increasing revenue.

As can be seen by the above issues, the positive issues relating to determination of demand are either dependent on many things and/or very difficult to quantify. However, the negative issues relating to demand are much easier to quantify. Increased fuel consumption, maintenance cost, capital cost, and usage cost are direct costs that provide the negative aspects relating to commercial vehicles demand on AHS.

Capital cost and usage costs are negative issues that will certainly provide the most negative aspects of AHS use for commercial vehicles. When a truck is purchased, all the electronics and other components required for AHS will be added to the basic cost of the truck. These costs will appear directly as a quantified negative aspect. Other quantified negative aspects will include the usage charges for AHS. If these rates are significantly more than toll rates of traditional roads, the added cost will be readily apparent. Usage charges for AHS may be a very large deterrent for commercial vehicles along corridors where traditional driving charges may be significantly less even though both modes of travel share the same right of way.

Other costs that may affect the decision of commercial vehicles to use AHS are operating costs. As mentioned in task 1, AHS trucks will require the use of automatic transmissions in trucks which are perceived to result in decreased fuel economy. An increase in fuel consumption is also a direct cost that is easily quantified once the exact operational conditions are determined. Also mentioned in task 1 was the unwillingness of the trucking industry to convert conventional transmissions to automatics due to the perceived increase in operating cost. This example reiterates the fact that the positive aspects (in the case of automatic transmissions would be comfort and convenience) must far outweigh the negative aspects in order for a change to occur.

The increased amount of components on an AHS truck may cause a perception that maintenance costs will increase. This may also be a negative factor toward AHS use in trucks even though self diagnostics required for AHS may detect maintenance issues early, hence reducing overall maintenance costs.

From the above discussions it is evident that demand forecasts for commercial vehicles on AHS are dependent on a number of issues that need to be addressed for each corridor. It is also noted that the issues presented here relating to rural demand will also apply to in some degree to urban situations.

Task 5. Determine Costs And Benefits

The following section is a subjective discussion of the costs and benefits of accommodating trucks and transit vehicles on the AHS. Truck and transit costs and benefits are treated incrementally. In other words, the additional costs and benefits that accrue if the AHS is designed for trucks and transit vehicles, as compared to a design for passenger vehicles only, are addressed.

This approach starts out with an important issue which is difficult to resolve. That issue is whether or not it is reasonable to even consider a passenger car only AHS as the base case for a benefit cost analysis. Many construction cost savings could be realized in this scenario. Pavement sections could be thinner; bridge structures lighter and spans longer, and overhead clearances reduced. On the other hand, such a design would preclude existing emergency and maintenance vehicles, and would require a completely new fleet of such vehicles to be built and maintained for use solely on the AHS. It is felt that this scenario is unreasonable because the early implementations of AHS are very likely to be retrofitted to existing freeways where at least some pavement and many of the required structures are in place. A rigorous determination of construction cost differentials between passenger car only and all-vehicle AHS is beyond the scope of a precursor study. For these reasons, the remainder of this task report deals with costs and benefits associated with operations of the various vehicle types on the AHS, which, for this analysis, is assumed to be physically capable of accommodating today's range of legal vehicle sizes and weights.

Costs

The question to be addressed is: "If an AHS is designed with elements to allow safe and comfortable passenger car operations, what additional costs are sustained if commercial/transit operation is added?"

If the assumption is accepted that pavement and structural elements are designed to accommodate commercial/transit vehicles, the remaining incremental cost of adding large vehicles is related to their performance. As presented in task 1 , truck acceleration is far lower than that of passenger cars. In AHS, speeds of through and merging traffic have to be essentially the same. The consequence of this requirement is that acceleration lanes typically six times longer than required by current standards are needed for heavy trucks and three times longer are required for buses. It is readily evident that heavy vehicles with today's acceleration attributes totally dominate the geometric design of AHS entry ramps (assuming a dedicated facility without a transition lane.) With reasonably short (five km or less) AHS interchange spacing, AHS becomes a two lane proposition, with the right lane being a de facto truck lane and AHS passenger vehicles being required to weave through trucks. These trucks would operate at a lower top speed than is possible for the AHS passenger cars as vehicles would enter this lane and exit via this lane, hence degrading operations an this lane.

From the above discussion it can be inferred that addition of trucks to the AHS could double the roadway infrastructure cost.

While this analysis tends to lump trucks and transit vehicles, it is important to give some consideration to transit on its own, for several reasons:

- The public may perceive AHS as a single occupant vehicle (SOV) intensive program. Transit-friendliness is important to avoid this perception.
- Increasing mainline vehicle throughput is only part of the transportation problem. Transit increases people throughput without corresponding traffic demand on local streets.
- Transit use reduces the societal demand to build parking facilities.
- Air quality legislation requires new projects in non-attainment areas to be tied to congestion management. Transit, with its route flexibility at both ends of the trip and its HOV nature, is a key tool for congestion management.
- Transit vehicles have much better acceleration than loaded heavy trucks.
- Transit vehicles can be given preferential treatment to maximize the AHS people throughput, not the vehicle throughput.
- Costs of equipping the transit fleet typically can be borne by public agencies, while equipping the truck fleet would have to be funded by the private sector.

Benefits

As mentioned in task 4 – Forecast Demand, benefits realized by transit use on AHS can be categorized into user benefits, transit authority's benefits, and political benefits. The comfort and convenience of a transit operation that can provide local pickups and combine it with the speed and predictability of a rapid transit type system, will potentially increase ridership on the transit system. Increased ridership on transit is a goal of every jurisdiction as the benefits associated with it are enormous. Increased ridership on transit leads to a decrease in vehicle usage during peak times which reduces congestion on the street network reducing the need to build more streets or highways, as well as aiding in the reduction of pollution. As this type of benefit is of a political nature, it is felt that this benefit could potentially be not only one of the most important benefits associated with inclusion of transit vehicles on AHS but of even greater magnitude, of AHS as a whole.

Other transit benefits are related to the operation of AHS type transit vehicles. Possible benefits may include decreased fuel consumption (especially in platooned operation), and decreased maintenance costs. Although these types of benefits may only affect the transit authorities initially, the increase in revenue may allow for reduced government subsidies to transit agencies.

Benefits of commercial vehicle AHS include improved safety, quicker trips, and more predictable travel times. While these benefits may initially accrue to the trucking fleet, society as a whole would eventually benefit through lower product costs attributable to lower overall freight and inventory costs. Cost related measures, such as "just-in-time" delivery would benefit from repeatable and predictable freight travel times.

With controlled acceleration, cruising speed, and deceleration, air quality should benefit from automation of commercial and transit trips, assuming total vehicle miles traveled (VMT) stays constant.

Task 6. Interface Requirements

The interface facilities discussed in Activity J – AHS Entry / Exit Implementation do not account for the possibility of inclusion of heavy vehicles within an AHS facility. There are a number of implications associated with heavy vehicle presence within either an urban or rural AHS interface facility. These implications include size and design of facilities required to handle various operational and physical configurations of heavy vehicles.

Urban

In order to best discuss the interface requirements of heavy vehicles, it is necessary to establish the types of vehicles permitted to use an urban AHS facility. As stated previously, heavy vehicles can be of many forms ranging from single axle to multi-unit multi-axle vehicles. Each of these vehicles will affect interface facility components due to varying size, performance, and weight characteristics.

The four primary components which the configuration of an interface facility is dependent on are (As stated in Activity J.):

- Check-in procedure.
- Demand of vehicles entering system.
- Procedure of merging vehicles.
- Physical and operational characteristics of vehicles using the system.

Due to the recommended check-in procedure, it is concluded that the interface facility will be able to handle the truck demand. As a result only the first, third, and fourth items are discussed here in relation to the inclusion of heavy vehicles within the AHS traffic stream.

Check-In Procedures

Results from Activity J indicate that delay associated with on site check-in testing will cause major operational problems for AHS users when demand is high. This finding resulted in the conclusion that these delays would be unacceptable and that "on the fly" check-in would be required. This type of check-in procedure would rely on in- vehicle monitoring and scheduled off site testing of mechanical components. A verification process at each AHS entry point would verify whether vehicles monitored systems are okay as well if scheduled testing is current.

Even though on site check-in of heavier vehicles may not cause the same operational problems as passenger cars, due to less demand, other issues such as frequency of testing affect certain types of heavy vehicle operations. Conceivably delivery trucks and transit vehicles could make several AHS trips per day. If on site testing was required at each check-in the delay associated with this testing would cause the travel time advantage on AHS to diminish. For these reasons it is concluded here that "on the fly" check-in is also required for heavy vehicles.

Presumably, a process similar to testing passenger vehicles would be implemented for heavy vehicles. However due to the difference in components between light and heavy vehicles there are issues relating to this type of procedure that requires discussion. These issues include:

- Safety implications associated with testing of load security especially on open decked units.
- Frequency of off site testing.
- Verification of truck trailer compatibility.

Safety Implications

If loads on heavy vehicles are not properly secured, they can shift or even fall off open decked units. Obviously if this situation occurred on an AHS lane, the potential consequences could be severe. As a result, it is important that procedures ensuring this does not happen are in place. Using "on the fly" check procedures discussed above, this type of scenario would be difficult to monitor and hence additional measures may be required to handle this scenario. These measures may include requirements for drivers to physically check loads prior to entering AHS or even excluding open decked vehicles from AHS.

Frequency Of Tests

Frequency of off site testing of mechanical components will affect the safety of the system as well as the benefits to the heavy vehicle users. If frequent off site testing was required to ensure safety on AHS, this may become a burden to the heavy vehicle owner. However, in an urban area the opportunity for transit and trucking companies to do testing at their own facilities may exist. This would allow testing of vehicles during non-operational periods such as at night. Although this type of testing would be convenient to transit authorities and larger trucking companies, it would limit heavy vehicle opportunities on AHS to larger type firms, potentially raising institutional issues associated with discrimination.

Verification Of Truck Trailer Compatibility

Tractors frequently drop off and pickup trailers to avoid being idle while other trailers are being loaded or unloaded. Presumably testing procedures will account for the components on a trailer as well as on the truck. Verification of systems at check-in will have to verify not only that the truck unit is communicating with the trailer, but also if off site testing is current on both truck and trailer. This leads to the point that not only do trucks have to be equipped to use AHS, but trailers will also require some equipment to be AHS compatible and both units will require testing.

Procedure For Merging Onto AHS

It is assumed that in urban areas AHS will be a dedicated facility with dedicated interface facilities. It is also assumed that passenger vehicles will travel within platoons. It is further assumed that heavy vehicles with the exception of transit vehicles will not be platooned. Therefore merging non-transit heavy vehicles onto AHS will involve accelerating the vehicle to the running speed of AHS and merging the vehicle into the AHS lane where a gap is present. This type of merging requires minimal storage on the ramps for heavy vehicles.

The procedure for merging transit vehicles onto AHS will depend on whether transit vehicles will operate singularly or in transit platoons. If buses are merged into AHS singularly (non platooned operation) , the above procedure involving heavy vehicles will apply. If transit vehicles are to be platooned, formation of these platoons must occur on the ramps as it would be operationally difficult to form transit platoons on a mixed use AHS lane as bus presence on AHS will be more sporadic than passenger vehicles. By forming platoons on the ramp, spatial requirements for bus platoons must be accounted for in the design of the interface facility.

Physical And Operational Characteristics Of Vehicles

Task 1 discusses the physical and operational differences between heavy and light vehicles. Among these differences, acceleration and size characteristics primarily affect the spatial requirements of an AHS interface facility.

AASHTO design guidelines for acceleration are based on the performance capabilities of passenger vehicles and do not account for the poor acceleration performance of heavier vehicles, as a result heavy trucks often enter traditional lanes at a much lower speed than the mainline running speeds. As traditional freeways are multilaned, the ability to pass exists and operations along the mainline do not degrade significantly during the merging operation. However in a one lane AHS the ability to pass will be non existent, therefore requiring an acceleration lane long enough to enable heavy vehicles to enter the AHS traffic stream at the AHS running speed to prevent degradation of the AHS travel speed. Table 12 shows the acceleration length requirements for a typical truck and a typical bus.

Table 12. Acceleration Length Requirements For Trucks And Buses

BUS	
Speed Change (From 0 to ... km/h)	Length Required (m) (8) (9)
80	675
90	1050
100	1550
110 *	1875
TRUCK (150 grams per watt)	
80	1225
90	1775
100	2450 **
110	3125 **

* Interpolated as engine governed speed at 103 km/h.
** Interpolated from graphs.

The acceleration length requirements shown in table 12 raise a key issue. Typical spacing of urban interchanges are approximately 1600 m which corresponds to the acceleration lengths required for buses to reach 100 km/h and trucks to reach 90 km/h. This implies that if AHS interface points are spaced similar to traditional interchanges, a separate auxiliary lane would be required along the entire urban corridor for truck/transit use and entering/exiting passenger vehicles would be required to weave through the auxiliary lane. As this could potentially be very expensive both in construction and right-of-way acquisitions, solutions are required to determine the best approach to handle transit and commercial vehicles.

Potential solutions to this problem include:

- Not allowing transit or commercial vehicles on the AHS.
- Limited access points for transit or commercial vehicles.
- Commercial and transit vehicles to access only at terminus locations.

While exclusion of commercial vehicles from using urban dedicated AHS may be possible, especially if the demand for commercial vehicles is low, exclusion of transit vehicles would be contrary to the present campaign to reduce single occupant vehicle usage. For this reason the first item does not appear to be an acceptable solution. The second and third items provide the ability to include transit and commercial vehicles onto AHS. The second item would limit access to heavy vehicles to select locations. This solution would still require the long acceleration lanes (length would depend on the type of vehicle permitted on the facility) but would not require a continuous auxiliary lane as the number of these ramps equipped to handle the heavy vehicles would be limited.

The third item would limit access to only the terminus points. This solution would limit transit trips on AHS to longer trips (express buses). By providing access to buses and commercial vehicles at terminal points no special acceleration lanes would be required as mainline traffic would be accelerating from the same speed as the heavy vehicles.

In addition to performance differences, the physical size difference between heavy and light vehicles requires geometric designs of interface facilities to accommodate maneuvers associated with long or multi-unit vehicles. Interface facilities described in Activity J allow for vehicles that do not meet entrance requirements to be guided back onto the non-AHS roadway. The spatial requirements for this type of maneuver are dependent on types of vehicles using the facility. Longer vehicles, whether multi-unit or not, require much larger roadway radii for maneuvers than passenger vehicles. It is difficult to quantify these requirements without designing the facility; however, the minimum outside turning radius of a 17.1 m tractor-semitrailer combination is 14 m whereas a design passenger car has a minimum turning radius of 8 m.

Rural

Interface requirements for heavy vehicles using rural AHS facilities are much different than urban requirements. Discussion in Activity J – AHS Entry/Exit Implementation assumes RSC 3 (rural) interfacing includes using traditional freeway ramps and a transition lane (developed as part of AHS) for deployment.

Under this type of interface, vehicles would enter a traditional freeway using existing ramps and then proceed to a transition lane. Once in the transition lane, verification of systems (similar to “on the fly” check-in) would occur before deployment to a space time slot. Utilization of this type of deployment for heavy vehicles would eliminate the need for a long acceleration lane as acceleration could take place on the traditional freeway lanes prior to entering the transition lane.

The same issues associated with “on the fly” check- in for heavy vehicles in urban areas apply to rural interfacing as well. In addition, there may be concern over the frequency of testing with respect to the potentially long trips associated with rural travel. Perhaps a policy would be necessary which would require exiting AHS after so many hours of continuous operation on AHS in order to test components not easily monitored by the vehicle, i.e. loads, brakes, etc. As discussed in task 3, similar policies exist presently for trucks hauling hazardous cargo.

Another issue associated with interfacing and testing is the availability of off site testing, especially in rural areas. For example, if for some reason a truck was denied access to AHS after exiting AHS in a rural area for fuel, presumably the vehicle could be repaired depending on the reason for failure. However if an off site test was required before access to AHS could occur and no testing facility existed, the truck would be forced to use conventional freeway lanes. If this was a regular occurrence, it may become an inconvenience to the trucker, potentially affecting heavy vehicle demand on AHS. This raises the issue of whether testing facilities can be operated by the private sector, hence eliminating costs of constructing off site testing facilities.

Exit Requirements

Rural exit procedures will require similar infrastructure as entrance facilities. A transition lane would be used to determine if both driver and vehicle are able to resume manual control. Presumably this would take place well before the desired freeway exit so the heavy vehicle operator would be able to adjust to driving conditions prior to negotiating lane changes with traditional traffic.

CONCLUSIONS

The physical and operational characteristic of commercial and transit vehicles differ significantly for passenger vehicles. As a result, the implication of these differences must be accounted for in the design and operation of AHS facilities that accommodate such vehicles. Generally physical characteristics relate to the infrastructure while the operational characteristic refer to the operations on the AHS facility. Physical characteristics of heavy vehicles require additional infrastructure compared to a passenger vehicle only facility. These additions include; wider lanes, increased vertical clearance, and increased pavement thickness. In addition to the physical differences between heavy and light vehicles, operational parameters of heavy vehicles including; acceleration, deceleration, effect of grades, capacity, comfort and safety, off tracking, trailer sway, load shifting, and use of automatic transmissions; may affect overall operation of a mixed use AHS lane (presumably passenger vehicles).

Although provision of separate AHS lanes for heavy and light vehicles may alleviate many of the issues associated with the physical and operational differences between these two types of vehicles, the costs associated with this may be prohibitive. However by comparing the demand and the overall operation of the lane, a combination of separate and shared lanes may provide the most cost effective solution of providing access to heavy vehicles without adversely affecting overall operations. In rural areas capacity is not a concern and the nature of the rural AHS is such that each vehicle is adequately spaced so inclusion of heavy vehicles would not hinder operations. In areas where terrain severely hinders heavy vehicles operations a separate lane could be provided in order for overall operations not to degrade. In urban areas where high capacities are expected with AHS, public concerns may exist for inclusion of heavy vehicles on the AHS lane. However it is felt that transit vehicles could share the same lane as passenger vehicle as their operational characteristics are not as adverse as trucks. Inclusion of transit on a AHS lane will take away some passenger vehicle capacity, however depending on demand of buses, overall passenger throughput could be increased by a factor of four.

In order for heavy vehicles to be included on AHS without separate lanes, a policy regarding headways between vehicles needs to be developed. This policy should address the following issues; multiple vehicle operation modes, exclusive passenger vehicles headway policy, actual and perceived risks associated with headway spacing, variations in vehicles performance, human factors, relationships to AHS subsection, interface to ITS, and institutional factors.

All the issues associated with inclusion of commercial and transit vehicles on AHS are only valid if demand for these vehicles to use an AHS facility exists. There are, in general, different issues relating to demand for both rural and urban situations. In urban areas, trip characteristics of transit vehicles match well with the expected operations of AHS hence a potential for high demand exists. Trip characteristics of local trucks whether large or small, are such that it is doubtful that AHS will provide any benefits and as a result demand from these types of vehicles is generally expected to be low. Certain types of intercity/interstate trucks will find urban AHS beneficial especially in intermodal type cities. In rural areas, issues affecting demand for trucks include; travel time savings, safety, fuel consumption, maintenance cost, comfort and convenience, arrival predictability, initial equipment cost, and usage costs. In order for demand of heavy vehicles to exist in rural areas, the benefits associated with these issues must far out weigh the negative aspects of these issues. The issues presented here are general in nature and may not apply to all areas. Therefore, demand issues should be done on a site specific basis.

Although the costs associated with inclusion of heavy vehicles on AHS are high, the benefits of inclusion of certain types of heavy vehicles, especially transit, are enormous. The most important benefit associated with transit use is the comfort and convenience for passengers leading to increased ridership potentially reducing congestion. Other potential benefits include lower operating costs, fuel efficiency, and decreased air pollution.

Interface requirements for heavy vehicles at AHS facilities must include check-in procedures that limit delay in order for the full benefits of AHS to be realized. However, due to the difference in components between light and heavy vehicles, light vehicle testing procedures must be modified to address the following heavy vehicle issues: safety implication associated with testing of load security, frequency of tests, and verification of truck and trailer compatibility. In addition to the additional testing required between heavy and light vehicles, infrastructure requirements at interface points are much different. The acceleration of heavy vehicles requires acceleration lengths corresponding to urban interchange spacing (1600 m) in order to avoid degradation of the mainline AHS traffic. Solutions developed for this problem include: limited access for transit and commercial vehicles, access at only terminus points, and exclusion of certain types of heavy vehicles in urban areas.

The same methods and issues associated with urban testing of heavy vehicles also apply to rural testing. However, the availability of off site testing is a concern as situations may arise that require testing in rural locations where the cost of providing this type of service may not be cost effective. Infrastructure requirements for rural areas differ significantly as it is assumed that access to AHS will be via existing freeway lanes and ramps, hence eliminating the need for an acceleration lane.

REFERENCES

1. Transportation Research Board, Highway Capacity Manual–Special Report 209, National Research Council, Washington, DC, 1985.

2. Discussion with Bill Spreitzer of General Motors, Warren, Michigan, April 1994.

3. Interview with Pete Devlin of the California PATH Program, University of California, July 1994.

4. Interview with company representative of J. B. Hunt Corporation, Richmond California, July 1994.

5. M. Kirkpatrick, "The Role of Critical Incidence and Prevalence Studies in Truck Safety Research," Automotive Crash Avoidance Research, Special Publication 699, Society of Automotive Engineers, Warrendale, Penn., 1987, pp. 19-29.

6. J. P. Hicks, "The Sensory Truck Tire," New York Times, July 5, 1992, p. F9.

7. G. R. Vallette, et al, "The Effect of Truck Size and Weight on Accident Experience and Traffic Operations," Final Report, Biotechnology, Inc., Falls Church, Va., FHWA, US Department of Transportation, 1980.

8. Institute of Transportation Engineers, Transportation and Traffic Engineering Handbook, 1982.

9. T. D. Hutton, "Acceleration Performance of Highway Diesel Trucks," Society of Automotive Engineers Inc., 1971.

BIBLIOGRAPHY

American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, 1990.

Delco Systems Operations, "Activity D – Lateral and Longitudinal Control Analysis," AHS Precursor Systems Analysis Report, November 1994.

Delco Systems Operations, "Activity H – AHS Roadway Deployment Analysis," AHS Precursor Systems Analysis Report, November 1994.

Delco Systems Operations, "Activity J – AHS Entry/Exit Implementation," AHS Precursor Systems Analysis Report, November 1994.

Delco Systems Operations, Activity I – Impact of AHS on Surrounding Non-AHS Roadways," AHS Precursor Systems Analysis Report, November 1994.

Homburger, W. S., and J. H. Kell, Fundamentals of Traffic Engineering, 12th Edition, Institute of Transportation Studies, University of California at Berkeley, October 1989.