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# **Definition and Evaluation of Bus and Truck Automation Operations Concepts: Final Report**

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*San José State University*

**California PATH Research Report  
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**Definition and Evaluation of Bus and  
Truck Automation Operations Concepts:  
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# **DEFINITION AND EVALUATION OF BUS AND TRUCK AUTOMATION OPERATIONS CONCEPTS**

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## **ABSTRACT**

Traffic congestion will continue to worsen and likely worsen at a faster rate than ever. People throughput and freight throughput have become critical issues for California and the rest of the nation. PATH has funded a research project entitled “Definition And Evaluation of Bus And Truck Automation Operations Concepts,” proposed by the authors. This report summarizes the major findings of the research project. During the one-year project, we reviewed literature and developed operating concepts for both urban bus automation and inter-city truck automation. We also selected a small number of most promising operating concepts for urban bus automation and inter-city truck automation, both with variations and intermediate steps.

On urban bus automation, we selected one unprotected automated busway system (ABUS) for city operations and two operating concepts for automated bus operations on or along a freeway. All or a subset of these three concepts can be integrated to form other operating concepts. On truck automation, we selected two operating concepts for a protected inter-city truck-AHS. These concepts describe how automated systems involving buses or trucks operate as a system and how they interact with the surrounding transportation systems. These systems, if implemented, will revolutionize the current bus or truck transportation systems. They certainly cannot be achieved suddenly, and hence can be regarded as end-state systems. Since these end-state operating concepts are intended for real-world implementation and such implementation requires the participation of many stakeholders, any creditable end-state operation concept must be accompanied by and even justified with credible deployment sequences.

We developed deployment sequences for these operating concepts to demonstrate the deployability of these concepts and to explain how to “get there from here.” We developed schematic descriptions for these concepts as well as their conventional counterparts. We also identified major benefit-cost elements that distinguish these concepts from their conventional counterparts.

## **DEFINITION AND EVALUATION OF BUS AND TRUCK AUTOMATION OPERATIONS CONCEPTS**

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### **EXECUTIVE SUMMARY**

Traffic congestion will continue to worsen and likely worsen at a faster rate than ever. People throughput and freight throughput have become critical issues for California and the rest of the nation. An automobile AHS has high potential but its successful deployment may actually depend on the successful deployment of automation technologies on buses and trucks first. More importantly, a bus-truck AHS has high potential in its own right in increasing the efficiency of moving people and freight. This one-year project sought to develop and evaluate operating concepts for a fully automated bus-truck AHS as well as intermediate steps facilitating the deployment of such an AHS. It utilized and built upon the large amount of information resulting from many years of research at PATH on AHS as well as information on truck and bus automation accumulated through efforts taking place around the world, e.g., the CHAUFFEUR Project.

This was a one-year research project. The performance period was intended to synchronize with the 2003 Demo in such a way that the findings could be used as input to the 2003 Demo effort. Among the information needs for the 2003 Demo is benefit-cost comparisons between automated urban bus operations and its conventional public-transit alternatives and between inter-city truck-AHS and its conventional freight-transportation alternatives. The conventional public-transit alternatives include light-rail systems and busway systems. We compared some aspects of the implementation of automated bus operations to their counterparts of an existing light-rail system in California; we also compared the automated bus operations to a conventional busway with respect to similar aspects. The conventional freight-transportation alternatives include addition of a conventional lane (to accommodate all vehicle types), addition of a truck lane, addition of an exclusive AHS truck lane (of three different configurations), and intermodal rail.

Due to the complexity of the issues involved in developing and evaluating bus-truck AHS and the size of the proposed budget, the scope of research was limited. The research work involved development of system design options, development of operating concepts and then identification of some benefit-cost elements for a more detailed benefit-cost analysis in the future. The focus was on those major cost-benefit elements that differ significantly among the alternatives. (Some of the actual numeric estimates were beyond the scope of this research, but will be a subject of the Phase II of this project to be conducted in the 2002-2003 PATH fiscal cycle.) Concepts were developed and evaluated for transportation corridors only. Only a limited number of essential aspects of operating concepts were addressed in detail while the rest, e.g., safety and technological feasibility, are addressed in a perfunctory manner. Demand was considered as a parameter, rather than to be derived based on demand modeling.

We reviewed literature and developed operating concepts for both urban bus automation and inter-city truck automation. We also selected a small number of most promising operating

concepts for urban bus automation and inter-city truck automation, both with variations and intermediate steps.

On urban bus automation, we selected one unprotected automated busway system (ABUS) for city operations and two operating concepts for automated bus operations on or along a freeway. All or a subset of these three concepts can be integrated to form other operating concepts. On truck automation, we selected two operating concepts for a protected inter-city truck-AHS, an open system and a closed system. The open system accommodates any properly equipped truck while the closed system can be used by only the tractors and even the trailers operated by selected AHS haulers. These concepts and their deployment sequences are summarized below. To demonstrate the deployability of these concepts and explain “how to get there from here,” we describe promising steps leading from the current transportation systems to the proposed systems.

### **AUTOMATION OPERATING CONCEPTS FOR URBAN BUS AUTOMATION**

#### **An Unprotected Urban Automated Busway System (ABUS)**

The proposed unprotected ABUS system and the proposed deployment steps are summarized in the following table.

**Table E- 1: A Four-step Deployment Sequence Toward the Proposed ABUS system**

<b>Step</b>	<b>Main Features</b>	<b>Main Benefits</b>	<b>Main Traffic Issues</b>
<b>1</b> Conventional Busway (with sufficient right-of-way)	<ul style="list-style-type: none"> <li>• Bus operations on light-rail right-of-way</li> </ul>	<ul style="list-style-type: none"> <li>• Same bus for line-haul and collection/distribution</li> </ul>	<ul style="list-style-type: none"> <li>• Scattered buses disturbing surrounding traffic</li> </ul>
<b>1'</b> Busway with Automation to Enable Bus Operations on Narrow Right-of-way	<ul style="list-style-type: none"> <li>• Automated precision turning/automated precision lane-changing</li> <li>• Automated lane-keeping</li> <li>• Automated bus-following</li> <li>• Automated precision docking (if desired)</li> </ul>	<ul style="list-style-type: none"> <li>• Same bus for line-haul and collection/distribution</li> <li>• Automation enabling busway operations on narrow right-of-way</li> </ul>	<ul style="list-style-type: none"> <li>• Scattered buses disturbing surrounding traffic</li> </ul>
<b>2</b> Manual Bus Convoying Through ITS	<ul style="list-style-type: none"> <li>• Clustering buses to reduce disturbance via ITS technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of disturbance to surrounding traffic due to signal preemption or priority</li> </ul>	<ul style="list-style-type: none"> <li>• Possible excessive disturbance as demand grows</li> </ul>
<b>3</b> Automated Closely-spaced Convoying (An ABUS)	<ul style="list-style-type: none"> <li>• Automated closely-spaced convoying</li> <li>• Automated precision turning/automated precision lane-changing, automated lane-keeping, automated vehicle-following and precision docking if not already implemented</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of disturbance to surrounding traffic due to signal preemption or priority</li> </ul>	<ul style="list-style-type: none"> <li>• Safety</li> </ul>
<b>4</b> Driverless Bus-following (Another ABUS)	<ul style="list-style-type: none"> <li>• Absence of driver on trailing buses</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of labor cost</li> </ul>	<ul style="list-style-type: none"> <li>• Safety</li> </ul>

### **A Protected Urban Bus-AHS on Freeway Median**

The differences between this bus-AHS operating concept and the ABUS concepts just described result from two facts: protection of the right-of-way and the location of the right-of-way in the median of a freeway. We describe the differences in their deployment sequences.

Step 1 or Step 1' still applies. Access to and egress from the bus-AHS can be made through on- and off-ramps connecting the left-most lane of the regular freeway directly with the bus-AHS lane. (New dedicated ramps connecting the bus-AHS lanes directly to the city streets can be built, but is not necessary, as will be explained later.) Disturbance to surrounding traffic is no longer a concern for bus-AHS, and, therefore, Step 2 is no longer necessary. Step 3 still applies but is motivated by a different benefit – less fuel consumption. Step 4 still applies for the same reason – reduction of labor cost. The driver of a bus can alight the bus at the first bus-AHS station along the route after driving the bus manually from the conventional freeway to the bus-AHS. When a bus needs to depart the bus-AHS when it reaches the last bus-AHS station on its route, a driver will board the bus and drive it off the bus-AHS.

### **Conventional “Freeway Flyer” Bus System Plus Protected Transfer Stations on Freeway Median**

This concept is similar to the existing concept of “Freeway Flyer” already popular in Los Angeles, e.g., The Harbor Transitway, and some other highly congested metropolitan areas. The freeway flyer service is characterized by using the same bus to perform local collection and distribution of passengers at a city or neighborhood and to transport the passengers to and from an activity center, e.g., Downtown LA. One disadvantage of this operation is that there are no intermediate stops and hence transfer opportunities on the freeway. (Having transfer stations off the freeway may have significantly adverse effect on the operational efficiency.) This concept is motivated by this fact and the possibility that sufficient right-of-way for accommodating two lanes of automated bus traffic throughout the length of segment of a corridor freeway (as required for the bus-AHS concept) may not be available. This concept however does require the availability of right-of-way at selected locations on the median of the freeway to accommodate bus transfer stations along the freeway. Automation technologies, particularly the lateral vehicle control technologies, may actually be required for the realization of such service concepts on urban freeways with little right-of-way to spare for such transfer stations.

## **AUTOMATION OPERATING CONCEPTS FOR INTER-CITY TRUCK AUTOMATION**

We propose in this report two operating concepts for an “end-state” AHS dedicated to inter-city trucking. Our approach is needs-driven and technology-steered. We first identify the needs of the long-haul trucking industry and the major concerns of key stakeholders. Based on customer needs, stakeholder concerns and available or promising truck-automation technologies, we then develop design options for several key aspects of truck-AHS operations. After comparing the relative merits of these options, we develop both operating concepts and their deployment sequences to satisfy the customer needs.

A truck-AHS, if eventually realized, will be a revolution in freight transportation. Its deployment requires a number of revolutionary measures on infrastructure improvement, roadway technology,

truck technology, system operations, operator training, liability distribution, public policy, etc. A key ingredient of a truck-AHS is a dedicated truck-lane, and a key operating characteristic is a truck-train that is electronically controlled and linked and is supervised or driven by the driver of the lead truck. The truck-train will travel on an exclusive lane separated from the manual traffic with a physical barrier.

A key position of the authors is that a dedicated truck-lane must exist before transportation agencies and the general public will commit to or even begin to accept the concept of truck automation. More precisely, a truck-lane alone must be able to provide sufficient benefits to justify its dedication or construction, without the help of the potential further benefits to be generated by truck automation. This position is motivated by the tremendous amount of risk involved in a commitment to a truck-AHS when much uncertainty exists about its possible eventual deployment.

Many feasibility studies for truck-lane dedication or construction have been conducted for busy freight corridors in the United States, but none have been built. A very recent such feasibility study can be found in [KAKU Associates, 2001]. A common conclusion of such feasibility studies is that the projected user fees can defray only a fraction of the total construction and operating cost, and the conclusion is based on the assumption of conventional trucking. However, this conclusion could have been significantly different if the feasibility studies included longer combination vehicles (LCVs) in the scope. LCVs are longer than conventional trucks, and hence can significantly increase the productivity of the driver and the equipment. Such an increase in productivity would yield significant benefits for the long-haul trucking industry, and that industry has been seeking relaxation of rules restricting the use of LCVs for this purpose. Stakeholder concerns against the use of LCVs include increased safety hazards to adjacent automobiles and increased damage to the roadway. Safety concerns can be minimized or eliminated with a physically separated truck-lane; the concern of excessive pavement damage can be minimized with strengthened pavement formulated specifically for such a truck lane. Physically separated truck-lanes that accommodate LCVs may hold the key to successful deployment of truck-lanes as well as to successful deployment of a truck-AHS later on.

### **General Features of an Inter-city Truck-AHS and Major Design Options**

The truck-AHS is placed in the median of an inter-city freeway. Access to the truck-AHS is controlled so that the automated truck traffic is separated from the rest of the traffic with physical barriers. The system is intended for long-haul freight transportation, and access points are spaced at large intervals, e.g., 100 miles. Trucks form closely spaced convoys so as to require only one driver in the lead truck. When compared to conventional long-haul trucking, it drastically reduces labor cost, capitalizes on reduced wind-drag for fuel efficiency (Ulmer, 1999), and increases mainline capacity. Moreover, this may also increase the utilization of equipment because the productivity of a trailing truck in a convoy is no longer directly tied to the presence of a driver on that truck, who is under strict work-hour restrictions.

Three key aspects are (a) the evolution of the composition of a (closely spaced automated) convoy on a truck-AHS, (b) integration of AHS and local collection-and-distribution operations, and (c) bridging rural truck-AHS sections through an urban area. Other possible important



aspects include truck-train scheduling by the AHS operator, truck-train organization through matching of departure time, origin-destination, power, braking capability, etc.

### **A Protected Inter-city Truck AHS Open to All Properly Equipped Trucks**

In this open system, any properly equipped trucks, including LCVs, can use the system. A convoy entering the mainline may join, at or near an on-ramp, another convoy already traveling on the mainline from the rear of the mainline convoy; a portion of a convoy traveling on the mainline may split off, at or near an off-ramp, to exit. In addition, no driver is required for the lead truck of the entering convoy or the exiting portion. Note that such convoy joining or splitting is restricted to take place only at or near an on- or off-ramp, respectively, and that these locations are closely monitored by the AHS operators, with the assistance of advanced technologies, to ensure absence of safety-impacting debris and to respond to possible non-nominal events.

The proposed open-system concept for a protected Inter-city Truck- AHS and the proposed deployment steps are summarized in the following table.

**Table E-2: A Six-step Deployment Sequence for the Proposed Open-System Truck-AHS**

<b>Step</b>	<b>Main Features</b>	<b>Main Additional Benefits</b>	<b>Main Issues</b>
O-1. Proof of Technology and Market Acceptance of Advanced Warning Technologies for Trucks	<ul style="list-style-type: none"> <li>• Range sensing and frontal collision warning</li> <li>• Vision-based Lane-departure warning</li> </ul>	<ul style="list-style-type: none"> <li>• Use on and off highways</li> <li>• Safety</li> <li>• Technology maturation</li> <li>• Price drop</li> </ul>	<ul style="list-style-type: none"> <li>• Proof of technology</li> <li>• Market acceptance</li> </ul>
O-2. Proof of Technology and Market Acceptance of (Non-Simultaneous Use of) Hands-off and Feet-off Automation Technologies for Trucks	<ul style="list-style-type: none"> <li>• Feet-off highway operations</li> <li>• Hands-off highway operations</li> <li>• Only one of the two features to be activated at any time; simultaneous use prohibited to avoid driver disengagement</li> </ul>	<ul style="list-style-type: none"> <li>• Driver stress reduction due to partial automation</li> <li>• Features like automated transmission reducing driver training requirements and expanding labor pool</li> <li>• Technology maturation</li> <li>• Price drop</li> </ul>	<ul style="list-style-type: none"> <li>• Ability of the driver to react to unexpected events by interfering or overriding partial automation</li> <li>• Possible abuse on city streets</li> <li>• Proof of technology</li> <li>• Market acceptance</li> </ul>
O-3. Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation	<ul style="list-style-type: none"> <li>• Construction or dedication of a physically separated truck lane, for safety, on or adjacent to freeway median</li> <li>• Dedicated on- and off-ramps and staging areas constructed at access points</li> <li>• Access to the truck lane in the median</li> </ul>	<ul style="list-style-type: none"> <li>• Higher freight throughput</li> <li>• Safety due to less mixing of light and heavy vehicles</li> <li>• Significantly higher productivity of the LCV driver and the equipment as well</li> <li>• Higher user fee justified by significant increase of</li> </ul>	<ul style="list-style-type: none"> <li>• Acceptance by the general public</li> <li>• Amount of toll charge</li> <li>• Possible protest by the rail industry</li> <li>• Legislative acceptance of allowing LCVs on the truck lane</li> <li>• Demand sufficiency to justify limited access only through staging areas</li> </ul>

	<p>only through the staging areas (Direct ramps linking the truck lane to the left lane of a conventional two-lane (each-direction) freeway can be investigated)</p> <ul style="list-style-type: none"> <li>• Operation of LCVs allowed only in the truck lane and the staging areas to increase trucking productivity</li> <li>• Sufficiently long to ensure “economy of distance” for LCV operations</li> </ul>	<p>productivity</p> <ul style="list-style-type: none"> <li>• Higher user fee increasing the likelihood of construction or dedication of a truck lane</li> </ul>	<ul style="list-style-type: none"> <li>• Potential for complete blockage by a single disabled truck, even if the combined width of the truck lane and the shoulder is sufficiently wide to allow lower-speed passage through the incident area</li> <li>• The provision of passing lanes if different cruising speeds are allowed.</li> <li>• Flow hindrance by trucks with slower cruising speeds if otherwise.</li> </ul>
O-4. Automated Driving in Mixed Traffic on the Truck Lane	<ul style="list-style-type: none"> <li>• Installation of magnetic markers or other “active” markers on the truck lane</li> <li>• Simultaneous hands-off and feet-off driving supported</li> <li>• Driver’s responsibility for safe operations</li> <li>• Longitudinal mixing with manually driven trucks</li> <li>• Vehicle-to-vehicle and vehicle-to-infrastructure communication required for all trucks using the truck lane to ensure safety in traveling and merging</li> </ul>	<ul style="list-style-type: none"> <li>• Redundancy in lateral guidance for higher safety</li> <li>• Stress reduction for (trained) drivers of automated trucks</li> </ul>	<ul style="list-style-type: none"> <li>• Safety of automated driving</li> <li>• Safety of mixing on mainline</li> <li>• Safety of merging between automated and manual truck traffic</li> </ul>
O-5. Automated Closely-spaced Truck Convoying in Truck Lane Accessible Only From Staging Areas	<ul style="list-style-type: none"> <li>• Exclusive use by automated trucks, including automated LCVs</li> <li>• Closely-spaced truck convoying</li> <li>• A “train system” of electronically linked and self-propelled trucks</li> <li>• If direct ramps linking the truck lane to the left lane of a conventional two-lane (each-direction) freeway were provided, they should</li> </ul>	<ul style="list-style-type: none"> <li>• Better fuel efficiency</li> <li>• Higher mainline capacity</li> <li>• Tightly spaced trucks leaving more space between convoys for safer and more efficient merging</li> <li>• Higher safety for mainline operations due to the homogeneity of traffic (of trucks only)</li> <li>• Higher merging efficiency due to the homogeneity</li> </ul>	<ul style="list-style-type: none"> <li>• Demand sufficiency to justify the dedication of truck lane to the exclusive use by automated trucks only.</li> <li>• Amount of toll charge</li> <li>• Modal-change overhead (between the conventional trucking and automated closely-spaced truck convoying)</li> <li>• Safety of closely-spaced truck convoying</li> <li>• Possible protest by the</li> </ul>

	be closed.		rail industry
O-6. Automated Convoying With no Drivers on Trailing Trucks of a Convoy	<ul style="list-style-type: none"> <li>• Driverless operations for trailing trucks</li> <li>• A possible new class of carriers: AHS Hauler for hire to haul other companies' trucks or just trailers; scheduled AHS Hauling services</li> </ul>	<ul style="list-style-type: none"> <li>• Significantly higher driver productivity as well as equipment productivity</li> </ul>	<ul style="list-style-type: none"> <li>• Safety of driverless operations of the trailing trucks</li> <li>• Modal-change overhead (between the manned "truck trailing" and driverless truck trailing)</li> <li>• Amount of toll charge</li> <li>• Possible protest by the rail industry</li> </ul>

### A Protected Inter-city Truck AHS Open to Only AHS Haulers

In this system, only tractors operated by a small number of qualified fleet can use the system. A convoy remains intact throughout its travel on the truck-AHS from the entry to the exit points. No joining by other convoys to form a longer convoy on the AHS or splitting into multiple smaller convoys on the AHS is allowed. The system not only allows end-to-end haulers to offer the end-to-end service (between the shipping docks of the shipper and the consignee, i.e., the receiver) but also allows the line-haul service and service of local collection and distribution to be performed by separate companies: AHS haulers and local feeder haulers. (These haulers may haul exclusively their own freight, but may also be contractors hauling for another carrier.) Note again that this truck-AHS is open only to the tractors operated by AHS haulers, which are qualified and designated as exclusive entities operating freight transportation on the truck-AHS.

The deployment sequence for the closed-system operating concept may be shorter, primarily because there is no need for the general long-haul trucking industry to accept the automation technology and to equip a sufficient number of trucks so that the dedication of a truck lane can be justified. Moreover, several steps required for the open-system operating concept regarding technology development and acceptance are consolidated into one step in the sequence for the deployment of the closed-system operating concept. This may lead to faster deployment, however at the expense of not opening the system to the general long-haul freight industry. The proof-of-technology and market acceptance step for this closed-system concept is very different from its open-system counterpart. The proof-of-technology component, which may actually be considered as part of research and development rather than deployment, is critical due to (a) the high reliability requirement for truck-AHS operations, (b) the extensive technology requirements and (c) the need to develop the technologies as a bundle, rather than increments. However, this proof-of-technology component may take place "off-site" and in parallel with infrastructure improvement. Market acceptance is still required, but is required of different and a much smaller number of institutions and is of different nature.

The proposed four-step deployment sequence and their differences from their open-system counterpart are summarized in Table E-3.

**Table E-3: A Four-step Deployment Sequence for the Proposed Closed-System Truck-AHS**

<b>Step</b>	<b>Differences, if any</b>
C-1: Proof of Technology and Market Acceptance	<ul style="list-style-type: none"> <li>• Proof of all component technologies is consolidated into one step.</li> <li>• Neither splitting a convoy into two nor joining two convoys into one is supported on the AHS.</li> <li>• Market acceptance is required by the much smaller sector of potential AHS haulers about equipping their trucks and operating the trucks on the AHS and by the long-haul trucking industry in general about contracting with AHS haulers to move its freight, not about equipping their trucks and operating the trucks on the AHS.</li> </ul>
C-2: Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation	The same as Step O-3.
C-3: Automated Driving in Mixed Traffic on the Truck Lane	<ul style="list-style-type: none"> <li>• Essentially the same as Step O-4 except that the AHS haulers of the closed system equip, possibly gradually, their AHS fleet with automated tractors and devices that can be attached to the trailers easily to enable communication with the tractor and the following convoys. Such a device may already be there if the AHS hauler rents or leases its own trailers for more efficient mode-change.</li> <li>• This step may last much shorter than its open-system counterpart because the deployment of the technology involves one or a small number of AHS haulers, not the general long-haul freight industry.</li> </ul>
C-4: Automated Closely-spaced Truck Convoying in Truck Lane Accessible Only From Staging Areas, with no drivers required on trailing trucks of a convoy	<ul style="list-style-type: none"> <li>• Essentially the same as Step O-5 and Step O-6 combined except the following: Since only AHS haulers can use the AHS, fitness checking for those trucks wishing to enter the AHS may be performed at the haulers’ maintenance facilities and/or real-time at all times, therefore fitness checking and the associated space at the staging area may not be required.</li> <li>• This step supports, for mainline travel, automated convoying with no drivers required on any trailing truck (i.e., the tractor plus the trailers) of the convoy. Note that this is part of Step O-6, not Step O-5. Also note that this technology would have been proven in Step C-1 and hence could be implemented immediately after mixed-traffic operations is discontinued.</li> </ul>

Due to the much smaller fleet of AHS-equipped tractors required for this closed-system operating concept than the open-system operating concept, maturation of technology may require more up-front investment in research and development, and equipment costs may be higher during the proof-of-technology step (i.e., Step C-1). However, since these costs can be distributed across all the carrier users, and the equipment utilization would be much higher, these cost issues may not be a “show-stopper.”

**MAJOR BENEFIT-COST ELEMENTS FOR COMPARISON BETWEEN AUTOMATION CONCEPTS AND THEIR CONVENTIONAL COUNTERPARTS**

We identified key benefit-cost elements of these operating concepts for a more detailed benefit-cost analysis in the future. The focus was on those major cost-benefit elements that differ

significantly among the alternatives defined earlier as the scope of this project. Detailed benefit-cost analysis will be the focus of Phase II of this project.

## 1. INTRODUCTION

Future traffic congestion at unimaginable levels has been predicted by many. With the completion of the construction of the National Highway System and the general lack of available right-of-way for adding lanes on existing freeways in the largest metropolitan areas around the nation, the predictions have received more and more attention. Increasing people throughput has become a necessary component of any credible solution to the current and future transportation problems.

California would be the sixth largest economy in the world if it were a nation. Goods movement is a critical component of California's prosperity. Recognizing the importance of goods movement in the state, Caltrans developed the Statewide Goods Movement Strategy as one of the two focal areas of the 1998 California Transportation Plan (CTP) Update (Caltrans, 1998a and 1998b). Increasing the efficiency of goods movement in the state has also become a necessary component of any credible solution to the current and future transportation problems.

Automated driving on freeways has been treated primarily as a means to increase automobile throughput on the nation's highways. The high potential for increasing automobile throughput is accompanied by a high level of risk resulting from the complexity of the technical, institutional and political issues involved in the design of a deployable system and in its staged deployment. The investigators believe that transit- and/or truck-oriented automated highway systems (AHS) could be a more promising concept, not only as an "end-state" by itself but also as an intermediate step toward the implementation of an AHS accommodating also automobiles.

Given the apparent need to improve people throughput on the nation's surface transportation systems and the various difficulties associated with the construction of large-scale urban commuter-rail systems, the concept of Bus Rapid Transit (BRT) systems has received much attention recently. A bus AHS can actually be viewed as a mature BRT system, and the principal investigator proposed a transit service for AHS debut in a paper published in the IVHS Journal in 1995. (The journal has been renamed as the ITS Journal.)

PATH funded a research project entitled "Definition And Evaluation Of Bus And Truck Automation Operations Concepts," proposed by the authors. This report summarizes the major findings of this research project. This report is organized as follows. Section 2 provides project information briefly. Section 3 describes and justifies the key elements of an operating concept for a bus-truck AHS. Section 4 summarizes the operating concept selected for urban bus automation, and Section 5 describes a sequence of four steps for the deployment of the operating concept. Two additional bus-automation operating concepts and their deployment sequences are also discussed in Section 5. Section 6 discusses the needs of the long-haul trucking industry; these needs drive the development of truck-AHS operating concepts as well as the development of their deployment steps. Section 7 discusses several major design options for inter-city truck automation. Section 8 proposes two operating concepts, and Section 9 summarizes their deployment sequences. Section 10 addresses possible deployment sites for the proposed truck-AHS and key deployment issues associated with the two deployment sequences. Section 11 provides the foundation for the comparative benefit-cost analyses to be performed within the scope of this project as well as for more detailed analyses to be conducted in the future. Section 12 identifies and defines major benefit-cost elements for comparison between the proposed automated bus systems and their conventional counterparts. Section 13 summarizes major

benefit-cost elements for comparison between the proposed truck-AHS and their conventional alternatives. Concluding remarks are given in Section 14.

## **2. PROJECT INFORMATION**

In this section, we briefly describe

- the scope of research
- related research
- research approach.

### **2.1 Scope Of Research**

A major milestone for PATH AHS research is the 2003 Demo. Through discussions with PATH management during the revision process of this research proposal, we learned the key information needs for the Demo, and agreed to the following scope of research:

#### **For Both Bus AHS and Truck AHS:**

- A corridor and not a network
- Drastic throughput gain not expected, but treated as a possible goal for the future
- Essential aspects of operations concepts (See Section C.1 below.)
- Evaluation:
  - Cost and Benefit:
    - Development of the basis for a benefit-cost analysis
    - Identification of the major benefit-cost elements
  - Technology: functional specification for the required technology, without any study of technology feasibility
  - Safety: an “intuitive” check of system safety (e.g., fail-safe capability), with safety evaluation set aside for the future
  - Demand as a parameter, with no demand modeling

#### **For Bus AHS:**

Relative Cost and benefit of the following key alternatives:

- Comparison between:
  - conventional light-rail system (involving downtown segments)
  - bus AHS, on current light-rail right of way or on planned new light-rail lines
- Comparison between:
  - bus AHS, unrestricted to light rail sites
  - busway without automation

#### **For Truck AHS:**

### Cost and benefit of the following key alternatives

- Adding a conventional lane (without dedication of any lanes to truck use)
- Adding a truck lane
- Adding an exclusive AHS truck lane that
  - accommodates “spontaneous” convoying among two or more longitudinally adjacent trucks already traveling on the truck AHS
  - does not accommodate convoying with no drivers in the trailing vehicles of course
- Adding an exclusive AHS truck lane that
  - accommodates convoying with no drivers in the trailing vehicles, with the convoy formed at a terminal on or near a “node” on the trucking corridor
  - does not accommodate “spontaneous” convoying among two or more longitudinally adjacent trucks
- Adding an exclusive AHS truck lane that
  - accommodates convoying with no drivers in the trailing vehicles, with the convoy formed at a terminal on or near a “node” on the trucking corridor
  - accommodates “spontaneous” convoying among two or more longitudinally adjacent trucks
- Intermodal Rail

## **2.2 RELATED RESEARCH**

Research and implementation efforts on BRT began at least a quarter century ago under the umbrella of dual-mode (bus) transportation. See, for example, (DeMarco, 1974). More recent efforts include the implementation of a BRT system in Adelaide, Australia, (South Australia DOT, 1988) and the study of a guided bus system in Eugene/Springfield area of Oregon (Carey et al., 1998). In the past couple of years, the subject of BRT took on a broader interpretation as any system that provides some key features of a urban commuter-rail system but with buses, particularly those systems that use advanced technologies to reduce or eliminate impediment to bus movement. The Federal Transit Administration has been providing technical and financial support for the nation’s transit agencies to develop BRT systems. For example, (FTA, 1998) summarizes key issues in BRT. In 1998, the FTA issued a Call for Applications for participation in a nationwide BRT implementation effort and has since completed the applicant selection process.

The Valley Transit Authority (VTA) of Santa Clara County is one of the ten applicants selected by the FTA. Caltrans decided to facilitate VTA’s effort and is sponsoring a research project through California PATH entitled “Implementation of ITS Technologies for Bus Rapid Transit.” This research complements that project in that this project developed full automation concepts as a clear long-term goal, proposed possible intermediate steps, and incorporated existing BRT concepts for the purpose of realizing the long-term goal. This research also complements an ongoing PATH effort on the development of BRT evaluation tools and techniques (California PATH, 1999).

Truck automation has also long been considered by many as a promising intermediate step toward an AHS that supports all major vehicle types. It was studied as part of the Precursor System



Studies prior to the formation of the National AHS Consortium (NAHSC). It has been an on-going research subject in Europe. The CHAUFFEUR Project has produced promising technologies and cost-benefit findings for truck automation that can be used in developing complete operational concepts and their evaluation. Recent published results include (Baum and Schulz, 1997), (Borodani et al., 1997), (Riva and Ulken, 1997), and (Schulze, 1997).

This research project also complements many recent PATH research efforts on AHS, including FHWA-sponsored Precursor Systems Analyses (PSA) projects, NAHSC-sponsored projects and, much more importantly, Caltrans-sponsored projects. The vast majority of research papers published by the principal investigator resulted from Caltrans-sponsored research, either on definition of AHS operating concepts or their evaluation. (The Reference and Bibliography section of this proposal lists only part of the publications.)

### **2.3 RESEARCH APPROACH**

Freeway congestion has been growing steadily, and this trend is projected to continue. Conventional transportation systems have failed to arrest this trend. The concept of automated highway systems (AHS) has received much attention because of its potential of drastically increasing automobile throughput without requiring a significant amount of infrastructure modification. The vast majority of the research attention has been focused on a fully automated high-throughput automobile-AHS, where a system is primarily considered as a vehicle-traffic control system.

AHS research and development is conducted for the ultimate deployment in the real world, and deployment issues are likely to impose constraints on AHS design (Tsao, 1995d). As a result, “system” in this context must include the whole transportation system and the society at large, and deployment issues must be investigated and fully considered at the outset of the AHS R&D process (Tsao, 2001). Some critical issues have not yet been fully addressed, e.g., how to ensure a sufficiently large population of equipped vehicles before opening the fully-automated AHS so as to avoid the so-called “empty-lane syndrome” or “the chicken-and-egg problem”, how to deal with failure events, human factor issues, liability issues, etc. As a result, operating concepts that are sustainable have not been developed. With this recognition, Hall and Tsao (Hall and Tsao, 1997) identified many AHS deployment issues, and Tsao (Tsao, 2001) developed a framework for anticipating, recognizing and organizing ITS deployment issues, particularly such issues regarding forward-looking concepts like AHS. Tsao (Tsao, 1995d) discussed critical issues associated with initial deployment of automation technologies and proposed a transit service for AHS debut. He suggested that a bus-AHS could be a goal by itself for high people-throughput or could be an intermediate step toward realizing a fully automated high-throughput automobile-AHS even when the latter is the only goal. AlKadri et al. (AlKadri et al., 1998) and Tsao (Tsao, 1998b) also proposed partial-automation concepts designed to help resolve the “chicken-and-egg” issue associated with AHS deployment. Shladover (Shladover, 2000), extending his earlier work (Shladover, 1999), stated, “The most serious challenge to the credibility of highway automation as a potential solution to transportation problems has been the lack of a convincing deployment strategy.” He proposed a set of principles that can be used to guide the design of AHS deployment strategies. He also proposed a set of potential steps beyond adaptive cruise control (ACC) toward an AHS that is protected with barriers and fences. The protection is motivated by the consideration that the driver can no longer be depended on to identify hazards or failures

because his or her attentiveness cannot be assured. He also provided example AHS deployment “road maps” for transit buses, heavy trucks and automobiles.

Despite these and other efforts aimed at facilitating AHS deployment, constructing a full-scale bus-AHS network, covering an entire metropolitan area with dedicated right-of-way and new infrastructure, requires a huge investment and strong public will. Something of a smaller scale could acquaint the public with the concept of automation and may help build support for an AHS. A smaller-scale system similar to a light-rail system along a commute corridor may present a feasible opportunity for the deployment of an automated busway (ABUS) or a bus-AHS system. An ABUS is any bus system that supports hands-off or feet-off driving. A bus-AHS is an ABUS that is implemented on dedicated and limited-access right-of-way in a freeway environment.

A well-known problem about any rail system is that its success hinges upon a convenient feeder system. The development of most of this nation’s metropolitan areas has centered on the use of automobiles as the primary or even the only means of people transportation. The resulting low population density prevents efficient deployment of transit systems. Moreover, when a rail system is implemented, demand for such a system is often inhibited because of the lack of parking at the stations or the nuisance and delay associated with transfer from and to a feeder bus.

An ABUS that has the capability of fulfilling both the speedy line-haul function and local collection/distribution may be a significantly better alternative. In addition, such a corridor ABUS may be a smaller-scale implementation of vehicle-automation technology that can help build the necessary public support for bus automation in particular and for AHS in general. Such a concept may use right-of-way similar to that of a light-rail system for the line-haul proportion. The major functional difference between the ABUS and the light rail system will be that the same buses, engaged in the collection-distribution function, will be used in the line-haul function of the ABUS also, thereby eliminating mode changes. With proper design, efficient commute bus services requiring at most one transfer between origins and destinations far from the bus-AHS but on the same commute corridor may be feasible. The proposed operating concepts can be viewed as an advanced form of the general concept of bus rapid transit (BRT) (Federal Transit Administration, 1998).

Like bus automation, truck automation has also been viewed by many as a viable goal by itself or as an intermediate step toward a fully automated high-automobile-throughput AHS. This report also discusses a truck-AHS that operates on a barrier-separated and dedicated lane on a freeway along an inter-city freight corridor where sufficient demand and right-of-way exist.

### **3. ELEMENTS OF A BUS-TRUCK AHS OPERATING CONCEPT**

In this section, we first discuss critical groups of issues to be addressed by a bus-truck AHS operating concept, and then summarize the principles used in developing such operating concepts.

#### **3.1 Critical Groups of Issues to be Addressed by Operating Concepts**

An operating concept consists of a set of rules of operation in the form of “Condition(s) calling for Action(s) by Actor(s)” (i.e., “If A, then B does C.”). Conditions and Actions may both be considered as “Events.” Events include nominal and non-nominal events; the latter include rare

operating conditions, failure-emergency events, etc. Actors include (a) components of the system and their operators and (b) relevant components of the context of the system and their operators. An actor may be the operator of the infrastructure or bus or an automated component of the system. Note that not all events result from intentional actions on the part of one or more actors, e.g., accidents, traffic congestion, etc.

Before any incident or accident occurs, the operators cooperate according to pre-specified protocols to achieve safety and efficiency of the system. However, after an accident or incident has occurred, an operator may find fault with the other operators to avoid responsibility. Liability distribution among the operators should be clearly defined, to the extent possible. In addition to actions regarding movement of vehicles, actions taken by operators also include strategies that would facilitate the eventual deployment of a mature AHS through one or more intermediate steps.

We address four groups of rules of operation:

- Nominal Operations
  - Mainline Operations
  - Access/egress Operations
- Non-nominal Operations
- Liability
- Deployment

More details about what constitutes an ITS operating concept can be found in Tsao (2001).

### **3.2 Principles for Developing AHS Operating Concepts**

No unrealistic technologies are assumed. We develop concepts involving vehicle-control and communication technologies that have been proven by recent technological advances as effective and cost-effective or are likely to be perceived by the community of infrastructure providers as promising. Proven technologies for automobiles are extrapolated for buses and trucks, but with the key differences in vehicle type in mind. For example, we do not assume the availability of technology that can reliably detect safety-impacting debris ahead on the lane, which continues to require human “intelligence.” Also, we do not assume the availability of a check-in system and an on-board diagnostic system that are so effective and perhaps predictive that the risk of safety-impacting or traffic-flow- impacting bus or truck failures can be considered negligible on AHS.

The services provided must be appealing to bus riders, shippers or freight forwarders and to bus or truck operators, in terms of better or new services. The services must be at least as good as the conventional alternatives or render improvements that may offset any deterioration in service.

For ease of discussion, the operating concepts will be described with bullet items in Sections 4 and 8. The rationale for a rule of operation is briefly mentioned in the parentheses following the rule, when necessary. For the operating rules related to non-nominal operations, liability and deployment, the issues motivating the rules are briefly stated at the beginning of the rule descriptions, followed by a mark “:”.

#### **4. AN OPERATING CONCEPT FOR AN AUTOMATED BUSWAY (ABUS) ON A COMMUTER CORRIDOR, WITHOUT ACCESS CONTROL TO RIGHT-OF-WAY**

In this section, we first provide in Subsection 4.1 the basis of the operating concept and then point out in Subsection 4.2 possible new or better services that can be offered by an urban automated busway (ABUS) over a corresponding light-rail system, followed by a brief benefit comparison between the ABUS system and the light-rail system in Subsection 4.3. Two operating concepts, together with their deployment steps, for a bus-AHS intended for possible implementation on dedicated and protected right-of-way along the median of a freeway, as variations from the ABUS operating concepts proposed in this Section, will be proposed in Section 5.

##### **4.1 The Basis of the Operating Concept**

The operating concept combines the strengths of a light-rail system with those of a bus system and formulates a new system concept that offers new and/or better services. It calls for (a) the use of only buses and no light-rail cars to transport passengers from their origins to their destinations without any mode change and (b) the use of advanced technologies to enable the space, travel-time and labor efficiencies achievable by light-rail operations. Proper use of automation technologies can also help achieve seamless coordination between bus movement and traffic signaling.

To avoid confusion, we first clarify the term system in two different contexts: bus operations and automated operations. The bus system operates on not only a dedicated right-of-way that is commonly required of a light-rail system but also on city streets. However, automation is used only on this dedicated right-of-way (for “line-haul”). Therefore, from the space perspective, the automated system encompasses only the dedicated right-of-way. Since the focus of this project is on the bus automation, we are primarily concerned with the automated operations occurring on the dedicated right-of-way. We will refer to operations occurring on this right-of-way as line-haul operations and sections on this right-of-way as line-haul sections, whether automation is used or not.

Since the access to the right-of-way is not controlled and the automation system is intended for implementation on city streets and not necessarily on freeways, this system is not necessarily an automated highway system (AHS). We refer to this system as an Automated Busway (ABUS) or an ABUS system. Again, the space occupied by this system consists of only the dedicated right-of-way. The operations of such an ABUS system can be thought of as a light-rail system where rail cars are replaced by (self-propelled) buses and physical linkages are replaced by electronic linkages. Automated lateral control reduces bus wandering and hence helps reduce the right-of-way requirements. On this system, the buses travel at low to medium speeds, just like their light-rail counterparts. There are at-grade intersections between the dedicated right-of-way and crossing city streets. Signaling at these intersections is prioritized or even pre-empted for ABUS operations when such signaling priority is safe.

Enabled by automated longitudinal control, a small number of buses form closely-spaced convoys, mimicking a short train of light-rail cars, so as to minimize disturbance to traffic on surrounding city streets and to enable safe line-haul operation of a whole bus convoy with only one driver (at the lead bus). The buses serve not only line-haul sections but also collect and distribute passengers off the ABUS. The flexibility offered by buses extends beyond local passenger

collection and distribution. For example, passenger transfer at a station between two buses of a bus convoy serving different routes is made possible; a bus can merge with or break off from a convoy at an access or egress location or at a station. We focus on situations where the right-of-way is wide enough to accommodate two lanes of automated bus traffic, one for each direction. This operating concept is summarized below. Details about this operating concept as well as promising intermediate steps facilitating the full implementation of the concept will be discussed in what follows. Figure 1 summarizes the basic trip concept for the proposed ABUS; Figure 2 depicts the basic geometry for ABUS on a dedicated lane.

#### **4.1.1 Normal Operations**

##### **4.1.1.1. Normal Mainline Operations:**

- One single lane in each direction, without a breakdown lane (mimicking a light-rail system)
- No access control to right-of-way, even without any physical separation from the rest of the roadway at some sections: This again mimics the operations of a light-rail system. In sections without physical separation from the rest of the roadway, the automated operations will be at safe and perhaps low speeds. The driver of the lead bus is responsible for anticipating and reacting to possible pedestrian and vehicle incursions.
- At-grade crossings with signals (mimicking light-rail)
- Automated lateral and longitudinal control (hands-off and feet-off)
- Low- to medium-speed operations, for safety (mimicking a light-rail system)
- On the AHS, buses form a convoy with a driver on the lead bus at least and with an upper limit on the length of a bus convoy (mimicking a train of light-rail cars). “Coupling” between buses occurs electronically.
  - ◆ Note that buses will have the right-of-way, and signals will be pre-empted for their passage.
  - ◆ Dispersed buses on the line-haul section will greatly interrupt the city-street traffic and therefore convoying (i.e., organizing buses into clusters) will be advantageous. Note that such convoying requires much coordination among different buses and bus routes. Also, such convoying may not be accomplishable by human drivers, particularly if the gaps are to be kept short and steady. It is definitely not feasible if the gaps are to be kept as short and as steady as the gaps between light-rail cars. (See the item below.)
  - ◆ Also note that scheduling buses so that convoys of reasonable length form is an important task. The necessary coordination goes beyond the physical separation of the buses in a bus convoy.
- Closely-spaced convoying:
  - ◆ Automated closely spaced bus convoying enables the operation of a bus convoy by only one driver, i.e., the driver of the lead bus of the convoy. A light-rail train is operated by one driver, and part of the reason why this can be safely achieved is that the light-rail cars are articulated and the absence of inter-car distance enables the driver to supervise the operation of the entire train safely.
  - ◆ The shorter the distance between two buses in a convoy, the less adverse effect on the traffic flow of surrounding city streets. Moreover, short gaps may prevent drivers of other vehicles or pedestrians from attempting daring acts between buses in a convoy,

particularly on city streets where the busway is not protected or barrier-separated from the rest of the roadways. This mimics the operations of a train of light-rail cars. Automobile drivers may attempt daring acts to get ahead of the lead bus and/or to cross the intersection before the bus convoy does. However, this is true for the corresponding light-rail operations too, and hence may not be a discriminator between the two types of operations. A possible exception results from the fact that a bus convoy is electronically coupled and convoy control must be able to react to sudden braking without causing any intra-convoy collisions.

- ◆ It turns out that convoing in this situation is critical, but the motivation is completely different from what originally motivated the concept of closely-spaced convoing - a drastic gain in automobile throughput on an AHS.

#### **4.1.1.2 Normal Access and Egress Operations:**

- Manual (or automated) entry into the ABUS from a crossing or parallel street; waiting for the arrival of a convoy or joining a waiting convoy at a station; driver getting off the bus and waiting for an exiting bus.
- Automated exiting out of a convoy (from any position of the convoy) at selected at-grade crossings; proper signal control at these crossings required; a driver boarding the exiting bus at the station before the bus leaves the station; if the exiting bus is the lead bus of a convoy, the driver of the lead bus leaves the bus, boards the following bus, and supervises the operations of that following bus and all other trailing buses in the convoy.
- The presence of a driver on the lead bus of a convoy required (This may introduce some constraints on operations. Determining the number of drivers on this ABUS is a constrained optimization problem.)
- Transfer stations at selected locations (Location selection is an optimization problem.)
- Optional bus pull-out areas (out of the mainline and the convoy) in a transfer station for special actions, e.g., for longer stay of a bus at the station (than the convoy), if the space is available.
- The flexibility offered by the bus operations opens up a whole new dimension of optimization possibilities and a new area of research.

#### **4.1.2 Operations Related to Non-nominal Events (Issues and Solutions)**

- Difficulty in replacing human cognitive ability and adaptability by machines: driver of the convoy leader to watch out for possible safety hazards for the whole (short convoy) at low to moderate speeds (mimicking the operation of a light-rail train); the operating speed to be set by the system; driver to override the speed set by the system to ensure safety.
- Difficulty in obstacle detection by machines: performed by the driver on the lead bus
- Safety problems due to machine failures: fail-safe low- to medium-speed operations; short convoy enabling the driver of the lead bus to monitor the entire convoy.
- Reliability requirement for minimizing failure rate on ABUS and probability of lane blockage: fleet maintenance; optional use of electrical buses, which have much fewer parts and higher reliability potential.
- Disabled bus: simple mechanical linkage for pushing or pulling a disabled bus out of ABUS by another bus.

- Difficulty in providing check-in function and infrastructure at entrances to reduce failure rate on ABUS: not necessary because of fleet maintenance

#### **4.1.3 Liability**

- Litigation: similar to light-rail counterpart. (Security concerns of passengers in driverless following bus are similar to their light-rail counterparts, and may not be a significant discriminator between the two types of operations. Video camera technology may be employed to alleviate some of the concerns.)

#### **4.1.4 Deployment**

- How to utilize more fully an ABUS when there are not enough fully equipped buses: support mixed traffic (including conventional buses) on the mainline and treat the AHS as an enhanced busway. An assessment will be made to determine whether mixed traffic can be accommodated for transition to all-automated-bus operations before all buses become automated. If such a system does not prove to be efficient, e.g., excessive disturbance to the surrounding traffic, then it may have to be restricted to AHS only. Perhaps more importantly, to support mixed traffic, the busway could not be narrowed, and a potential cost saving would be lost.
- How to build up a population of ABUS-equipped buses before opening: features useful off or without ABUS (vision-based lateral recognition and control system; range-sensor based longitudinal sensing and control system; partial innovation of only automated longitudinal control or automated lateral control but NOT BOTH to avoid driver inattentiveness); magnetic marking of the ABUS lane combined with magnetic sensing of the markers by the buses may actually be necessary for closely-spaced convoying, but at least provides redundancy for higher reliability.

#### **4.2 New or Better Services**

- No need for transfers from feeder buses to line-haul section.
- Stations enabling transfers between buses and routes.
- Enabling intra-convoy transfers, not just inter-convoy transfers: A transfer at a station may be between two buses in the same convoy, involving no waiting for another convoy.
- End-to-end time-definite bus services from one location to another in the corridor but far off the ABUS within a specified amount of time, not just conventional multi-modal bus services. Scheduling, including transfer scheduling, is an optimization problem, which could be and likely should be solved together with the transfer location optimization problem.

#### **4.3 Other Major Benefits over Urban Light-Rail**

- Much more flexibility in entraining and detraining buses than light-rail cars.
- Much more flexibility in joining or leaving a convoy, at access or egress points and at stations provided with the optional bus pull-out areas.
- Less infrastructure, except for the optional bus turn-out areas in a station.

Before closing this section, we summarize the main features of the proposed ABUS operating concept. This concept was motivated to combine the strengths of bus and light-rail operations by mimicking the light-rail operations with buses on the line-haul section and by using the same buses for local collection and distribution of passengers. Automation and ITS features are motivated to reduce the disturbance to the surrounding traffic caused by signal preemption or prioritization and to enable bus operations on narrow right-of-way in busy urban commute corridors. Automated longitudinal control can further enable closely spaced bus conveying, which in turn enables the operation of a bus convoy by only one driver, i.e., the driver of the lead bus of the convoy. (A light-rail train is operated by one driver, and part of the reason why this can be safely achieved is that the cars are articulated and the absence of inter-car distance enables the driver to supervise the train operation safely.) Last but not least, automated longitudinal control enables better and perhaps seamless coordination between bus movement and traffic signaling, which improves travel time and reduces disturbance to surrounding traffic.

## **5. A DEPLOYMENT SEQUENCE FOR AN AUTOMATED BUSWAY (ABUS) ON A COMMUTER CORRIDOR, WITHOUT ACCESS CONTROL TO RIGHT-OF-WAY**

We propose a four-step deployment sequence for the operating concept of an automated busway (ABUS) proposed in Section 4. In fact, some of the intermediate operating concepts involve bus automation already and actually should be viewed as ABUS systems themselves. Variations of the four-step sequence are also proposed to accommodate the possible varying degrees of right-of-way availability. These concepts, including the “end” and the intermediate operating concepts, require no protected right-of-way and can be considered as alternatives to the light-rail option at the planning stage, or as a replacement to an existing light-rail system.

Two bus-AHS concepts intended for possible implementation on dedicated and protected right-of-way along the median of a freeway are also proposed. Major implementation issues are identified, and important future research subjects suggested.

In order to develop realistic operating concepts, we use the Santa Clara County Light-rail System as the backdrop for concept development. Santa Clara Light-rail System has two fundamentally different types of right-of-way: unprotected and protected right-of-way. The southern segment between Children’s Discovery Museum and the Santa Theresa stations is primarily built on the exclusive right-of-way on the median of State Route 87 while the rest of the system is built on city streets, including downtown streets and major arterials. Figure 3 depicts the Santa Clara Light Rail System operated by the Valley Transportation Authority (VTA); Figure 4 summarizes the basic trip concept for light rail. Figures 5 and 6 provide more detailed descriptions of the right-of-way of the Santa Clara Light-rail System at two different locations: the intersection of the North First Avenue and Skyport Boulevard and the intersection of North First Avenue and Brokaw Road. Skyport is a major road leading to the San Jose International Airport while Brokaw Road is a major thoroughfare.

For ease of application of the proposed concepts to other corridors or sites, we develop separate concepts for these two types of right-of-way arrangements. The two types of operating concepts can be easily integrated to form one operating concept for corridors with both types of right-of-way, e.g., the Santa Clara County Light-rail corridor.



The operating concept for the protected section of the San Jose Light-Rail Corridor is an AHS concept because the protected right-of-way can be viewed as a highway system by itself. The light-rail system is primarily built on the median of a freeway (State Route 87), and proposed bus AHS can be accessed directly from the freeway, without the need for constructing additional ramps connecting city streets with the freeway median. We propose one operating concept for this section of the San Jose Light-rail System.

The operating concept for the unprotected section of San Jose Light-Rail Corridor is not an AHS because the light-rail is not built on a highway, but built along busy downtown streets and boulevards with at-grade crossings. We define an ABUS system as one in which all buses on the system are equipped in such a way that bus driving can be “hands-off” as well as “feet-off” although such hands-off and feet-off driving may not always be invoked when such buses are traveling on the busway. Note that no technologies capable of detecting reliably the presence of pedestrians, safety-impacting debris and intruding vehicles on the busway are assumed for ABUS, and therefore driver presence and intelligence is required for safe driving. However, when buses form a short closely spaced convoy, drivers may not be required on the trailing buses. This is similar to the operations of light-rail systems.

The rest of this section is organized as follows. Sections 5.1 addresses a four-step deployment sequence toward the ABUS operating concepts defined in Section 4 while Section 5.2 through Section 5.5 discusses possible implementation issues associated with deploying the four steps. Section 5.6 describes two bus-AHS operating concepts. Concluding remarks are given in Section 5.7.

## **5.1. UNPROTECTED AUTOMATED BUSWAY SYSTEMS FOR CITY OPERATIONS AND A FOUR-STEP EVOLUTIONARY DEPLOYMENT SEQUENCE**

Rather than describing the individual ABUS concepts first and then the deployment sequence toward them, we describe the four steps beginning with the first step. Details about the end-state ABUS operating concept have been provided in Section 4 and are also given in Tsao and Botha (2001). Their focus was on a description of an “end-state” while the primary focus of this paper is the deployment sequence and issues. In addition, we hope that describing functional increments toward the ABUS operating concepts would make it easier to capture the essence of the concepts and to evaluate the concepts’ deployability, including the sources of benefits and costs.

### **5.1.1 The Ultimate Goal of a Four-step Deployment Sequence**

The ultimate goal of the four-step deployment sequence is to combine the strengths of a light-rail system and those of a bus system and to formulate new system concepts that offer new and/or better services. At the end of the four steps, the bus operations on the line-haul section mimic those of a light-rail system, but possess much flexibility. The flexibility will become clear later.

To facilitate understanding, imagine that an existing light-rail system is to be replaced by bus operations. The same four-step sequence can be considered as an alternative to a light-rail option when alternative options are being considered for improving transportation facilities along a busy

commute corridor. The sequence can also be viewed as an extension to existing Bus Rapid Transit (BRT) implementations. The operating concepts apply equally well to a network of busways.

It turns out that the availability of right-of-way plays a pivotal role in deploying ABUS systems. In urban settings where the right-of-way allocated to a light-rail system is considered too narrow for human drivers to safely keep the bus in lane at the light-rail speeds, some degree of bus automation may be required. In others, manual driving will suffice. This difference will result in different deployment sequences. However, since the resulting difference in deployment sequencing occurs primarily in Step 1, we will explicitly describe two different sets of possible features for Step 1, rather than specifying two separate four-step sequences.

Since the right-of-way of the San Jose Light Rail System is likely to be narrow for an ABUS system, we assume the need to minimize the use of right-of-way in the four deployment steps for that system. By the very nature of the setting in which such ABUS systems are designed for, it is likely that the available right-of-way will be narrow for most possible urban implementations. It is logical to describe the operating concept for such a setting first and then discuss the more unrealistic setting. However, since the operating concepts for an ABUS with sufficient amount of right-of-way are simpler, we choose to describe them first and then describe the more complicated operating concepts for an ABUS with narrow right-of-way.

### **5.1.2 The Four Steps**

The four steps are summarized below. Implementation issues will be addressed in the following sections.

#### Step 1: A Conventional Urban Unprotected Busway

We first discuss the urban settings in which the light-rail right-of-way is sufficient for implementing a conventional busway, on which buses can be driven safely by manual drivers at the light-rail speeds, and then those settings in which the light-rail right-of-way is too narrow for manual bus drivers.

Replace light-rail cars with conventional buses, but use the same right-of-way as a conventional busway. Buses travel on the light-rail right-of-way at light-rail speeds, i.e., low speeds in downtown and moderate speeds along urban boulevards, but also collect and distribute passengers in city streets or neighborhoods off the right-of-way.

Movements of buses on the busway are not coordinated, and, as a result, they tend to be more “scattered” along the busway than their light-rail-car counterparts, which are linked mechanically into small trains of light-rail cars. Since signals along the busway are prioritized for bus movement, the scattering of the buses would create a higher degree of disturbance to the surrounding traffic. This is a distinct possibility when demand for travel on the busway increases. This higher degree of disturbance could be so undesirable that the next step would be justified.

We now describe an alternative to Step 1.

### Step 1': An Urban Unprotected Busway with Automated Lane Keeping and Automated Precision Turning/Automated Precision Lane-changing

Because the right-of-way is too narrow for travel by conventional buses, automating the task of keeping buses on the busway may be required. This feature has been referred to as *automated lane-keeping* in the literature. It is possible that automated lane-keeping can be performed only with both lateral control and longitudinal control of the vehicle automated. Other features can be included too, e.g., (*automated*) *precision docking*. Note that precision docking may require both lateral and longitudinal control of the bus.

In addition, buses will need to make turning movements at intersections when they enter or depart the busway. Note that, for entering the busway, they would start the turning movement at the right-hand lane and must enter the narrow busway within as short a distance as possible and without infringing on the right-of-way for the traffic on the adjacent lane on the left. If the buses are to be manually driven onto or off the busway from the crossing street, such turning movements may require a significant amount of additional driving skill or additional right-of-way at the intersections than what a light-rail system would require. (Note that no such turning movements are required for a light-rail system except for those intersections where the light-rail track turns.) Automated turning movement has the potential of minimizing the amount of additional right-of-way required. We refer to this feature as (*automated*) *precision turning*. Note that automated precision turning may require both lateral and longitudinal control of the bus. An alternative to the wide turning movements for entering or departing the light-rail right-of-way is to have buses enter from or depart to the regular traffic lane adjacent to the light-rail right-of-way through a lane-change maneuver. The narrow right-of-way may require automated precision lane-changing, which is discussed in more detail in Section 3.

With the automated lateral and longitudinal control of the bus implemented for purposes of automated lane-keeping, automated precision turning and possibly precision docking, following the bus ahead at a safe distance can be automated without much difficulty. This feature has been referred to *automated vehicle following* in the literature.

As in Step 1, movements of buses on the busway are not coordinated, and the degree of disturbance to the surrounding traffic could be so undesirable that the next step would be justified.

### Step 2: A Busway with Manual Bus Convoying through ITS Technologies

The main goal is to reduce the degree of disturbance to the surrounding traffic. Through the use of ITS technologies, including communications and fleet management technologies, the movements of buses on the busway can be well coordinated so that they form bus convoys and bus convoys are properly spaced. Such coordination may reduce the disturbance to surrounding traffic. We refer to this feature as *manual bus convoying*.

As the demand for travel on the busway further increases, such coordination may still incur an unacceptable amount of disturbance to the surrounding traffic. The next step is designed to remedy the situation.

Step 3: Automated Closely-spaced Convoying of buses to further reduce the disturbance to the surrounding traffic. (An Automated Busway)

Further shorten the following distance between two buses with the help of automation, and organize buses into short closely spaced convoys. Safety and ride quality are also important performance measures. This step features “feet-off” driving for the trailing buses, and we refer to this feature as *automated closely-spaced convoying*.

If features of automated lane-keeping, automated precision docking and automated precision turning have not been implemented before this step, then they can be implemented as part of this step. Although they can be implemented in a separate future step, we assume that this is implemented in this step, if they have not already been implemented. With their implementation, the required right-of-way can be reduced, and ride quality improved. With their implementation, driving on the line-haul section becomes “hands-off” for both lead and trailing buses.

Note that this motivation for automated closely spaced convoying is completely different from the motivation for platooning, which is to double or triple the capacity of an automobile AHS by packing a freeway lane with automobiles safely.

Although the task of longitudinal control of a lead bus may also be automated, the driver of the lead bus is responsible for anticipating intruding vehicular or passenger traffic from the surrounding roadways or sidewalks into the right-of-way and reacting to such and other non-nominal events by overriding automated driving.

Step 4: Driverless operations for trailing buses in a convoy. (Another ABUS Concept)

If safety permits, the trailing buses of a convoy may not require a driver. However, the lead bus of a convoy continues to require a driver.

This step makes the bus operations on the line-haul section resemble the current light-rail operations. This step has the potential of significantly reducing the labor cost for operating the system described in Step 3. We refer to this step as *Driverless bus following*. Due the absence of rail tracks and drivers, steering failure on the part of such trailing buses may cause significant safety hazards. This issue must be studied thoroughly. Utilizing the driverless feature fully may incur operational complexity, and such complexity will be discussed in Section 6.

A Summary of the End-state Operating Concept

The bus-AHS operates on right-of-way that is commonly required of a light-rail system and serves the line-haul function. The operations of such a bus-AHS can be thought of as a light-rail system where rail cars are replaced by (self-propelled) buses and physical linkages are replaced by electronic linkages. Buses form closely spaced convoys, mimicking a short train of light-rail cars, so as to minimize disturbance to traffic on surrounding city streets. The buses serve not only line-haul sections but also collect and distribute passengers off the bus-AHS. The flexibility offered by buses extends beyond local passenger collection and distribution. For example, passenger transfer between convoys serving different routes is made possible at a station; a bus can merge with or break off from a convoy at an access or egress location or at a station. Also, passenger transfer

can be made within a convoy, which may consist of buses serving different routes. Driverless operations of the trailing buses may significantly reduce labor cost. Note that if the driverless operations cannot be made sufficiently safe or efficient, the deployment can stop at the previous step, which is by itself an automated busway system.

### A Summary of the Four Steps

These four steps as well as their main features, main benefits and main traffic issues are summarized in Table 1. Note that, among other issues, we focus on only the traffic issues because minimizing disturbance to the surrounding traffic is a major driving force behind the deployment sequence.

**Table 1: A Four-step Deployment Sequence for the Proposed ABUS system**

<b>Step</b>	<b>Main Features</b>	<b>Main Benefits</b>	<b>Main Traffic Issues</b>
<b>1</b> Conventional Busway (with sufficient right-of-way)	<ul style="list-style-type: none"> <li>• Bus operations on light-rail right-of-way</li> </ul>	<ul style="list-style-type: none"> <li>• Same bus for line-haul and collection/distribution</li> </ul>	<ul style="list-style-type: none"> <li>• Scattered buses disturbing surrounding traffic</li> </ul>
<b>1'</b> Busway with Automation to Enable Bus Operations on Narrow Right-of-way	<ul style="list-style-type: none"> <li>• Automated precision turning/automated precision lane-changing</li> <li>• Automated lane-keeping</li> <li>• Automated bus-following</li> <li>• Automated precision docking (if desired)</li> </ul>	<ul style="list-style-type: none"> <li>• Same bus for line-haul and collection/distribution</li> <li>• Automation enabling busway operations on narrow right-of-way</li> </ul>	<ul style="list-style-type: none"> <li>• Scattered buses disturbing surrounding traffic</li> </ul>
<b>2</b> Manual Bus Convoying Through ITS	<ul style="list-style-type: none"> <li>• Clustering buses to reduce disturbance via ITS technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of disturbance to surrounding traffic due to signal preemption or priority</li> </ul>	<ul style="list-style-type: none"> <li>• Possible excessive disturbance as demand grows</li> </ul>
<b>3</b> Automated Closely-spaced Convoying	<ul style="list-style-type: none"> <li>• Automated closely-spaced convoying</li> <li>• Automated precision turning/automated precision lane-changing, automated lane-keeping, automated vehicle-following and precision docking if not already implemented</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of disturbance to surrounding traffic due to signal preemption or priority</li> </ul>	<ul style="list-style-type: none"> <li>• Safety</li> </ul>
<b>4</b> Driverless Bus-following	<ul style="list-style-type: none"> <li>• Absence of driver on trailing buses</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of labor cost</li> </ul>	<ul style="list-style-type: none"> <li>• Safety</li> </ul>

### **5.1.3 Possible Further Features**

Possible further features include automated precision control of bus movements on the line-haul section. This feature resembles the control of rail cars on urban heavy-rail commuter systems, but

requires coordination with the signaling system of the surrounding traffic to minimize the disturbance to the surrounding traffic.

## **5.2. IMPLEMENTATION ISSUES FOR THE FIRST STEP - UNCOORDINATED BUSES (POSSIBLY WITH AUTOMATED LATERAL CONTROL)**

We use the current San Jose Light Rail System as the reference site and identify possible implementation issues. Some solutions are also suggested; issues requiring an in-depth investigation are identified. Investigations into some of the issues have already begun, and the results will be reported separately.

### **5.2.1 Physical Barrier**

Since buses on a busway do not have physical tracks to restrain the buses from moving off the lane, a physical barrier may be required to separate the busway traffic on the two opposite directions. Physical barriers may also be required to separate the busway from the rest of the roadway system at locations where no at-grade crossings exist.

These barriers may not have to be as bulky and strong as the Jersey barriers commonly installed on freeways because the operating speeds on the busway are significantly lower than their freeway counterparts. Moreover, the barriers separating the busway from the adjacent roads may not have to be as strong and bulky as those separating the two lanes on the busway (of opposite directions). However, there are certain minimum dimensions required in structural concrete design, which may apply here. The design of such barriers is an important implementation issue.

### **5.2.2 Narrow Right-of-way**

Due to the intense competition for right-of-way among different uses of urban road space, the right-of-way of urban light-rail tends to be narrow. Light-rail operations tend to require less right-of-way than a busway due to the use of physical tracks to keep light-rail cars “in the lane”. If a physical barrier between the two lanes (of opposite traffic directions) and/or a physical barrier between the busway and the adjacent roads (with one on each of the two sides) are required, this barrier requirement may further increase the need for additional right-of-way. Narrow right-of-way and these related issues are important implementation issues that must be carefully studied.

### **5.2.3 The Increased Desirability of Automated Lane-keeping**

The right-of-way issues pointed out above increase the need for lane-width reduction on the busway, and further increase the desirability of automated lane-keeping.

### **5.2.4 Lack of Right-of-way for Turning Movements**

On a light-rail system, the light-rail cars stay on the physical tracks and never turn onto or off from the light-rail right-of-way (in the median of road). Therefore, no additional right-of-way has been allocated for such turning movements. However, busway operations require such turning movements at some intersections between the light-rail right-of-way and the adjacent roads. Therefore, additional right-of-way may be required to support such turning movements at such

intersections. Note that buses make wide turns and making a right turn from the rightmost lane of a street onto the narrow right-of-way of a light-rail system in the median may be difficult for a driver. (Making a left turn from the leftmost lane onto the narrow right-of-way may be somewhat easier for a driver, but such turning movements may involve waiting.) This implementation issue must be carefully studied to determine the costs and benefits and hence the feasibility of such a busway.

A possible solution to this issue is for buses to enter the busway from the adjacent lane of the adjacent road by a lane-change maneuver at the intersection. Another possible solution is to begin the physical barrier (if required) at a location beyond the intersection so that the clearing can allow entering or departing buses to make safe turns.

### **5.2.5 Desirability of Automated Precision Turning and/or Automated Precision Lane-changing**

Automated precision turning may be a solution by itself but can certainly be coupled with other possible solutions to overcome this possible issue. If the entering and departing maneuvers are implemented with lane-change maneuvers, rather than turning movements, then *automated precision lane-changing* may be considered. The issues resulting from the lack of right-of-way for turning movements increase the desirability of automated precision turning and automated precision lane-changing. The benefits and costs of such automation features must be carefully studied.

#### **Automated Lane-keeping, Precision Turning and Precision Lane-changing Best Implemented in This Step**

Automated lane-keeping and automated precision turning/automated precision lane-changing may best be implemented in this step because their implementation in that step would reduce the amount of right-of-way on the line-haul section and at its intersections with crossing city-streets where buses enter or depart the busway, and hence would increase the likelihood of the implementation.

### **5.2.6 Adverse Impact on Surrounding Traffic Due to Signal Pre-emption or Prioritization**

As pointed out in the previous section, because of the scattered buses along the busway due to lack of movement coordination and the signal pre-emption (or bus signal prioritization), the traffic on the surrounding streets, particularly the cross traffic, may be more significantly disturbed by the busway than by light-rail operations carrying comparable amount of passengers. This issue must be studied quantitatively, including defining performance measures and predicting (or measuring) the impact on the performance for the busway and the light-rail system.

### **5.2.7 Safety of Automated Functions**

The safety of automated lane-keeping, precision turning and precision lane-changing must be thoroughly studied, not only for line-haul operations but also for operations at intersections with the adjacent roads. In fact, the latter may be more important than the former because the latter will not have the protection of physical barriers.

### **5.2.8 Air Pollution (to Downtown Pedestrians and Restaurant Patrons)**

Some light-rail systems are electrified, and there is no air pollution within or near the system. (There is of course still pollution at the power generation station.) Aside from the general issue of air pollution, the specific issues of busway air pollution creating unpleasant environment for downtown pedestrians walking next to the light-rail right-of-way and for downtown restaurant patrons eating next to the right-of-way, if the busway is not electrified.

## **5.3. IMPLEMENTATION ISSUES FOR THE SECOND STEP - MANUAL BUS CONVOY THROUGH ITS**

### **5.3.1 Bus Waiting for Other Buses at or Close to a Station to Form or Join a Convoy**

At least two ways exist for an entering bus to form a convoy with another bus or join a bus convoy already formed on the busway. It can move into the station and wait for the bus(es) to arrive at the station or wait at a location that is adjacent or very close to the entrance so that it can form or join a bus convoy on the busway from behind after the bus(es) has traveled past the entrance. The waiting option may require additional right-of-way if no adverse effect should incur on the surrounding traffic.

### **5.3.2 Catching up with the Bus(es) Ahead or Slow Down to be Caught up, with Some Limitation**

A convoy may be formed or joined while all the buses involved are moving. This can be achieved by speeding up to catch up with or slowing down to be caught up by the other buses, or both. A convoy may also be formed or joined while some buses are being stopped at a signal. Speed limits may constrain this approach to convoy formation or lengthening.

### **5.3.3 The Disturbance Reduced by the Manual Convoying Weighed Against the Delay to the Buses and Passengers: Performance Measures and Computer Simulation**

The primary purpose of convoying is to minimize the disturbance to the surrounding traffic. However, since convoying may require waiting or deceleration of buses, the travel time of the bus passengers will be adversely affected. The reduction of disturbance to the surrounding traffic should be weighed against the resulting longer travel time as well as travel-time variability that the bus passengers may experience.

Performance measures for the two opposing criteria must be developed first. Computer simulation may be the best or even only credible way to determine the trade-off between the two



criteria. The trade-off may depend on demand levels, and, therefore, simulation will need to be run at multiple levels.

## **5.4. IMPLEMENTATION ISSUES FOR THE THIRD STEP - AUTOMATED BUS CLOSELY-SPACED CONVOYING**

### **5.4.1 Likely Achievable Short Separation Between Two Buses**

Although shortening the separation between two longitudinally adjacent automobiles and the related vehicle-following issues in the context of automobile convoying have received much attention in the past decade, research into bus following and separation shortening has not produced credible safe target separation. The importance of this issue hinges upon the potential of fuel savings if such savings are also an important performance measure. It may also depend upon the degree to which automated closely spaced convoying helps minimize the disturbance to the surrounding traffic.

### **5.4.2 Safety**

The safety of closely spaced bus convoying is also an open issue and must be thoroughly studied. The safety level may hinge upon the separation between two buses, which may be a parameter for the safety study.

### **5.4.3 Benefit of Automated Closely-spaced Convoying over Manual Convoying to be Investigated: Computer Simulation**

The additional reduction of disturbance of the busway traffic to the surrounding traffic achievable by automated closely-spaced convoying must be studied, although this additional reduction may be significant when compared to the reduction of disturbance due to manual bus convoying enabled by bus communication, fleet management and other ITS technologies. Under the assumption that forming such convoys results in no significant difference in waiting by the passengers on the buses, the amount of such additional reduction will be the primary gauge for the benefits of automated closely-spaced convoying from the perspective of traffic engineering.

### **5.4.4 Fuel Savings resulting from Automated Closely-spaced Convoying**

Through computer simulation as well as some experimental work on actual trucks, preliminary estimates of fuel savings have been reported. Such estimates may be useful for predicting fuel savings achievable by automated closely spaced convoying. Simulating such bus convoying at low to medium speeds or experimenting with actual buses may be required. In any event, further simulation and experiments with actual heavy vehicles are required for precise and accurate estimation of such fuel savings.

## **5.5 IMPLEMENTATION ISSUES FOR THE FOURTH STEP - AUTOMATED CLOSELY-SPACED CONVOYING WITHOUT DRIVERS ON TRAILING BUSES**

### **5.5.1 How to Let Go the driver of a Trailing Bus?**

The primary way to let go of the driver of a trailing bus is to have the driver drive the bus onto the busway first so that the driver can get off the bus. The bus will wait at the station for other bus(es) to catch up with it to form a convoy or a larger convoy, if this is how the convoy is formed. Recall that the convoy can also be formed by having the driver wait at a location close to the station and drive the bus onto the busway and join other bus(es) to form a convoy or a larger convoy from the back. In this case, the driver can also get off the bus at the station.

If a convoy is formed while the buses are moving (either through speeding up, slowing down or both), then the driver(s) of the trailing buses can get off at the next station.

### **5.5.2 How to Ensure the Presence of a Driver on the Lead Bus?**

One way to ensure the presence of a driver on the lead bus is to assign a number of line-haul drivers that only operate buses that are on the busway and do not drive the buses off the busway for collection or distribution. Determining the minimum number of such drivers is an issue.

### **5.5.3 How to Simply Operations**

Similar to the strategy of assigning drivers dedicated to driving buses on the busway, a number of drivers can be assigned to each of the stations at which buses can enter and depart the busway for local collection and distribution of passengers. These drivers do not drive on the busway, but drive only for local collection and distribution.

### **5.5.4 Automation Failure and Safety**

Automation functions may fail, and without the presence of a driver on the trailing buses, such failures may not be corrected or contained in time and may pose serious safety hazards to the passengers on the busway as well as the surrounding traffic. Failures, failure responses and their impacts are critical issues and must be thoroughly studied. A fail-safe design is likely a must. These issues make a big difference in system and design requirements.

### **5.5.5 Reduction in Labor Cost: Computer Simulation**

The primary and perhaps the only benefit of this step is labor saving. Therefore, this is a critical issue for determining the worthiness of the step. Predicting the amount of such savings may require computer simulation.

### **5.5.6 Weighing the Savings Potential Against the Safety Hazards**

The savings achievable by the driverless operations must be weighed against the possible safety hazards introduced by the absence of drivers of the trailing buses. This is a critical issue.

## **5.6. OPERATING CONCEPTS FOR BUS AUTOMATION ON OR ALONG A FREEWAY**

This subsection proposes two concepts for bus automation involving bus operations on or along a freeway. The first concept is predicated on the availability of sufficient right-of-way in the freeway median to accommodate two lanes of automated bus traffic. The second requires much less right-of-way but does require sufficient amount of right-of-way for accommodating transfer stations in the freeway median at selected locations. These two operating concepts and the ABUS operating concept proposed in Section 4 can be mixed to generate more operating concepts. Such mixing may be required for real-world implementation to accommodate varying degrees of right-of-way availability along an urban commute corridor.

### **5.6.1 An Operating Concept For A Protected Bus AHS**

In this subsection, we propose a protected urban bus AHS. The differences between this bus-AHS operating concept and the ABUS concepts described in the previous sections result from two facts: protection of the right-of-way and the location of the right-of-way in the median of a freeway. We describe the differences in their deployment sequences.

Step 1 or Step 1' still applies. Access to and egress from the bus-AHS can be made through on- and off-ramps connecting the left-most lane of the regular freeway directly with the bus-AHS lane. (New dedicated ramps connecting the bus-AHS lanes directly to the city streets can be built, but are not necessary, as will be explained later.) Disturbance to surrounding traffic is no longer a concern for bus-AHS, and, therefore, Step 2 is no longer necessary. Step 3 still applies but is motivated by a different benefit – less fuel consumption. Step 4 still applies for the same reason – reduction of labor cost. The driver of a bus can leave the bus at the first bus-AHS station along the route after driving the bus manually from the conventional freeway to the bus-AHS. When a bus needs to depart the bus-AHS when it reaches the last bus-AHS station on its route, a driver will board the bus and drive it off the bus-AHS.

### **5.6.2 An Operating Concept for a Conventional “Freeway Flyer” Bus System Plus Protected Transfer Stations on Freeway Median**

This second concept is similar to the existing concept of “Freeway Flyer” already popular in Los Angeles and some other highly congested metropolitan areas. The freeway flyer service is characterized by using the same bus to perform local collection and distribution of passengers at a city or neighborhood and to transport the passengers to and from an activity center, e.g., Downtown LA. One disadvantage of this operation is that there are no intermediate stops and hence transfer opportunities on the freeway. (Having transfer stations off the freeway may have significantly adverse effect on the operational efficiency.) This concept is motivated by this fact and the possibility that sufficient right-of-way for accommodating two lanes of automated bus traffic throughout the length of segment of a corridor freeway (as required for the first concept) may not be available. This concept however does require the availability of right-of-way at selected locations on the median of the freeway to accommodate bus transfer stations along the freeway.

The transfer stations will require additional right-of-way, for vehicle operations as well as for passenger movement. Automation technologies can help reduce the amount of additional right-of-way required. Automated lateral control may reduce the requirements for lane width and enable precision docking at such a transfer station, and/or enable precision entry into such a station.

These two concepts can be implemented according to the availability of right-of-way. Note again that they and the ABUS concept defined in Section 4 can be integrated to form new operating concepts. Also note that although one commute corridor is the primary focus of this paper, the concepts proposed in this paper can be generalized to a network of corridors. If continuous automated bus travel is to be accommodated from one corridor freeway to another, additional highway-to-highway connector ramps will be required. However, the availability of right-of-way or the feasibility of constructing the additional set of highway-to-highway connector ramps could be a major issue, in which case the integrated concept may be the only feasible implementation.

## **5.7. CONCLUSION**

Several ABUS operating concepts have been introduced. They are not bus-AHS concepts because they operate on unprotected downtown areas and urban boulevards. A bus-AHS is introduced. Although they are addressed in the context of replacing an existing light-rail system for convenience of discussion, they can be considered as an alternative to a light-rail system as an additional option for improving urban transportation systems. Moreover, their implementations are not restricted to a corridor. In fact, the ABUS concepts would enjoy the “network effect” in the sense that the benefit of an ABUS system increases as the scope of the network increases.

## **6. THE NEEDS OF THE U.S. LONG-HAUL TRUCKING INDUSTRY AND TRUCK-AHS**

The concept of automated highway systems (AHS) has been primarily motivated by the rapidly worsening traffic congestion on metropolitan highways and the potential of AHS to drastically increase vehicle throughput, particularly automobile throughput, without requiring a significant amount of additional right-of-way. AHS-related research has primarily been focused on automobile-AHS. Various operating concepts have been developed for an “end-state AHS” [e.g., Tsao et al., 1993; Sengupta et al., 1996]. However, little attention has been paid to the critical issue of how to realize such ultimate systems through a planned sequence of deployment steps. The difficulties of deploying such an ultimate AHS in the real world have become clear in recent years [e.g., Tsao 1995b, 1995c, 2001; Tsao and Ran, 1996], and the slow progress in deployment research seems to have led to a decrease in interest in the topic and in funding for research.

Sections 6 through 10 focus on the automation of inter-city trucking for the purpose of increasing trucking productivity, of which vehicle throughput on highways is only one of many factors. Several systems studies investigating truck automation were funded under the AHS Precursor Systems Analysis (PSA) Program (Calspan, 1995). DaimlerChrysler has been developing and testing the technologies enabling automated truck convoying (Riva and Ulken, 1997; Borodani et al., 1997; Ulmer, 1999) as well as conducting economic evaluation of the technologies (Baum and Schulz, 1997).

We propose in this report two operating concepts for an “end-state” AHS dedicated to inter-city trucking. Our approach is needs-driven and technology-steered. We first identify the needs of the long-haul trucking industry and the major concerns of key stakeholders. Based on customer needs, stakeholder concerns and available or promising truck-automation technologies, we then develop design options for several key aspects of truck-AHS operations. After comparing the relative merits of these options, we develop both operating concepts and their deployment sequences to satisfy the customer needs. Note that many of the findings resulting from automobile-AHS research remain to be useful for truck-AHS, e.g., (Hall et al., 2001).

A truck-AHS, if eventually realized, will be a revolution in freight transportation. Its deployment requires a number of revolutionary measures on infrastructure improvement, roadway technology, truck technology, system operations, operator training, liability distribution, public policy, etc. A key ingredient of a truck-AHS is a dedicated truck-lane, and a key operating characteristic is a truck-train that is electronically controlled and linked and is supervised or driven by the driver of the lead truck. The truck-train will travel on an exclusive lane separated from the manual traffic with a physical barrier.

A key position of the authors is that a dedicated truck-lane must exist before transportation agencies and the general public will commit to or even begin to accept the concept of truck automation. More precisely, a truck-lane alone must be able to provide sufficient benefits to justify its dedication or construction, without the help of the potential further benefits to be generated by truck automation. This position is motivated by the tremendous amount of risk involved in a commitment to a truck-AHS when a tremendous amount of uncertainty exists about its possible eventual deployment.

Many feasibility studies for truck-lane dedication or construction have been conducted for busy freight corridors in the United States, but none have been built. A very recent such feasibility study can be found in [KAKU Associates, 2001]. A common conclusion of such feasibility studies is that the projected user fees can defray only a fraction of the total construction and operating cost, and the conclusion is based on the assumption of conventional trucking. However, this conclusion could have been significantly different if the feasibility studies included longer combination vehicles (LCVs) in the scope. LCVs are longer than conventional trucks, and hence can significantly increase the productivity of the driver and the equipment. Such an increase in productivity would yield significant benefits for the long-haul trucking industry, and that industry has been seeking relaxation of rules restricting the use of LCVs for this purpose. Stakeholder concerns against the use of LCVs include increased safety hazards to adjacent automobiles and increased damage to the roadway. Safety concerns can be minimized or eliminated with a physically separated truck-lane; the concern of excessive pavement damage can be minimized with strengthened pavement formulated specifically for such a truck lane. Physically separated truck-lanes that accommodate LCVs may hold the key to successful deployment of truck-lanes as well as to successful deployment of a truck-AHS later on.

Sections 6 through 10 are organized as follows. The rest of this section summarizes the needs of the long-haul trucking industry and the concerns and desires of key stakeholders. These needs, concerns and desires will be used for developing both “end-state” AHS operating concepts and intermediate steps toward them. After pointing out the primary sources of benefit as motivation for a truck-AHS, Section 7 summarizes, contrasts and compares design options for several key

aspects of a truck-AHS, including closely-spaced automated truck convoying and integration of line-haul and local operations. Based on the customer needs, stakeholder concerns and design options, two promising system operating concepts will be summarized in Section 8 and their deployment sequences will be proposed in Section 9. Section 10 discusses possible deployment sites, and key issues that may hinder the deployment of the two operating concepts.

In the literature on intelligent transportation systems (ITS), the potential of many advanced technologies for improving the performance of surface transportation systems is recognized, and, as a result, many forward-looking ITS concepts have been developed to capitalize on the potential. However, it has been observed (e.g., Tsao, 2001) that the initial “technology push” should be expanded to integrate with “customer (or user) pull” as well as stakeholder participation. This section addresses the potential needs of the customer of a truck-AHS and stakeholder concerns. These needs and concerns will be used for developing not only “end-state” AHS operating concepts but also intermediate steps toward them.

### **6.1 A Major Concern of the Long-haul Trucking Industry: Productivity**

To limit safety hazards and damage to roadway pavement, limits on weight, size and configuration have long been imposed on trucks (e.g., Transportation Research Board, 1982; Federal Highway Administration, 2000). Here, configuration refers to the number and sizes of trailers that are hauled by a tractor. The most common configurations in the State of California are straight truck, single (i.e., a tractor hauling a semi-trailer) and double (i.e., a tractor hauling two trailers of 28 feet or shorter).

The California law regarding permitted truck configurations is too complex to be summarized in this paper, due to space limitation. We expand on the length restriction on the tractor-semi-trailer configuration briefly below. The following configurations are in general permitted in California although local governments can impose stricter limits: “A semitrailer while being towed by a motortruck or truck tractor, if the distance from the kingpin to the rearmost axle of the semitrailer does not exceed 40 feet for semitrailers having two or more axles, or 38 feet for semitrailers having one axle if the semitrailer does not, exclusive of attachments, extend forward of the rear of the cab of the motortruck or truck tractor.” For ease of discussion, we will use 48 feet as the typical upper limit for the length of a semi-trailer, following other authors before us [e.g., Lankard and Lehrer, 1999].

The trucking industry tries to increase its productivity by using LCVs; many states in the nation have permitted their operations on selected highways and the access roads (March, 2001). Most notably among the LCVs are the Rocky Mountain Double (i.e., a tractor, a 48-foot trailer and a 28-foot trailer), the Triple Trailer Combination (i.e., a tractor and three 28-foot trailers) and the Turnpike Double (i.e., a tractor and two 48-foot trailers). Larger trucks are more efficient because they use less fuel per pound than smaller trucks. Fuel consumption increases as gross vehicle weight increases, but an LCV can haul considerably more cargo with a relatively small reduction in fuel mileage (Lankard and Lehrer, 1999).

Currently, no LCVs are allowed in California (California Legislative Counsel, 2001). A primary issue is safety, and a primary concern is the safety hazards such trucks may impose on the surrounding traffic, particularly the automobiles (e.g., Lankard and Lehrer, 1999). However,

safety may actually be improved if LCVs are allowed only on a dedicated and physically separated truck lane and in exclusive staging areas.

A major advantage of the truck-AHS to be proposed is its ability to support flexible configurations through electronic coupling of trucks. This allows a large number of driverless trailing trucks that can be hauled by one driver thereby extending the advantage of LCVs. This would certainly boost the productivity of a driver as well as that of the equipment significantly. Moreover, LCVs need to be assembled and disassembled mechanically and manually at staging areas at or near entrances and exits, which incurs facility costs, operating costs and delay. Electronic coupling of trucks, as part of truck automation, can avoid these disadvantages.

To reduce the likelihood of driver fatigue and the associated safety hazards, limits on a driver's work hours are imposed by both the Federal Motor Carrier Safety Administration (FMCSA) and the states (California Department of Motor Vehicles, 2001). These limits obviously have a significant negative impact on the productivity of a driver and that of the equipment, and have been a subject of considerable debate (Transportation Research Board, 1982; McCormick, 1999). If the work-hour limits can be relaxed, the productivity of a driver as well as that of the equipment can be increased.

Another possible source of productivity increase is relaxed work-hour limits. The operating characteristics of a truck require that the driver pay close attention to the road and continuously anticipate the behavior of the surrounding vehicles, resulting in a great amount of stress. The operating characteristics of a truck are different from those of an automobile, and truck steering must be gentle to avoid jack-knifing or the "crack-the-whip" effect (California Department of Motor Vehicles, 2001). With the aid of automated driving and the physical separation of trucks from automobiles, a truck driver may be able to drive safely for longer hours than otherwise. However, relaxing hours-of-service limits may be difficult. In fact, the Federal Motor Carrier Safety Administration proposed in 2000 to impose stricter hours-of-service limits on interstate trucking, as part of an FMCSA's safety action plan that includes an overall goal of reducing truck-related fatalities by 50 percent by the year 2010 (U.S. DOT, 2000). (In 1999, there were 5,203 truck-related fatalities.)

## **6.2 Transportation Agencies' Concern About Efficiency of Freight Movement**

Traffic congestion on the nation's highways has a significant impact not only on the movement of passengers or passenger vehicles, but also on the nation's freight movement and economic well-being. Consequently, the efficiency of goods movement has received much attention, and some state and the federal governments have begun to pay attention to the issues faced by the freight industry. For example, one of the two focal areas of the 1998 California Transportation Plan (Update) is goods movement (California Department of Transportation, 1998a; California Department of Transportation, 1998b). Other states have also realized the importance and the urgency of this issue. For example, the states along the freight corridor of I-10 have recently begun to work together to try to relieve the impact of traffic congestion on I-10 on goods

movement. These states formed a consortium known as National Automated Truck Facility (NATF), which is a multi-state pooled fund project.

Tsao and Rizwan (Tsao and Rizwan, 2000), in studying the air-express freight forwarding business recently, pointed out a “vicious cycle” regarding urban traffic congestion and freight movement. Given a fixed amount of freight to be delivered to customers, a typical reaction to traffic congestion on the part of freight carriers is to send more trucks. However, this leads to more congestion. Unlike passengers, who can benefit from using public transit or HOV lanes, freight transportation has nothing similar to resort to. Dedicated truck lanes, combined with automation, may provide options for increased throughput for freight traffic.

### **6.3 Transportation Agencies’ Concern About Pavement Damage Caused By Heavy Trucks**

It is widely held that heavy trucks inflict a disproportionate amount of damage to pavement compared to the rest of vehicle population. Lankard and Lehrer reported that Frank McCullough of the University of Texas at Austin estimated that the damage done by one pass of a tractor-trailer rig is equivalent to the damage done by the passing of 2,000 to 3,000 automobiles (Lankard and Lehrer, 1999). The proposed truck-AHS concept will concentrate most of the trucks in one lane and also narrow their driving path in that lane, because the automated guidance will decrease the amount of “wander” in the lane. Both of these AHS characteristics will allow more efficient design and construction of the pavement, because the strengthening can be applied where required.

### **6.4 The Driving Public’s and the Transportation Agencies’ Concern About Safety and Throughput Related to Heavy-Vehicle Traffic on Conventional Highways**

Mixing of small and heavy vehicles on the highway has been a significant source of safety concerns. When an accident or incident involving a large truck and smaller vehicles, e.g., automobiles, occurs, the safety consequences for the smaller vehicles are likely severe. Moreover, the consequent impact on highway throughput may be drastic. Not only the driving public but also the trucking industry will likely welcome this separation of truck traffic from the rest of the freeway traffic.

On a truck-AHS, truck behavior, e.g., speed, may be regulated more directly. Regulating the speed of the trucks could lead to smaller deviations of the individual truck speeds from the average speed. Smaller deviations in speed should result in fewer accidents (Solomon, 1964). Because many trucks will also be removed from the rest of the traffic stream, the variability of the speed of the rest of the traffic will also decrease, which could also decrease the number of accidents. Vehicle-to-vehicle and vehicle-to-infrastructure communication may increase the mutual understanding among neighboring trucks and hence also reduce the likelihood and severity of an accident among trucks.

### **6.5 Truck Manufacturers’ Inclination To Provide And Sell New Features**

Truck manufacturers, like automobile manufacturers, tend to welcome affordable technological innovations that will improve safety, complexity of vehicle control and comfort. They also tend to



welcome cost-effective technological innovations that will improve the fuel efficiency and driver productivity. Note that the truck industry's adoption of truck technology or new features depends also heavily on the return on investment (ROI). A general rule of thumb seems to be return of investment within two years [Calspan, 1995]. Few trucks on the road today are equipped with automatic transmission, which is a requirement for truck-AHS. Automated transmission provides driver comfort and perhaps safety and may open up the labor pool due to reduced training requirements, but may result in lower fuel efficiency. This goes to show the necessity to develop AHS operating concepts that would be sufficiently appealing to the trucking industry, from the perspective of productivity improvement and return on investment.

## **7. GENERAL FEATURES OF A TRUCK-AHS AND DESIGN OPTIONS**

This section first briefly describes the generic key features of the operations of a protected inter-city truck-AHS and then proposes alternative design options for the other key aspects. The inter-city truck-AHS proposed in (Tsao and Botha, 2001) combines the strengths of a freight rail system with those of a trucking system and formulates a new system concept that offers new and/or better services. This paper expands those concepts and develops new ones; it also proposes steps for their deployment.

### **7.1 General Features of a Truck-AHS**

The truck-AHS is placed in the median of an inter-city freeway. Access to the truck-AHS is controlled so that the automated truck traffic is separated from the rest of the traffic with physical barriers. The system is intended for long-haul freight transportation, and access points are spaced at large intervals, e.g., 100 miles. Trucks form closely spaced convoys so as to require only one driver in the lead truck. When compared to conventional long-haul trucking, it drastically reduces labor cost, capitalizes on reduced wind-drag for fuel efficiency (Ulmer, 1999), and increases mainline capacity. Moreover, this may also increase the utilization of equipment because the productivity of a trailing truck in a convoy is no longer directly tied to the presence of a driver on that truck, who is under strict work-hour restrictions. In the rest of this section, we discuss in detail three key aspects of a truck-AHS and their design options, and compare their relative merits. Operating concepts based on the design options will be described in the next section. Note that an automated truck on a truck-AHS may be an LCV. Figure 11 depicts the basic trip concept for a truck-AHS. Figures 12 and 13 focus on the access from the staging area to the mainline for an AHS truck-lane implemented on the left and right sides of the freeway direction, respectively. Figure 14 depicts the basic geometry for the mainline of a truck AHS.

The three key aspects are (a) the evolution of the composition of a (closely spaced automated) convoy on a truck-AHS, (b) integration of AHS and local collection-and-distribution operations, and (c) bridging rural truck-AHS sections through an urban area. Other possible important aspects include truck-train scheduling by the AHS operator, truck-train organization through matching of departure time, origin-destination, power, braking capability, etc.

### **7.2 Design Options for Convoying**

Closely spaced automated truck convoying is a key source of benefit, including reduction in the number of drivers required, reduction in fuel consumption and increase in mainline capacity. The

actual benefit hinges upon how such a convoy evolves in terms of its composition, particularly how it is formed, changed and eventually dispersed. There exist at least four fundamental ways for a convoy to evolve in composition:

- (C-a) **Static Convoying - Common Truck Destination:** A truck convoy consists of trucks that have a common destination (i.e., exit). It is formed only in a staging area located at or near an access point, and it remains intact throughout its travel on the truck-AHS, from the entry to the exit points. Joining other convoys to form a longer convoy or splitting into multiple smaller convoys is not allowed on the truck-AHS. Only one driver is required for the convoy.
- (C-b) **Static Convoying - Different Truck Destinations:** Same as Option (C-a) except that a truck convoy may consist of trucks destined for different exits. A convoy traveling on the mainline must exit at an off-ramp in its entirety in order to allow those of its constituent trucks destined for that off-ramp to exit. After discharging those trucks, the remainder of the convoy, if any, may be expanded to include additional trucks, and the resulting convoy reenters the truck-AHS.
- (C-c) **Dynamic Convoying - Driver-Supervised Merging and Splitting:** A convoy entering the mainline may join, at a location where the on-ramp and the mainline merge, another convoy already traveling on the mainline. A portion of a convoy already traveling on the mainline may split off from the convoy, at a location where the mainline splits to accommodate an off-ramp, to exit the mainline. But, the lead truck of the entering convoy and the lead truck of the exiting portion must have a driver. Merging of two convoys anywhere else on the mainline is also supported, primarily for fuel efficiency but not for labor savings.
- (C-d) **Dynamic Convoying - Infrastructure-Supervised Merging and Splitting Only at On- and Off-Ramps, Respectively:** This option is the same as (C-c) but with two exceptions. First, no driver is required for the lead truck of the entering convoy or the exiting portion. Second, merging or splitting of convoys can take place only at or near an on- or off-ramp, respectively.

In our comparison of the evolution of convoy composition, we focus on four efficiency criteria: (1) labor requirement (i.e., requirement for a driver), (2) fuel consumption, (3) the space requirements for accommodating entry and exiting at a staging area, and (4) the space requirements for accommodating trucks on the mainline (i.e., the mainline capacity). In some instances, we will point out possible differences in safety and cost. However, since the cost depends heavily on detailed designs, which are not available at this time, we cannot consider them explicitly. Safety effects are hard to determine at this point because the operating characteristics of the automation technology are not yet known.

We compare Options (C-a) and (C-b) first. Options (C-a) and (C-b) are both “end-to-end” convoy operations (from the entry point to the exit point). In cases where the demand between a given origin-destination pair is so high that the trucks traveling from the given origin to the given destination alone can form sufficiently long convoys to fully capitalize on the labor-saving, fuel-saving and mainline-capacity potential of closely-spaced convoying, there is no need to combine trucks destined for different exits to form a larger “combination” convoy under Option (C-b). Therefore, these two options offer similar efficiency with respect to all four efficiency criteria.

However, in all other cases, the two options may lead to major differences in all four criteria. On one hand, Option (C-b) offers the opportunity to form larger convoys for possible higher labor savings (due to few drivers), higher fuel savings (due to longer convoys) and higher mainline capacity (again due to longer convoys). On the other hand, under Option (C-b), a convoy must exit the truck-AHS at all the exits involved and re-enter it after dropping off the corresponding trucks (and perhaps picking up other trucks too). When compared to Option (C-a), this will lead to more traffic in the staging areas involved and may require much larger staging areas or may cause a significant amount of traffic congestion in the staging areas. (The congestion should not be allowed to become so severe that it spills back on to the truck-AHS.) For a fair comparison with Option (C-a), the labor, fuel and mainline-capacity advantages of Option (C-b) need to be studied and weighted against its space or congestion disadvantage. Quantitative modeling is required for the comparison.

We now compare Options (C-a) and (C-c). Trucks ready to enter the truck-AHS at a particular staging area can be grouped into convoys according to their exit destinations. Under either of the two options, those trucks that are destined for the same exit can form one or more convoy and only one driver is needed for each such convoy. The size of such a convoy depends on the tolerable delay for a truck to wait for the arrival of a sufficient number of other trucks with the same destination exit in order to fully capitalize on the potential in labor, fuel and mainline-capacity efficiency offered by closely spaced convoying. The operating efficiency associated with larger convoys must be weighed against the possible longer delays. If the size of such a convoy is “sufficiently” large in terms of fulfilling the potentials offered by closely spaced convoying, then there is no need to form a “combination” convoy with other convoys destined for different exits under Option (C-c). In this case, the two options (C-a) and (C-c) have identical performance.

The case in which the number of trucks destined for a common exit is small, given the tolerable delay due to waiting for other trucks destined for the same exit, renders different performance in terms of efficiency for the two options. Under (C-c), a convoy can join, within the staging area, other convoys destined for different exits to form one larger convoy or can join a convoy already traveling on the mainline. Although such joining will not lead to any more labor savings than Option (C-a), it can offer higher fuel efficiency and higher utilization of the space on the mainline, both of them due to closely-spaced convoying. Therefore, Option (C-c) is more efficient than Option (C-a) overall.

The comparison between Options (C-a) and (C-d) is straightforward. Since Option (C-d) provides more flexibility than Option (C-a), it requires fewer drivers and enables the formation of longer (closely-spaced) convoys. Therefore, it achieves higher labor savings, fuel efficiency and mainline capacity. It also requires the same amount of space for staging, and hence is more efficient than Option (C-a) overall. However, it does require a higher level of technology and traffic coordination.

We now compare Option (C-b) and Option (C-c). They should achieve similar fuel efficiency. Under Option (C-c), although multiple drivers will be needed, one for each destination involved, a truck will not leave the mainline truck-AHS until it reaches its destination. On the other hand, Option (C-b) requires only one driver but may require more space for the staging areas or may cause more staging-area congestion than Option (C-c). Again, quantitative modeling is required for a proper efficiency comparison.

The comparison between Options (C-b) and (C-d) is also straightforward. Both options enjoy the same labor savings, fuel efficiency and mainline capacity. But, Option (C-b) may require more space for the staging areas or may lead to more traffic congestion at the staging areas. Therefore, Option (C-d) is more efficient than Option (C-b) overall.

Finally, we compare Options (C-c) and (C-d). Option (C-c) requires a driver on the lead truck of an entering convoy or an exiting portion of a mainline convoy because of the general requirement of a driver on the lead truck of a convoy. However, this requirement is imposed primarily because of the need for the driver to react to abnormal events, e.g., the presence of safety-impacting debris and other obstacles difficult to detect using technology [Tsao and Ran, 1996]. If the joining and the splitting operations are allowed only at or near the entrances and exits, which can be closely monitored by human infrastructure operators with the help of advanced technologies, then a driver may not be required for the lead truck of an entering convoy or the lead truck of an exiting portion of a mainline convoy. This actually motivated Option (C-d). The two options can achieve similar fuel-efficiency, have similar space requirements for the staging area, and offer similar mainline capacity. However, Option (C-d) provides less labor-intensive operations than Option (C-c). Therefore, Option (C-d) is more efficient than Option (C-c) overall.

The features and the relative efficiencies of the four convoying options are summarized in Table 2. Their rankings in operational efficiency are summarized in Table 3. Note again that all this discussion has been focused on only operational efficiency. Technological feasibility and safety have been assumed, and cost issues have been set aside.

**Table 2: Design Options for Convoy Evolution and Their Relative Operational Efficiency**

<b>Design Options</b>	<b>Features</b>	<b>Relative Efficiency: (1) Labor, (2) Fuel, (3) Staging and (4) Mainline Capacity</b>
(C-a) Static Convoying - Common Truck Destination: no splitting or joining on AHS	<ul style="list-style-type: none"> <li>• Formed only in a staging area</li> <li>• Remaining intact throughout its travel on the truck-AHS, from the entry to the exit points</li> <li>• Joining other convoys to form a longer convoy or splitting into multiple smaller convoys not allowed</li> <li>• Only one driver required for the convoy</li> </ul>	(1) Less efficient than C-b and C-d in labor; same as C-c (2) Less efficiency than C-b, C-c and C-d in fuel efficiency (3) More efficient than C-b in staging; same as C-c and C-d (4) Less efficient than C-b, C-c and C-d in mainline capacity (Dominated by C-c and C-d, i.e., less efficient than C-c and C-d overall)
(C-b) Static Convoying - Different Truck Destinations	(5) Same as C-a except that a truck convoy may consist of trucks destined for different exits. (6) Same technology requirements as C-a	(Comparison with C-a made above) (1) More efficient than C-c in labor; same as C-d (2) Same as C-c and C-d in fuel efficiency (3) Less efficient than C-c and C-d in staging (4) Same as C-c and C-d in mainline capacity (Dominated by C-d)
(C-c) Dynamic	<ul style="list-style-type: none"> <li>• An entering convoy allowed to join</li> </ul>	(Comparisons with C-a and C-b made)

<p>Convoying - Driver-Supervised Merging and Splitting:</p>	<p>another convoy already traveling on the mainline at an on-ramp</p> <ul style="list-style-type: none"> <li>• A portion of a convoy already traveling on the mainline allowed to split off to exit at an off-ramp</li> <li>• A driver required on the lead truck of the entering convoy or the exiting portion</li> <li>• Merging of two convoys anywhere else on the mainline also supported, primarily for fuel efficiency but not for labor savings</li> <li>• More advanced technology required than all previous Options</li> </ul>	<p>above)</p> <ol style="list-style-type: none"> <li>(1) Less efficient than C-d in labor</li> <li>(2) Same as C-d in fuel efficiency</li> <li>(3) Same as C-d in staging</li> <li>(4) Same as C-d in mainline capacity</li> </ol> <p>(Dominated by C-d)</p>
<p>(C-d) Dynamic Convoying - Infrastructure-Supervised Merging and Splitting Only at On and Off-Ramps, Respectively</p>	<ul style="list-style-type: none"> <li>• Same as (C-c) but with two exceptions.</li> <li>• No driver required for the lead truck of the entering convoy or the exiting portion.</li> <li>• Merging and splitting of convoys taking place only at or near an on- and off ramp, respectively</li> <li>• More advanced technology required than all previous Options</li> </ul>	<p>(Comparisons with C-a, C-b and C-c made above)</p>

**Table 3: Rankings in Operational Efficiency Among Design Options for Convoying**

Design Option	C-a	C-b	C-c	C-d
<b>Labor</b>	3	1	3	1
<b>Fuel</b>	4	1	1	1
<b>Staging Area</b>	1	4	1	1
<b>Mainline Capacity</b>	4	1	1	1

**7.3. Design Options for Integration of AHS Operations with Local-Carrier Operations**

So far, we have focused on truck-AHS operations. Since end-to-end freight transportation (from the shipper’s to the receiver’s, i.e., the consignee’s, loading docks) involves a mode change at the staging area, the degree of integration of the truck-AHS operations and local-carrier operations also plays an important role in the overall efficiency of using a truck-AHS. In fact, the desirability of Options (C-a) through (C-d) also depends on this degree of integration. We now develop design options and compare their merits.

The design options center around the institutional structure for and interaction among the entities providing the freight service from one end to the other, particularly the line-haul service and the local collection-and-distribution service. On one extreme is the Option (I-a) of having a carrier provide the end-to-end service (from the shipper’s to the receiver’s loading docks), including provision of all tractors and even the trailers to be used on and even off the truck-AHS and all the required drivers. Note that multiple companies providing such end-to-end hauling service may

operate on the freight corridor, but each and every one of them provides the complete end-to-end service. Option (I-b) not only allows the end-to-end haulers of Option (I-a) to offer the end-to-end service but also allows the line-haul service and the local collection-and-distribution service to be performed by separate companies: AHS haulers and local feeder haulers. Tsao and Botha (Tsao and Botha, 2001) refer to a carrier offering the service of hauling other companies' trucks or just trailers on a truck-AHS, in addition to its own freight, as an AHS Hauler. By this definition, an end-to-end hauler is also considered as an AHS hauler. Note that the truck-AHS is open only to the tractors operated by the AHS haulers. The local feeder haulers may haul their own freight exclusively, but may also be contractors hauling for another carrier. The exclusive use by the AHS haulers disqualifies the system as an *open system*. In fact, both Options (I-a) and (I-b) are *closed systems* to be used exclusively by the end-to-end haulers or the AHS haulers, respectively. Under both Options (I-a) and (I-b), a truck convoy can be formed by trucks or tractors operated by different carriers, subject to their negotiation.

The institutional arrangement of truck-AHS under Option (I-c) is much more flexible. Any properly equipped truck can enter and use the truck-AHS. This option can be considered as an *open system*. In such an open system, "fitness checking" may be required before permitted entry to the AHS, and hence additional space may be required at a staging area to accommodate the checking and the possible accompanying queue. In a closed system under either Options (I-a) or (I-b), such checking may be performed at the maintenance facilities of the small number of AHS carriers. Under Option (I-c), carrier B can negotiate with carrier A so that trucks of carrier B can tag along those of carrier A to form a "joint" convoy driven by a single driver of carrier A in the lead truck of the joint convoy.

We now discuss the relative merits of these three institutional options with respect to four different criteria: (1) jurisdiction requirements for mode-change operations, (2) engineering requirements for mode-change operations, (3) degree of possible synergy in combining the AHS and local collection-and-distribution operations, (4) compatibility with possible accommodation of within-urban-area (automated) freight transportation and (5) degree of system openness. Note that although system openness allows more user institutions, it may not be an overall desirable feature. The design options for integrating AHS and local feeder operations, their features and relative merits are summarized in Table 4.

Option (I-a) can achieve the highest operating efficiency among the three options. Since only one institution provides the end-to-end service, there is no need to check bill of lading, inspect the freight for possible damage and complete paperwork and other activities required between two institutions. These activities not only take time but also take space. The delay due to these hand-off activities adds to the cost of transportation for the carriers and for their customers. Such hand-off is required under the other two options (I-b) and (I-c). If it takes place in the staging area, then significantly more space may be required for the staging areas. This will add to the cost and may decrease the feasibility of an inter-city truck-AHS. Whether the hand-off takes place in or away from the staging areas, the space requirement will likely add to the cost of using a truck-AHS.

Since, under Option (I-a), one company performs both local collection and distribution and mainline AHS operations, dual-mode trucks can be used to maximize the efficiency of mode-change operations. However, note that use of dual-mode trucks is not required under this or any

other option. Use of dual-mode trucks is not as likely under Options (I-b) and (I-c). As mentioned earlier, fitness checking for any truck wishing to use the AHS may be required under Option (I-c) and may have to take place in the staging area. This adds engineering complexity to the AHS operations. This additional complexity may be significant unless a complete condition check can be performed electronically.

A key determinant of efficiency is the amount of productivity loss due to back-haul inefficiency (i.e., a truck's empty return to base) and dead-heading (i.e., a driver's personal return trip to base). Under Options (I-b) and (I-c), a truck is driven to the staging area after local collection for the line-haul. An AHS hauler may or may not use the tractor of that truck for travel on the AHS, depending on if the tractor is properly equipped or whether the AHS hauler accepts an equipped tractor not owned, operated and maintained by itself. If the tractor does not go on the AHS, it and its driver need to either return to a depot without a load or wait for a load to exit from the truck-AHS. Even if the tractor goes on the AHS, the driver usually should not (unless he or she works for an end-to-end hauler and it is efficient for the end-to-end hauler to do so), and hence he or she should wait for an exiting truck of his or her company or to arrange for a personal return trip. Such loss of productivity due to the need to arrange for back-haul or drivers' personal return trips (i.e., "empty return," or "dead-heading") may be significant unless the volume of freight for a carrier is sufficiently large so that the drivers and the possible tractors can be utilized shortly after they are freed.

It is conceivable that only local brokerage carriers specializing in providing the feeder service (i.e., local collection and distribution) or very large end-to-end carriers would be able to avoid excessive loss of productivity due to inefficient arrangement of the return trips. In any case, Option (I-a) will be able to suffer the least amount of productivity loss due to empty return or dead-heading because of the all-encompassing nature of the carriers and because the local and AHS operations can be planned and controlled in one combined optimization process.

Trucks are very diverse in terms of their capabilities, e.g., braking, acceleration and power for hill-climbing; the braking capability depends mainly on the weight they carry, which is a major variable with a wide possible range. It is well known that the safety distance between two longitudinally adjacent vehicles on an AHS depends on their individual braking capabilities [e.g., Michael et al., 1998]. In convoying of automated trucks, both the safe distance between two neighboring trucks in the same convoy and the safe distance between two neighboring convoys hinge upon the trucks' braking capabilities and, more importantly, how the trucks are organized into convoys. The safety and efficiency of a convoy would be maximized if they have similar braking, acceleration and hill-climbing capabilities, with the weights carried by the trucks considered. (The performance of a convoy is limited to that of the least capable truck of a convoy.) Such organizing is difficult to achieve for an *open system* like (I-c), but can be more easily achieved with a *closed system* like either (I-a) or (I-b).

However, the feasibility of the formation of all-encompassing service providers required for (I-a) without going through (I-c) or (I-b) needs to be carefully studied. Another possible disadvantage of closed systems like (I-a) and (I-b) has to do with urban freight transportation (i.e., transportation of freight between two points within an urban area) if the urban portion of the inter-city truck-AHS is to be open to such freight transportation also. Such within-urban-area freight transportation may require an open system like (I-c). The design options for integrating

AHS and local feeder operations, their features and relative merits are summarized in Table 4. Rankings of these design options with respect to the five criteria are summarized in Table 5.

**Table 4: Design Options for Combining AHS and Local Operations**

<b>Design Option</b>	<b>Features: Carrier Institution, Institutional Roles</b>	<b>Merits: (1) Jurisdiction Simplicity, (2) Engineering Simplicity, (3) Ease of Staging, (4) Synergy in Planning and Control, (5) Compatibility with Urban AHS &amp; (6) Openness</b>
(I-a) Closed system with end-to-end haulers providing service from the shipper's to the receiver's (i.e., the consignee's) loading docks	<ul style="list-style-type: none"> <li>• Open only to end-to-end haulers providing service between the shipper's and the consignee's (i.e., the receiver's) loading docks; possibly multiple such end-to-end hauling companies</li> <li>• Provision of all tractors and even the trailers to be used on and even off the truck-AHS (by the end-to-end haulers); provision of all drivers too</li> </ul>	<ol style="list-style-type: none"> <li>(1) No hand-off between two different carriers and hence no need for verification of bill of lading, damage inspection, paperwork and other activities required between two carriers</li> <li>(2) Facilitating the use of dual-mode trucks for more efficient mode-change</li> <li>(3) No or little additional staging requirement due to absence of hand-off requirements and high potential of dual-mode trucking</li> <li>(4) Enabling centralized optimal planning and control of operations, but requiring all-encompassing service providers; minimization of back-haul inefficiency and dead-heading possible</li> <li>(5) Possibly incompatible with an urban truck-AHS or urban truck-bus-AHS, which may require an open system</li> <li>(6) Least open among the three</li> </ol>
(I-b) Closed system with end-to-end haulers, AHS haulers providing only mainline services and local feeder haulers providing local collection and distribution services	<ul style="list-style-type: none"> <li>• AHS haulers and local feeder haulers as additional service providers</li> <li>• Only those tractors operated by AHS haulers to be allowed on the AHS, including the end-to-end haulers</li> <li>• Local feeder haulers possibly hauling for another carrier as contractors</li> </ul>	<ol style="list-style-type: none"> <li>(1) Hand-off between AHS haulers and local feeder haulers required and hence verification of bill of lading, damage inspection, paperwork and other activities also possibly required; not only time- but spacing-consuming, leading to higher transportation and even infrastructure costs</li> <li>(2) Use of dual-mode trucks for more efficient mode-change still possible but requiring special institutional agreement; mode-change operations becoming more complex without dual-mode trucks</li> <li>(3) Significant amount of additional staging space likely required due to the likely need for hand-off and the complexity of mode-change, although hand-off can be performed off-site (away from AHS entrances/exits)</li> <li>(4) Allowing a more flexible institutional arrangement, but at a possible price of some loss of efficiency due to sub-optimal planning, and control of operations; back-haul inefficiency and dead-heading likely; cooperation and coordination between AHS haulers and local feeder haulers possible</li> <li>(5) Possibly incompatible with an urban truck-AHS or urban truck-bus-AHS, which may require an open system</li> <li>(6) More open than (I-a) but less open than (I-c)</li> </ol>
(I-c) Open system where any	<ul style="list-style-type: none"> <li>• Open to any properly-equipped trucks</li> </ul>	<ol style="list-style-type: none"> <li>(1) Hand-off between AHS haulers and local feeder haulers required as in (I-b); no such hand-off</li> </ol>



properly equipped trucks can use the truck-AHS.		<p>required for the other carriers as long as they alone provide end-to-end services</p> <p>(2) Mode-change operations also including verification of vehicle “fitness” (for AHS travel)</p> <p>(3) Less significant amount of additional staging required due to a smaller amounts of hand-off and complex mode-change operations, assuming that fitness checking can be performed electronically and hence requires little additional staging space</p> <p>(4) Possible further loss of efficiency when compared to the two closed systems summarized above because cooperation and coordination among AHS, local feeder and the other carriers could be more difficult</p> <p>(5) Compatible with an urban truck-AHS or urban truck-bus-AHS, which may require an open system</p> <p>(6) Most open among the three</p>
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**Table 5: Efficiency Rankings: Options for Combining AHS and Local Operations**

Design Option	I-a	I-b	I-c
Jurisdiction Simplicity	1	2	3
Engineering Simplicity	1	2	3
Ease of Staging	1	3	2
Synergy In Planning And Control	1	2	3
Compatibility With Urban Ahs	3	3	1
Degree of System Openness	3	2	1

#### 7.4 Design Options for Bridging Rural AHS Sections of an Inter-city Truck-AHS Through an Urban Area

From the viewpoints of driver and equipment productivity, fuel efficiency and mainline capacity, it is clear that the benefit of a truck-AHS featuring closely spaced automated conveying increases with the length of the truck-AHS. This can be viewed as a special case of economy of scale, and may be called “economy of distance.” Although the right-of-way requirement may not be a serious issue in rural areas, it could be a show-stopper for urban areas. Alternatives for bridging two arbitrary rural truck-AHS sections through an urban area and possible issues associated with the alternatives are summarized in Table 6. The criteria include (1) cost, (2) safety hazards and disruption to existing traffic during construction, (3) seismic hazards in earthquake prone areas, and (4) effect on benefit of truck-AHS. The last option actually involves two truck-AHSs separated by an urban area, and may create sufficient mode-change activities that may offset much, if not all, of the benefit accrued on the truck-AHS.

**Table 6: Options for Bridging Two Rural AHS Sections Through An Urban Area**

Options	Possible Issues
(U-a) Constructing a truck-AHS using the unused right-of-way of the urban portion of the existing freeways serving the freight corridor	<ul style="list-style-type: none"> <li>Such right-of-way may not exist.</li> </ul>
(U-b) acquiring new right-of-way and expanding the urban portion of the existing freeways serving the freight corridor	<ul style="list-style-type: none"> <li>This option may be prohibitively costly.</li> </ul>
(U-c) Dedicating an existing lane of the freeway and using other space currently used for existing	<ul style="list-style-type: none"> <li>Opposition from existing users may prevent implementation.</li> </ul>

traffic	
(U-d) double-decking the existing urban portion or part of it	<ul style="list-style-type: none"> <li>• It may be prohibitively costly.</li> <li>• It may also pose seismic hazards in areas with high seismic activities.</li> <li>• Disruption to and safety hazards for existing traffic during construction are possible.</li> </ul>
(U-e) use of other existing freeways for urban-area bypass	<ul style="list-style-type: none"> <li>• Such bypass freeways may not be available, or may not have sufficient right-of-way.</li> </ul>
(U-f) construction of new freeways for urban-area bypass	<ul style="list-style-type: none"> <li>• It may be prohibitively costly.</li> </ul>
(U-g) combinations of the above	<ul style="list-style-type: none"> <li>• The relative merits depend on the combination and the site.</li> </ul>
(U-h) no bridging: ending the truck-AHS at one end of the urban area and resuming it at the other end, with the freight movement between the two ends “bridged” by conventional trucking.	<ul style="list-style-type: none"> <li>• The overhead of mode change associated with U-f may actually offset much, if not all, benefit of a truck-AHS.</li> </ul>

A detailed quantitative comparative study of these different options of an urban truck-AHS requires site specifics, a detailed specification of the system and a set of “operating scenarios,” including possible demand (i.e., origin-destination) volumes and arrival and departure patterns. It clearly requires a huge amount of effort and is beyond the scope of this paper.

Before closing this section, we summarize several key aspects of deploying a truck-AHS in urban vs. rural areas not only to illustrate some of the related issues and problems and point out relative merits associated with the design options for deploying an inter-city truck-AHS but also to point out some issues associated with deploying a truck-AHS in an urban area alone without being a part of deploying an inter-city truck-AHS. The factors for consideration are summarized in Table 7. A detailed discussion of these factors is beyond of scope of this paper.

**Table 7: Comparison between Truck-AHS Deployment in Urban and Rural Areas**

<b>Key Factors</b>	<b>Urban Truck-AHS</b>	<b>Rural Truck-AHS</b>
Main Customers	<ul style="list-style-type: none"> <li>• Time-sensitive local carriers, including overnight express carriers</li> <li>• Carriers of high-value freight</li> <li>• Possibly constructed as an AHS for heavy vehicles, including buses</li> </ul>	<ul style="list-style-type: none"> <li>• Long-haul carriers</li> </ul>
Primary Customer Needs	<ul style="list-style-type: none"> <li>• Congestion relief, including recurrent and non-recurrent</li> </ul>	<ul style="list-style-type: none"> <li>• Productivity improvement, including labor and equipment</li> </ul>
Key Benefits and Motivation	<ul style="list-style-type: none"> <li>• Reduced travel time for trucks</li> <li>• Higher travel-time and service reliability for urban trucking</li> <li>• Higher safety due to separation of truck traffic from automobile traffic</li> <li>• Higher fuel efficiency</li> <li>• Higher system capacity</li> </ul>	<ul style="list-style-type: none"> <li>• Higher driver productivity, in terms of labor savings</li> <li>• Higher equipment productivity, in terms of higher utilization (due to higher degree of decoupling of truck movement from driver presence and restriction of driver work hours).</li> <li>• Higher fuel efficiency</li> <li>• Higher mainline capacity</li> <li>• Reduced travel time</li> <li>• Higher safety due to separation of some truck traffic from automobile</li> </ul>

		traffic
Contrast of Major Operational Features	<ul style="list-style-type: none"> <li>Closely-spaced automated truck convoys, but with no driverless trucks entering or exiting the ahs</li> <li>No LCV assembled or disassembled</li> <li>No staging areas required nor provided; a small “check-in” and buffer area possible</li> <li>Frequent access-egress points</li> </ul> (Closely spaced automated truck convoys with driverless trailing trucks accommodated on rural truck-AHS can still pass through the urban AHS.)	<ul style="list-style-type: none"> <li>Closely-spaced automated truck convoys with driverless trailing trucks</li> <li>LCVs also accommodated</li> <li>Large staging areas required to assemble truck convoys and to assemble LCVs</li> <li>Long distance between neighboring access-egress points, e.g., 100 miles</li> </ul>
Availability of Right-of-way	<ul style="list-style-type: none"> <li>Low</li> <li>A possible major cost factor if not a possible “show-stopper”</li> </ul>	<ul style="list-style-type: none"> <li>High in general</li> <li>Mountains and cliffs possibly posing severe constraints</li> </ul>
Ease of Construction	<ul style="list-style-type: none"> <li>Difficult</li> </ul>	<ul style="list-style-type: none"> <li>Easier in general</li> </ul>
Impact on Surrounding Areas:	<ul style="list-style-type: none"> <li>High in emission and noise throughout the length</li> <li>High in congestion near the access and egress points</li> </ul>	<ul style="list-style-type: none"> <li>Low in general</li> <li>Large staging areas needed for entry and exit</li> </ul>
Cost/Financing (for trucking, which accounts for a small percentage of overall traffic)	<ul style="list-style-type: none"> <li>High value of time for the user with commensurate user fees and accommodation of passenger buses possibly justifying the cost</li> </ul>	<ul style="list-style-type: none"> <li>With LCVs allowed and the accompanying higher user fees collected (than smaller trucks), financial feasibility more likely</li> </ul>

## 8. OPERATING CONCEPTS FOR A PROTECTED INTER-CITY TRUCK-AHS ON A FREIGHT CORRIDOR

It should be clear, based on the design options addressed in the previous section, that combining the options for convoy evolution with the option for integrating AHS and local operations would result in many possible system operating concepts for an inter-city truck-AHS. This section focuses on the discussion of two alternative system operating concepts: Option (I-c) combined with Option (C-d) and Option (I-b) combined with Option (C-b). They will be referred to as an open truck-AHS with dynamic (closely-spaced) conveying near ramps and a closed truck-AHS with static (closely-spaced) conveying of trucks destined for different exits, respectively. For ease of discussion, they will also be referred to as an open truck-AHS with dynamic conveying and a closed truck-AHS with static conveying, respectively, or simply as the open system and the closed system, respectively. There exist other system operating concepts, either as variations of the two concepts or as mixture of them, but a discussion of the two end-state concepts will assist in understanding major differences that may exist among other alternative system operating concepts.

We first develop the open-system operating concept and then point out the difference between it and the closed-system one. Detailed evaluation of and comparison among these two and other system operating concepts is a worthy topic for future research.

### 8.1 An Open-system Operating Concept with Dynamic Closely-spaced Conveying for a Protected Inter-city Truck-AHS

This system operating concept features Options (C-d) and (I-c). A convoy entering the mainline may join, at or near an on-ramp, another convoy already traveling on the mainline from the rear of the mainline convoy; a portion of a convoy traveling on the mainline may split off, at or near an off-ramp, to exit. In addition, no driver is required for the lead truck of the entering convoy or the exiting portion. Any equipped truck or LCV can enter and use the truck-AHS. Part of this system operating concept was reported in (Tsao and Botha, 2002). We now summarize normal operations and operations related to abnormal events of this open system. We focus on AHS operations only; their integration with local feeder operations is omitted.

## Normal Operations:

### *Normal Mainline Operations*

- A single lane in each direction physically separated from manual traffic, without a full breakdown lane but with a shoulder that is sufficiently wide so that the single lane plus the shoulder will be able to accommodate one disabled truck on the shoulder and one lane of through traffic at a moderate speed. Note that the shoulder will likely be needed for other purposes also. For example, tire treads separated from truck tires may move or be moved onto the shoulder. In such a case, the traffic will not be impeded by the presence of such large debris. Where additional right-of-way is available, a full second lane can be provided to be used as a passing lane or a breakdown lane.
- Automated vehicle control, including lateral and longitudinal control, enabling hands-off and feet-off truck operation
- Automated convoying, with an upper limit on the length of a convoy: The lead truck of a convoy must have a driver. The driver of the lead truck is responsible for detecting debris ahead on the lane or other abnormal events that cannot be reliably or cost-effectively detected by automation; the driver may also be tasked with actually driving the truck, with or without any automation.
- Driverless trailing trucks: No drivers are required on the trailing trucks of an automated convoy.
- Closely spaced convoying: The shorter the distance between two trucks in a convoy, the less “wind-drag” on both trucks and hence the higher fuel efficiency. Moreover, the shorter the distance, the higher the mainline capacity. The achievable minimum safe distance is a subject of future research.

### *Normal Access and Egress Operations:*

- Dedicated on- and off-ramps and staging areas: Design of staging areas will require future research.
- Multi-destination convoying: A convoy may consist of trucks destined for different exits. However, trucks destined for a common exit are grouped into a consecutive block to facilitate the exiting process as much as possible. If an entering truck does not have to join a convoy already traveling on the mainline at the rear or the front of the convoy and can insert itself between any two adjacent trucks of the convoy, then the potential of this block-wise configuration can be maximized.

- Negotiated cross-carrier convoying: Different carriers may negotiate for the terms that govern grouping their trucks in one convoy.
- Convoy entry into the AHS mainline after assembled in an staging area
- Automated convoy merging at on-ramp: An entering convoy or truck may “tag” onto the end of a convoy already traveling on the mainline at or near an on-ramp, without first entering the AHS mainline as a separate convoy (with long inter-convoy distances from the neighboring convoys) and then merging with a neighboring convoy. This feature may reduce much disturbance to mainline traffic at access locations and increase the mainline capacity (Hall et al., 2001). Such tagging is a form of convoy merging, but is performed at or near an on-ramp. With on-ramp areas closely monitored by the infrastructure for possible safety-impacting debris or events, such convoy-tagging requires no driver on the lead truck of the entering convoy, and hence reduces labor requirements.
- Convoy exiting into a staging area at the destination exit.
- Automated convoy-splitting at off-ramp: Convoy splitting to facilitate exiting of a portion of the convoy: Without such splitting, the whole convoy would have to exit the mainline to let the exiting trucks leave the convoy and hence may cause congestion at staging areas under some conditions. Such convoy splitting is performed only at or near an off-ramp. The lead truck of the exiting portion needs not have a driver; the splitting operation is supervised by the infrastructure, which monitors the off-ramp area closely.
- “Simultaneous splitting and exiting”: A portion of a convoy splits away from the convoy as it exits the mainline and moves into the off-ramp. In other words, the exiting portion needs not separate itself from the rest of the convoy at full inter-convoy distances before moving into the off-ramp. This feature may also reduce disturbance to mainline traffic at egress locations and increase the mainline capacity (Hall et al., 2001).

### **Operations Related to Abnormal Events (Issues and Solutions)**

- The driver of the convoy leader watches out for possible safety hazards, e.g., obstacles or large debris, for the whole convoy. (Replacing human cognitive ability and adaptability by machine is difficult.)
- Standards for fleet maintenance will have to be developed so as to minimize vehicle failure rate and hence lane blockage probability.
- Organizing trucks of different characteristics into different convoys to maximize the rates of acceleration and deceleration for the convoy and to minimize probability and severity of intra-convoy collision, e.g., braking capability, etc. Organizing trucks of different destinations, different arrival times (at the origin staging area) or different carriers into convoys to maximize operational efficiency
- A disabled truck is to be parked on the shoulder; traffic will have to slow down and stay to the safe side of the lane (through automation).
- Intra-convoy collision would involve lesser liability issues if all trucks in a convoy are operated by the same company. Otherwise, normal liability principles would apply or new ones might be needed. The latter may involve negotiation among companies participating in a convoy.

## **8.2 A Closed-System Operating Concept**

This system operating concept features Options (C-b) and (I-b). More explicitly, a convoy remains intact throughout its travel on the truck-AHS from the entry to the exit points. No joining by other convoys to form a longer convoy or splitting into multiple smaller convoys is allowed. The system not only allows end-to-end haulers to offer the end-to-end service but also allows the line-haul service and service of local collection and distribution to be performed by separate companies: AHS haulers and local feeder haulers. (The local feeder haulers may haul exclusively their own freight, but may also be contractors hauling for another carrier.) Note that this truck-AHS is open only to the tractors operated by AHS haulers, including the end-to-end haulers.

We point out and list only the differences of this operating concept from its open-system counterpart defined in Section 4.1.

*Normal Operations:*

*Normal Mainline Operations (No Differences)*

*Normal Access and Egress Operations:*

The whole convoy must exit the mainline to let the exiting trucks leave the convoy in the staging area, and trucks may be added to the remainder of the convoy in the staging area before re-entering the mainline. All the items listed above for the open-system concept apply except:

- No automated convoy merging at all: Automated tagging of an entering convoy or truck onto the end of a mainline convoy is not supported. In fact, no automated convoy merging is supported at any location.
- No automated convoy splitting all: The whole convoy would have to exit the mainline to let the exiting trucks leave the convoy (if not all trucks in a convoy are destined for the same exit).
- No “Simultaneous splitting and exiting”

*Operations Related to Abnormal Events (Issues and Solutions)*

The differences from their open-system counterpart are:

- Development and enforcement of fleet maintenance standards may be easier because of the smaller number of institutions involved in the closed AHS operations.
- Organizing trucks according to their characteristics, destinations, arrival times (at the origin staging area), carriers, etc., to optimize the operational efficiency may be easier because of the simpler institutional structure of this closed system.
- Intra-convoy and inter-convoy collision would tend to involve lesser liability issues because all trucks involved are operated by only a few AHS haulers.

## **9. DEPLOYMENT SEQUENCES TOWARD THE PROTECTED AUTOMATED HIGHWAY SYSTEMS FOR INTER-CITY TRUCKING**

In this section, we discuss two alternative deployment sequences, one for the open-system operating concept with dynamic convoying and the other for the closed-system operating concept

with static convoying. Major differences related to the deployment issues are also briefly discussed. For a general framework for evaluating ITS deployment strategies, the reader is referred to [Tsao, 2001]. Some critical issues in deploying AHS and some specific criteria for evaluating AHS deployment strategies can be found in [Tsao, 1995b and 1995c; AlKadri et al., 1998; Tsao, 1998b]. Critical AHS deployment issues include the requirement of a physically separated and dedicated truck lane for safety, the requirement of a sufficiently large population of vehicles equipped with advanced technology to avoid the “empty-lane syndrome,” “chicken-and-egg” issue (i.e., building vehicle population first or building infrastructure first), the long-haul industry’s requirement for a fast return on investment (ROI), the risk of opposition from the current user of the public right-of-way (e.g., opposition to disallowing use of a truck-lane by conventional trucks after converting the truck-lane to AHS, the opposition to taking away an existing car lane for exclusive truck use), competition or opposition from other modes of transportation (e.g., automobile, intermodal rail, etc.), human-factors issues, liability issues, etc. Detailed evaluation of and comparison among these two and other possible deployment sequences is a worthy future research topic.

### **9.1 A Deployment Sequence for the Open-System Operating Concept with Dynamic Convoying**

We propose six deployment steps toward the open-system operating concept with Dynamic Convoying for the inter-city truck-AHS summarized in Section 4.1. Additional steps or more refined steps can be defined, and some of them will be addressed at the end of this subsection.

We believe that having a plausible implementation sequence is a big factor for the successful implementation of the truck-AHS or any AHS (Tsao, 1998; Tsao, 1995b). The sequence was therefore conceived to have initial steps that could be beneficial by themselves and could lead to the implementation of the end state.

The market acceptance steps, i.e., Steps O-1 and O-2, are independent of the step of truck-lane construction/dedication, i.e., Steps O-3, and, therefore, these two groups of steps can proceed in parallel.

#### **Step O-1: Proof of Technology and Market Acceptance of Advanced Warning Technologies for Trucks (Largely Done Already)**

**Step O-1.1:** Develop and deploy radar-based, infrared based or other range-sensors and frontal crash warning systems for trucks to use on conventional highway lanes as well as off highways.

**Step O-1.2:** Develop and deploy machine-vision-based lane identification and lane-departure warning systems for trucks to use on conventional highway lanes as well as off highways.

#### **Step O-2: Proof of Technology and Market Acceptance of Hands-off and Feet-off Automation Technologies for Trucks (Simultaneous Use Prohibited)**

**Step O-2.1:** Based on the systems developed and deployed in Step O-1.1, develop and deploy vehicle-following and other longitudinal vehicle-control systems that enable feet-off driving. This includes automatic transmission because manual transmission requires operation of clutch by a foot. (Truck Adaptive Cruise Control (ACC) is already on the market.)

**Step O-2.2:**

- Based on the machine-vision-based lane identification and lane-departure warning systems developed and deployed in Step O-1.2, develop and deploy lane-keeping and other lateral vehicle control systems that enable hands-off driving.
- The driver can delegate certain driving tasks to the automation feature. But the driver supervises the automated operations and continues to be responsible for the safe operation of the truck.
- Disallow the simultaneous use of both the hands-off and the feet-off features, to prevent driver disengagement from driving tasks. (Driver disengagement is a critical human-factors issue.)

**Step O-3: Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation:**

- Select an important and congested freight corridor where the benefits of automation will be evident. This issue will be further discussed in the section on possible deployment sites. It will be important to ascertain that the dedication of a lane will be physically plausible.
- Construct or dedicate a new truck lane with an accompanying shoulder in the median of the main freeway along the corridor or dedicate the leftmost lane of the existing lanes for each direction for the exclusive use by trucks. The lane must be physically separated from the remainder of the highway. Construct dedicated on- and off-ramps for direct access to and egress from the dedicated truck lane at selected locations on the freeway. Other configurations and placements of the dedicated truck lane are also possible, such as placing it on the right-hand side of the roadway, double-decking, etc. However, placement in the median with access at long intervals, e.g., 100 miles, may be most cost-effective. (Access at shorter intervals, e.g., 20 miles, may also be cost-effective.)
- Construct staging areas at selected access points.
- Allow LCVs on the truck lane (and only on the truck lane and the staging areas, and nowhere else). Such LCVs are not currently allowed in California and many other states, but we propose that they be allowed on dedicated and physically separated truck lanes.
- Dedicate a “sufficiently long” truck-lane. LCV operations also exhibit “the economy of distance.” Due to the need for assembly or disassembly of trailers when entering from or exiting into, respectively, a conventional lane, LCV operations will not be beneficial unless the physically separated truck-lane is “sufficiently” long.
- Tolls can be collected electronically either at the interface areas, i.e., the on- or off-ramps, or at selected locations along the freeway.

(Trucks originated from an access point on the inter-city freeway not selected as an access point to the truck-lane can use the conventional lanes to reach a truck-lane access point and then enter



the truck-lane through the staging area. Trucks destined for an access point not selected as a truck-lane access point can use the conventional lanes to complete the trip after using and exiting the truck-lane through a staging area. The option of providing a truck (but not an LCV) with direct access to a truck-lane from a conventional lane or direct egress from a truck-lane to a conventional lane through a ramp at locations with two conventional lanes (in each direction) can also be investigated. The advantage in access efficiency must be weighed against the possible disadvantage in truck weaving through the conventional lanes.)

**Step O-4: Automated Driving in Mixed Traffic on the Truck Lane:**

- Install magnetic markers or other “active” markers on the truck lane to provide those equipped trucks (i.e., those equipped with the corresponding marker detectors) with an additional guidance function, for redundancy initially and for eventually enabling closely-spaced truck convoying in adverse weather, lighting and other conditions.
- Support automated driving (i.e., hands-off and feet-off driving) in midst of manually driven traffic, but under the supervision of the driver, who continues to be responsible for the overall safety of truck operations. (“Mixed traffic” refers to the mixing of automatically controlled vehicles and manually controlled vehicles, although the manual control may be enhanced with information transmitted from the infrastructure or neighboring vehicles.)
- All trucks must be equipped with (a) vehicle-to-vehicle communication capability in such a way that the both automated and manually driven trucks can know and anticipate the intent of the trucks in front or in back and (b) vehicle-to-infrastructure communication in such a way that, together with the vehicle-to-vehicle communication, the traffic entering the truck lane through an on-ramp can merge into the mainline traffic safely. (Note that provision of one single truck lane is assumed. Adjacent trucks may be either in front or in rear.)
- This mixed-traffic step is motivated to avoid the “empty-lane syndrome.” If the population of equipped vehicles can be built quickly, then this step may not be needed.

**Step O-5: Automated Truck Lane Accessible Only From Staging Areas:**

- Dedicate the truck lane to automated traffic only; disallow non-equipped trucks on the truck lane.
- Reduce lane width; use the width no longer needed, together with the possible existing shoulder or previously unused right-of-way in the median, to build a shoulder that is wide enough so that the single lane plus the shoulder will be able to accommodate one disabled truck on the shoulder and one lane of through traffic at a speed that may be higher than the condition without automation.
- In addition to automated driving (i.e., hands-off and feet-off driving), truck-to-truck communication ensures safety (through real-time exchange of information regarding vehicle status and movement plans) and enhances ride quality on the mainline (due to movement coordination and the companion reduction in jerky motion), and truck-to-infrastructure communication, together with the vehicle-to-vehicle communication, enable efficient merging (in addition to safe merging, which is achieved in the previous step).

- Trucks travel in closely-spaced convoys. (This feature may be added in a future step if it cannot be achieved within this step.)
- The driver of the lead truck of a convoy is responsible for detecting and responding to debris ahead on the lane or other abnormal events that cannot be reliably or cost-effectively detected by and responded with automation.
- “Fitness” checking to determine whether the equipment is functioning properly can be performed in the staging area before a truck moves toward the dedicated on-ramp leading from the staging area directly into the truck lane or at least before a truck reaches the on-ramp. The fitness-checking facility can be installed at locations away from the actual on-ramp; this can prevent blocking of the on-ramp and can avoid the need for a “turn-off” lane from the on-ramp back to the staging area, for those trucks failing the fitness check to return to the staging area.

(If on- or off-ramps directly connecting a truck lane and a conventional lane were provided in Step O-3, then they must be closed in this Step.)

**Step O-6: Automated Convoying With no Driver on Trailing Trucks of a Convoy:**

- Support, for mainline travel, automated convoying with no drivers required on any trailing truck (i.e., the tractor plus the trailers) of the convoy.
- With the assistance of advanced technology, human operators monitor the roadway at and near an on- or off-ramp for possible presence of safety impacting debris and other possible safety-impacting events.
- Support automated tagging of a driverless entering convoy onto a mainline convoy at or near an on-ramp; support simultaneous automated splitting and automated exiting of a portion of a mainline convoy at or near an off-ramp without requiring a driver on the exiting portion.

Other features can also be supported, and the corresponding steps added. For example, trucks can be organized into convoys according to the braking capability (with their load considered) so that safety can be maximized. Also, if convoys of trucks are allowed to travel on the truck-AHS at different cruising speeds, then passing lanes may be needed and can be provided. If such a passing lane is provided on the truck-AHS, then trucks may be organized into convoys according to their optimal or typical cruising speeds.

These six steps are summarized in Table 8.

**Table 8: A Six-step Deployment Sequence for the Proposed Open-System Truck-AHS**

<b>Step</b>	<b>Main Features</b>	<b>Main Additional Benefits</b>	<b>Main Issues</b>
O-1. Proof of Technology and Market Acceptance of Advanced Warning Technologies for Trucks	<ul style="list-style-type: none"> <li>• Range sensing and frontal collision warning</li> <li>• Vision-based Lane-departure warning</li> </ul>	<ul style="list-style-type: none"> <li>• Use on and off highways</li> <li>• Safety</li> <li>• Technology maturation</li> <li>• Price drop</li> </ul>	<ul style="list-style-type: none"> <li>• Proof of technology</li> <li>• Market acceptance</li> </ul>
O-2. Proof of Technology	<ul style="list-style-type: none"> <li>• Feet-off highway</li> </ul>	<ul style="list-style-type: none"> <li>• Driver stress</li> </ul>	<ul style="list-style-type: none"> <li>• Ability of the driver to</li> </ul>

<p>and Market Acceptance of (Non-Simultaneous Use of) Hands-off and Feet-off Automation Technologies for Trucks</p>	<p>operations</p> <ul style="list-style-type: none"> <li>• Hands-off highway operations</li> <li>• Only one of the two features to be activated at any time; simultaneous use prohibited to avoid driver disengagement</li> </ul>	<p>reduction due to partial automation</p> <ul style="list-style-type: none"> <li>• Features like automated transmission reducing driver training requirements and expanding labor pool</li> <li>• Technology maturation</li> <li>• Price drop</li> </ul>	<p>react to unexpected events by interfering or overriding partial automation</p> <ul style="list-style-type: none"> <li>• Possible abuse on city streets</li> <li>• Proof of technology</li> <li>• Market acceptance</li> </ul>
<p>O-3. Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation</p>	<ul style="list-style-type: none"> <li>• Construction or dedication of a physically separated truck lane, for safety, on or adjacent to freeway median</li> <li>• Dedicated on- and off-ramps and staging areas constructed at access points</li> <li>• Access to the truck lane in the median only through the staging areas (Direct ramps linking the truck lane to the left lane of a conventional two-lane (each-direction) freeway can be investigated)</li> <li>• Operation of LCVs allowed only in the truck lane and the staging areas to increase trucking productivity</li> <li>• Sufficiently long to ensure “economy of distance” for LCV operations</li> </ul>	<ul style="list-style-type: none"> <li>• Higher freight throughput</li> <li>• Safety due to less mixing of light and heavy vehicles</li> <li>• Significantly higher productivity of the LCV driver and the equipment as well</li> <li>• Higher user fee justified by significant increase of productivity</li> <li>• Higher user fee increasing the likelihood of construction or dedication of a truck lane</li> </ul>	<ul style="list-style-type: none"> <li>• Acceptance by the general public</li> <li>• Amount of toll charge</li> <li>• Possible protest by the rail industry</li> <li>• Legislative acceptance of allowing LCVs on the truck lane</li> <li>• Demand sufficiency to justify limited access only through staging areas</li> <li>• Potential for complete blockage by a single disabled truck, even if the combined width of the truck lane and the shoulder is sufficiently wide to allow lower-speed passage through the incident area</li> <li>• The provision of passing lanes if different cruising speeds are allowed.</li> <li>• Flow hindrance by trucks with slower cruising speeds if otherwise.</li> </ul>
<p>O-4. Automated Driving in Mixed Traffic on the Truck Lane</p>	<ul style="list-style-type: none"> <li>• Installation of magnetic markers or other “active” markers on the truck lane</li> <li>• Simultaneous hands-off and feet-off driving supported</li> <li>• Driver’s responsibility for safe operations</li> <li>• Longitudinal mixing with manually driven trucks</li> <li>• Vehicle-to-vehicle and</li> </ul>	<ul style="list-style-type: none"> <li>• Redundancy in lateral guidance for higher safety</li> <li>• Stress reduction for (trained) drivers of automated trucks</li> </ul>	<ul style="list-style-type: none"> <li>• Safety of automated driving</li> <li>• Safety of mixing on mainline</li> <li>• Safety of merging between automated and manual truck traffic</li> </ul>

	<p>vehicle-to-infrastructure communication required for all trucks using the truck lane to ensure safety in traveling and merging</p>		
<p>O-5. Automated Closely-spaced Truck Convoying in Truck Lane Accessible Only From Staging Areas</p>	<ul style="list-style-type: none"> <li>• Exclusive use by automated trucks, including automated LCVs</li> <li>• Closely-spaced truck convoying</li> <li>• A “train system” of electronically linked and self-propelled trucks</li> <li>• If direct ramps linking the truck lane to the left lane of a conventional two-lane (each-direction) freeway were provided, they should be closed.</li> </ul>	<ul style="list-style-type: none"> <li>• Better fuel efficiency</li> <li>• Higher mainline capacity</li> <li>• Tightly spaced trucks leaving more space between convoys for safer and more efficient merging</li> <li>• Higher safety for mainline operations due to the homogeneity of traffic (of trucks only)</li> <li>• Higher merging efficiency due to the homogeneity</li> </ul>	<ul style="list-style-type: none"> <li>• Demand sufficiency to justify the dedication of truck lane to the exclusive use by automated trucks only.</li> <li>• Amount of toll charge</li> <li>• Modal-change overhead (between the conventional trucking and automated closely-spaced truck convoying)</li> <li>• Safety of closely-spaced truck convoying</li> <li>• Possible protest by the rail industry</li> </ul>
<p>O-6. Automated Convoying With no Drivers on Trailing Trucks of a Convoy</p>	<ul style="list-style-type: none"> <li>• Driverless operations for trailing trucks</li> <li>• A possible new class of carriers: AHS Hauler for hire to haul other companies’ trucks or just trailers; scheduled AHS Hauling services</li> </ul>	<ul style="list-style-type: none"> <li>• Significantly higher driver productivity as well as equipment productivity</li> </ul>	<ul style="list-style-type: none"> <li>• Safety of driverless operations of the trailing trucks</li> <li>• Modal-change overhead (between the manned “truck trailing” and driverless truck trailing)</li> <li>• Amount of toll charge</li> <li>• Possible protest by the rail industry</li> </ul>

## 9.2 A Deployment Sequence for the Closed-System Operating Concept with Static Convoying

The deployment sequence for the closed-system operating concept with static convoying may be shorter, primarily because there is no need for the general long-haul trucking industry to accept the automation technology and equip a sufficient number of trucks so that the dedication of a truck lane can be justified. Moreover, several steps required for the open-system operating concept regarding technology development and acceptance are consolidated into one step in the sequence for the deployment of the closed-system operating concept. This may lead to faster deployment, however at the expense of not opening the system to the general long-haul freight industry. The proof-of-technology and market acceptance step for this closed-system concept is

very different from its open-system counterpart. The proof-of-technology component, which may actually be considered as part of research and development rather than deployment, is critical due to (a) the high reliability requirement for truck-AHS operations, (b) the extensive technology requirements and (c) the need to develop the technologies as a bundle, rather than increments. However, it may take place “off-site” and in parallel with infrastructure improvement. Market acceptance is still required, but is required of different institutions and is of different nature. We propose a four-step deployment sequence and address only the differences from the sequence proposed in Section 5.1 for the open-system operating concept.

### **Step C-1: Proof of Technology and Market Acceptance:**

- Proof of technology for the following technologies:
  - Communication with other trucks and the infrastructure, for coordination of movement with other trucks and for exchanging information with the infrastructure for safety and efficiency.
  - Vehicle-following and other longitudinal vehicle-control systems that enable feet-off driving. (This includes automatic transmission.)
  - Lane-keeping and other lateral vehicle control systems that enable hands-off driving. (The vision-based lane recognition system proposed in Step O-1.2 is not necessary, although it may be desirable for supplementing the magnetic-marker-based lane recognition system in order to increase redundancy and reliability.)
  - Closely-spaced automated convoying
  - Driverless truck following
  - Merging of a (whole) convoy into the mainline from an entrance
  - Diverging of a (whole) convoy from the mainline into an exit
  - (Neither splitting a convoy into two nor joining two convoys into one is supported on the AHS.)
- Acceptance by
  - the much smaller sector of potential AHS haulers
  - the long-haul trucking industry in general regarding the use of the AHS.

### **Step C-2: Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation**

(Same as Step O-3)

### **Step C-3: Automated Driving in Mixed Traffic on the Truck Lane:**

Essentially the same as Step O-4 except:

- The AHS haulers of the closed system equip, possibly gradually, their AHS fleet with automated tractors and devices that can be attached to the trailers easily to enable communication with the tractor and the following convoys. Such a device may already be there if the AHS hauler rents or leases its own trailers for more efficient mode-change.

(This phase, i.e., the duration between Steps C-3 and C-4, may last much shorter than its open-system counterpart (i.e., between Steps O-4 and O-5) because the deployment of the technology involves one or a small number of AHS haulers, not the general long-haul freight industry.)

**Step C-4: Automated Truck Lane Accessible Only From Staging Areas:**

Essentially the same as O-5 except the following:

- Since only AHS haulers can use the AHS, fitness checking for those trucks wishing to enter the AHS may be performed at the haulers’ maintenance facilities and/or real-time at all times, therefore fitness checking and the associated space at the staging area may not be required.
- Support, for mainline travel, automated convoying with no drivers required on any trailing truck (i.e., the tractor plus the trailers) of the convoy. (Note that this is part of Step O-6, not Step O-5. Also note that this technology would have been proven in Step C-1 and hence could be implemented immediately after mixed-traffic operations is discontinued.)

Due to the much smaller fleet of AHS-equipped tractors required for this closed-system operating concept than the open-system operating concept, maturation of technology may require more up-front investment in research and development, and equipment costs may be higher during the proof-of-technology step (i.e., Step C-1). However, since these costs can be distributed across all the carrier users, and the equipment utilization would be much higher, these cost issues may not be a “show-stopper.”

The differences of these deployment steps from their open-system counterparts are summarized in Table 9.

**Table 9: A Four-step Deployment Sequence for the Proposed Closed-System Truck-AHS**

<b>Step</b>	<b>Differences from Its Open-System Counterpart, if any</b>
C-1: Proof of Technology and Market Acceptance	<ul style="list-style-type: none"> <li>• Proof of all component technologies is consolidated into one step.</li> <li>• Neither splitting a convoy into two nor joining two convoys into one is supported on the AHS.</li> <li>• Market acceptance is required by the much smaller sector of potential AHS haulers about equipping their trucks and operating the trucks on the AHS and by the long-haul trucking industry in general about contracting with AHS haulers to move its freight, not about equipping their trucks and operating the trucks on the AHS.</li> </ul>
C-2: Construction/Dedication of a “Sufficiently Long” Physically Separated Truck-Lane on Inter-city Freeways with LCVs Allowed Through New Legislation	The same as Step O-3.
C-3: Automated Driving in Mixed Traffic on the Truck Lane	<ul style="list-style-type: none"> <li>• Essentially the same as Step O-4 except that the AHS haulers of the closed system equip, possibly gradually, their AHS fleet with automated tractors and devices that can be attached to the trailers easily to enable communication with the tractor and the following convoys. Such a device may already be there if the AHS hauler rents or leases its own trailers for more efficient mode-change.</li> <li>• This step may last much shorter than its open-system counterpart because the deployment of the technology involves one or a small number of AHS haulers, not the general long-haul freight industry.</li> </ul>

<p>C-4: Automated Closely-spaced Truck Convoying in Truck Lane Accessible Only From Staging Areas, with no drivers required on trailing trucks of a convoy</p>	<ul style="list-style-type: none"> <li>Essentially the same as Step O-5 and Step O-6 combined except the following: Since only AHS haulers can use the AHS, fitness checking for those trucks wishing to enter the AHS may be performed at the haulers' maintenance facilities and/or real-time at all times, therefore fitness checking and the associated space at the staging area may not be required.</li> <li>This step supports, for mainline travel, automated convoying with no drivers required on any trailing truck (i.e., the tractor plus the trailers) of the convoy. Note that this is part of Step O-6, not Step O-5. Also note that this technology would have been proven in Step C-1 and hence could be implemented immediately after mixed-traffic operations is discontinued.</li> </ul>
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**10. IMPLEMENTATION OF THE PROPOSED DEPLOYMENT SEQUENCES: POSSIBLE SITES AND ISSUES**

In this section, we first propose possible deployment sites for the proposed inter-city truck-AHS operating concepts and then discuss possible issues that may hinder the deployment of the two proposed concepts. Some final remarks on development of operating concepts and deployment sequences are given at the end of this section.

**10.1 Possible Deployment Sites**

In discussing possible deployment sites, we take a California perspective. I-10 in Southern California may be a very attractive deployment site because of several reasons, although it is not one of the three sites identified by Hall et al. (Hall et al., 1997). The three sites they selected are I-80 between San Francisco and Sacramento, I-5 between Los Angeles and San Francisco and I-15 between Los Angeles and Las Vegas. Hall et al.'s objective was to identify sites within the state of California that may be appropriate for an AHS Field Operational Test (FOT). Those sites were selected for their characteristics suitable for testing truck-AHS operations, not for actual deployment of the technology. They used six categories of criteria: safety and reliability, local cooperation and participation, test cost, ability to serve real trips, ability to conduct desired tests, direct impacts of a test. However, our focus is actual deployment and we wanted to also consider long-haul freight corridors where the truck-AHS could also be a substitute for rail.

The I-10 corridor offers such a possibility and also has some other features that may make it a candidate deployment site within the state of California. First, there has been a multi-state consortium investigating ways to improve the efficiency of goods movement on I-10, i.e. the I-10 Automated Dedicated Truck Lane Project. Second, most western states along I-10, including California, New Mexico and Texas, do not currently permit LCVs. These states can help improve the efficiency of inter-state trucking greatly if it allows LCVs on (and only on) a dedicated and physically separated truck lane. Such potentially drastic benefits may warrant the states' construction of a new truck lane or dedication of an existing lane for exclusive truck use and, perhaps more importantly, may attract sufficient toll-paying truck traffic to pay for the construction or dedication cost. Third, partnership between the public sector and freight industry may be required for deployment of a truck-AHS. We believe that, in addition to the requirement that a truck-AHS should be constructed along a busy freight corridor, only frequent users of the freight corridor can be expected to invest in truck automation, at least during the initial

deployment of a truck-AHS. As a result, frequent users must be identified. One possible group of frequent users is the trucking companies hauling ocean freight containers from a large seaport to inland cities or seaports on another coast. This type of intermodal freight has been moved with long-term contracts between ocean carriers and trucking companies for the past two decades (McKenzie et al., 1989). Such contracts would be conducive to the formation of a large group of frequent users (i.e., trucks using the truck-AHS). There are a small number of heavy-traffic corridors carrying a large amount of such intermodal freight in the U.S., including the corridor leading from Long Beach, California, through I-10 to large cities and seaports along the way (Smith, 1990).

I-15 and then I-80 or I-80 by itself could be good candidates for deploying an inter-city truck-AHS too because both of them carry a large amount of intermodal (between ocean and highway) freight. I-5 could also be a good candidate. Figure 15 depicts the part of the interstate highways I-5, I-10 and I-15 that spans the major cities south of Sacramento, Las Vegas and El Paso, Texas.

## **10.2. Possible Issues And Solutions Associated With The Proposed Truck-AHS And The Proposed Deployment Sequence**

### **The Requirement of a Dedicated Truck Lane**

Although truck lanes are common on freeway sections where the grade is steep, they are not common elsewhere. Major possible issues include:

- availability of right-of-way on inter-city freeways;
- the willingness of the government and ultimately the willingness of the general public to construct a new lane or to dedicate an existing lane for exclusive use by trucks (in each direction) on inter-city freeways (for the purposes of improving freight movement and safety and for eventually deploying a truck-AHS);
- potential intense competition for right-of-way with passenger or transit vehicles in cities, unless truck by-passes can be constructed or trucks and transit vehicles (and possibly automobiles) can share the same right-of-way of an urban AHS; (Note that although the truck-AHS is intended primarily for improving inter-city trucking, continuous automated driving through a city may be critical for the success of the truck-AHS. If such continuous automated driving is not provided, driverless truck-following may be supported only on rural freeways. As a result, “mode changes” in the form of switching between (a) the new mode of driverless truck-following on rural freeways and (b) the conventional mode of manual truck driving through a city may diminish the benefit potential of the truck-AHS.

### **Passing Lane**

If only one lane (for each direction) will be available on the truck-AHS along its entire length, then truck and infrastructure design must be able to eliminate the need for passing. If provision of a passing lane at selected locations is required, then a significant amount of additional right-of-way may be required.



### **Possible Objection by the Railroad Industry and the Intermodal Rail Industry**

Containerization has become a dominant mode for ocean carriers. Deregulation of the ocean freight in the U.S., particularly the 1984 Shipping Act, gave ocean carriers the freedom to operate as efficiently as possible, particularly in choosing ports and inland carriers to deliver the freight to their customers. The U.S. rail industry consequently accommodated containers. The imbalance of trade between the U.S. and Asia led to more eastbound containerized freight than westbound on the continental U.S.. To more fully utilize the containers on their westbound journey on the continental U.S., ocean carriers have successfully lured much domestic freight to fill the otherwise empty containers, and, as a result, containerization has also become a popular method of transporting domestic freight on rail and on the highway (McKenzie et al., 1989).

There has been much competition between the (intermodal) rail industry and the trucking industry (e.g., McCormick, 1999). Railroad companies have made arguments in favor of intermodal rail. For example, the Association of American Railroads (AAR) estimated that a railroad can move a given quantity of freight for one-fifth the fuel, one-sixth the accidents, one-seventh of the labor (in the unit of one employee), one-tenth of the land required to carry the same load by truck (McKenzie et al., 1989). However, the quality of door-to-door service is the missing element in the railroads' ability to compete with trucking. Shippers and freight forwarders consider intermodal rail service as inferior by almost every measure: door-to-door transit time, reliability, damage and loss experience, tracing and claim settlement, documentation, responsiveness, ease of use, etc. (McKenzie et al., 1989). For long-haul freight, such shortcomings are more likely to be outweighed by the cost advantage. This may explain why the strength of intermodal rail has been in the market of dry-van (i.e., non-refrigerated) truck-load traffic between major cities more than 700 miles apart. More precisely, Smith (Smith, 1990) reported that intermodal service accounted for 70% of that market.

To compete with trucking, the rail industry has developed and adopted many innovations. The most recent and the most significant one would be double-stacking (stacking one container on another on the same "flatcar"), which virtually doubles the freight throughput on those corridors where the required higher clearance could be accommodated. But, even with double-stacking, intermodal rail in general was considered not competitive for trips shorter than 500 miles (McKenzie et al, 1989) and the situation may not have changed. A study suggested that double-stack service could be fully competitive with trucks in dense-traffic corridors of 725 miles or longer (Smith, 1990). However, McKenzie et al. (McKenzie et al, 1989) reported that, even in the over-500-mile market segment, intermodal rail accounted for less than 20% of the market.

Another significant innovation is the "carless" technology. Carless technology combines the two transportation modes of rail and truck into one by equipping a highway trailer with retractable rail wheels. It has been developed to maximize efficiency by eliminating or at least minimizing the need of a railcar. Since no specialized lift equipment is needed for operating such bi-modal trailers, they can run out of small terminals and can deliver door-to-door. McKenzie et al. (McKenzie et al, 1989) reported that the only major manufacturer of such bi-modal trailers was RoadRailer, and the manufacturer estimated that the break-even mileage was 400-500 miles, and that, for higher longer distances, RoadRailer would become more competitive than trucking.

Despite this estimation, this bi-modal service has not become a significant component of the intermodal rail service.

If an inter-city truck-AHS is eventually built, it must be able to significantly improve inter-city trucking, leading to possible diversion of intermodal freight traffic from rail to trucking. Such an improvement may be viewed by the intermodal rail industry as creating unfair competitive advantages for the trucking industry by the public sector. The actual degree of this advantage for the trucking industry depends on the amount of toll charges, and must be carefully studied. Note that double-stacking requires higher vertical clearance of overpasses, and, in order to raise the clearance, the rail industry needed and in many instances received assistance from the governments involved. Therefore, the public sector has already provided competitive advantages to the (intermodal) rail industry. However, the effort involved in raising the vertical clearance on railroads is likely to be much less than the public-sector effort required to implement a truck-AHS.

The relative capabilities of rail and truck-AHS addressed in this and earlier sections are summarized in Table 10. It is well known that rail is more cost-effective for long trips, when compared to conventional trucking. It is anticipated that truck-AHS will be cost-effective for shorter trips while conventional trucking continues to be the choice for short trips. Truck-AHS, if deployed, is likely to be implemented on a few busy freight corridors. Therefore, use of truck-AHS may involve more circuitous routes (than use of conventional freeways) for those origins and destinations not close to the truck-AHS. Even for those origins and destinations close to the truck-AHS, some of the mainline efficiency of a truck-AHS may be offset by the overhead incurred by the mode change, e.g., the possible dead-heading, possible driver’s wait for the return load, transfer of trailer (if applicable). Estimating the range of trip lengths and other characteristics making the use of a truck-AHS attractive requires future cost-benefit analysis.

**Table 10: Relative Capabilities of Long-haul Rail and Truck-AHS**

<b>Type of Capability</b>	<b>Rail</b>	<b>Truck-AHS</b>
Local Collection and Distribution	<ul style="list-style-type: none"> <li>• None</li> <li>• Drayage performed with the different mode of trucking</li> </ul>	<ul style="list-style-type: none"> <li>• Achievable through dual-mode truck operations, for both open or closed systems</li> <li>• Also achievable due to relative ease of attaching trailers to and detaching trailers from an AHS-tractor, without use of dual-mode trucks</li> </ul>
Access and Egress	<p>Involving complex and time-consuming mode change:</p> <ul style="list-style-type: none"> <li>• transfer of freight, either in container or trailer, onto or off a railcar (flatcar)</li> <li>• waiting for pick-up by a train with available capacity (through rail switching) or forming a train with other railcars</li> <li>• Rigid train schedules: normally one daily train for long-haul routes but multiple daily departures for short haul on some freight corridors (expedited</li> </ul>	<p>Much simpler mode change:</p> <ul style="list-style-type: none"> <li>• same trailers</li> <li>• driving trucks to assigned position if dual mode; dropping off trailers at assigned position otherwise</li> <li>• entering or exiting the mainline by merging into or diverging from mainline traffic</li> <li>• more frequent and flexible departures of “truck trains”</li> </ul>

	piggyback services)	
Mainline Operations: Fuel Consumption	Low (1/5 of consumption by conventional trucking, according to an AAR report)	Higher fuel consumption, but lower than conventional trucking
Mainline Operations: Labor requirement	Low (1/7 of labor required by conventional trucking, according to AAR)	Higher labor requirement, but possibly comparable under Design Option (C-d); much lower than conventional trucking
Mainline Operations: Land Requirement	Low (1/9 of land required by conventional trucking, according to AAR)	Greater land requirement, but lower than conventional trucking due to automated closely-spaced convoying, etc.

The degree of possible future protest by the intermodal rail industry is difficult to predict at this point. The freight industry in the U.S. has been turning multi-modal, and at least three large multi-modal transportation companies have emerged – American President Companies (i.e., APC), CSX/Sea-Land, and Burlington Northern Worldwide (i.e., BN Worldwide) (McKenzie et al, 1989). Although some of the companies have historical and even current ties with the railroad industry and may consequently side with the rail industry, truck-AHS may actually create net benefits and hence may become attractive for these companies. Deployment of an inter-city truck-AHS will likely be not only an engineering issue, but also a major economic, and public-policy and political issue.

### **Tolls**

The amount of possible toll charged is an important issue for a truck-AHS because the benefits depend on the amount of traffic using the truck-AHS, and the amount of traffic using the truck-AHS depends on the amount of toll charged. It may also have serious implications for the long-standing competition between the trucking industry and the intermodal rail industry, because the amount of possible diversion of freight traffic from the intermodal-rail mode to AHS-trucking depends on the toll charges.

### **Safety And Liability**

Although beyond the scope of this research, safety and liability are critical issues. Safety issues cannot be addressed adequately without actual design or at least design specifications. However, studying issues regarding liability distribution may be possible at the concept level.

### **Partnering With The Private Sector**

Deploying the proposed truck-AHS concepts requires proactive championship by the public sector as well as active participation by a number of private industries, e.g., truck manufacturers, truck operators and/or their parent multi-modal transportation companies, insurance companies, etc. The required participation and cooperation will be unprecedented, and may very well take the form of a private-public partnership.

### **10.3. Remarks On Development Of Truck-AHS Operating Concepts And Deployment Sequences**

AHS research has been primarily motivated to drastically increase automobile throughput on congested urban freeways. Despite its potential, no plausible deployment steps, taking into consideration engineering (including safety and human factors), market-penetration, public-policy

and political issues seem to have been developed so far. But, this does not mean that automation cannot provide significant benefit for the nation's surface transportation systems. We investigated the potential of automation technologies for improving the operational efficiency of heavy vehicles, including trucks and buses, and reported on “end-state” operating concepts recently (Tsao and Botha, 2001; Tsao and Botha 2002). Developing such operating concepts is nothing but an intellectual exercise unless major deployment issues are anticipated and plausible deployment strategies developed (Tsao, 1995b). Those end-state operating concepts were conceived with explicit consideration of real-world implementation issues. We first identified the needs of the long-haul trucking industry and the major concerns of key stakeholders. Based on customer needs, stakeholder concerns and available or promising truck-automation technologies, we then developed design options for various aspects of truck-AHS operations. After comparing the merits of these options, we developed system operating concepts and deployment sequences to satisfy the customer needs.

The truck-AHS we proposed requires a dedicated lane for each direction, but few dedicated truck lanes exist now in the U.S., except at locations with steep grades. We believe that a possible major roadblock (or “show-stopper”) for implementing the truck-AHS is the requirement of a dedicated truck lane. Such lanes will not be dedicated or built unless they truly satisfy the needs of the long-haul trucking industry in a cost-effective and the stakeholders welcome them or at least can accept them. Productivity seems to be the number-one concern of the long-haul trucking industry, which has been campaigning for wider acceptance of LCVs by major stakeholder groups. We observed that most stakeholder concerns about the operations of such LCVs can be alleviated by physically separating LCVs (as well as many other smaller trucks) from the automobile traffic and limiting their operations to truck lanes and the staging areas. The cost-effectiveness of a truck lane and that of a truck-AHS must be carefully studied from the perspectives of both the trucking industry and transportation agencies, but are beyond the scope of this paper. Only when such dedicated truck lanes have been accepted by the public and have been heavily used by the trucking industry could truck automation be considered a real possibility.

We compared design options for three key design issues for a truck-AHS: convoy evolution, integration of truck-AHS operations with local feeder operations and bridging two sections of rural truck-AHS through an urban area. Based on their relative merits, we proposed two system operating concepts as well as two deployment sequences, one for an open system with dynamic convoying and the other for a closed system with static convoying. We also compared their relative merits.

The rivalry between the trucking industry and the rail industry is well known (e.g., McCormick, 1999). A truck-AHS, if cost-effective from the perspectives of both trucking industry and transportation agencies and eventually built, may be considered as an unfair advantage provided by the public sector to the trucking industry. The degree of the opposition is difficult to predict now, and so is the degree to which such opposition can be neutralized by other forces, e.g., the purchasers of rail services like multi-modal transportation companies (which use both trucking and rail) and the proponents of a more efficient freight system for national defense purposes.

Research on truck-AHS so far seems to have been focused on the automation technologies, rather than guided by some systems operating concepts encompassing in a comprehensive way both technical and non-technical solutions. It is our hope that the operating concepts and the

deployment sequences we proposed begin to fill the void or at least would encourage research into developing deployable truck-AHS operating concepts and feasible deployment sequences.

## **11. ELEMENTS OF THE PROPOSED BENEFIT-COST ANALYSIS**

### **11.1 Introduction**

The overall goal of this section is to discuss elements of the benefit-cost analysis that is proposed for the next phase of the project. Specifically, the following will be discussed:

- Objectives of the analysis.
- Basic approach to the benefit-cost analysis and potential pitfalls
- Proposed options for analysis
- Some complicating factors
- Basic cost estimation methodology.

### **11.2 Objectives of the Analysis**

The ultimate goal of the benefit-cost analysis is to determine the operating domains wherein the AHS modes could possibly be more desirable than the conventional modes.

The proposed approach is to assess the benefits and costs from a societal perspective. Individual stakeholders often view benefits and costs differently from the societal viewpoint. Quantitative analysis will only be performed for the societal viewpoint while stakeholders' perspectives will be discussed on a qualitative level.

### **11.3 Basic Approach to the Benefit-Cost Analysis and Potential Pitfalls**

It is worthwhile to review some of the salient features of benefit-cost analysis to enable some perspective on the possible shortcomings of and some of the practical issues involved in such an analysis.

The term “benefit-cost analysis” is used in a generic sense here. The term encompasses the whole family of benefit-cost analyses and not just the benefit–cost ratio. The terms “benefits” and “costs” are not consistently used in practice with regard to meaning. When evaluating transportation systems, the term “benefits” often means a reduction in user costs. The term “costs” indicates an increase in system costs, e.g. construction costs. These meanings are consistent with conducting the analysis from the societal viewpoint, which is the approach that will be used in the project.

Instead of using benefits and costs, it is often convenient to use “total cost” (the sum of user and system costs) when analyzing the performance of systems. When using total costs for a comparison, the best alternative is the one with the lowest costs. In the event of comparing the incremental total costs of an alternative to the base case, a negative value for the incremental costs would signify an improvement. When using a total cost analysis correctly, it will be precisely equivalent to using a comparison of benefits and costs correctly.

As stated before, the ultimate goal is to determine the operating domains wherein the AHS modes could be more desirable than the conventional modes. In its simplest form, one could imagine a

graphic showing increasing passenger volume on the X-axis and total cost (user and system costs) for each alternative mode (light rail, conventional bus and AHS-bus) on the Y-axis. The mode with the lowest total cost for a specified passenger volume would be the appropriate mode for that volume level. The volume will be the yearly volume.

Since the available resources do not allow for an estimation of the total cost of each alternative, only differences in cost will be considered between a pair of alternatives. Each pair will consist of an automated option plus a conventional alternative.

Ideally, the comparison should be made between optimally configured systems that are functionally the same at each traffic volume level. Time and budget constraints would make optimization impossible. The proposed approach is to determine “reasoned” systems, without modeling and optimization. Only the end-state systems will be considered in this part of the analysis.

#### **11.4 Proposed Options for Analysis**

The proposed comparison will consider the following combinations:

##### **Transit:**

- Bus-AHS versus a conventional light-rail system
- Bus-AHS versus a non-automated exclusive busway

##### **Freight Transportation:**

- Truck-AHS on a dedicated lane plus remaining conventional lanes versus all conventional lanes
- Truck-AHS on a dedicated lane plus remaining conventional lanes versus a dedicated non-automated truck lane plus remaining conventional lanes
- Truck-AHS on a dedicated lane versus inter-modal rail.

It should be noted that a pair-wise comparison should indicate which one of the two alternatives is superior, but this result will not give any indication that the superior alternative is worthwhile or superior to any alternative outside the pair-wise comparison. The latter can only be achieved by making comparisons with other alternatives such as an automobile only condition. This does not mean that that these comparisons are not important, but only that the available resources do not allow for them. Care should therefore be taken to interpret the results within the context in which they are obtained.

#### **11.5 Some Complicating Factors**

When doing a comparison, it would be desirable to hold all variables, related to the quality of service and that cannot be quantified, constant for all alternatives and to make the two systems functionally the same i.e. to transport the same traffic volume (passengers or freight) over the same distance. For instance, in the case of the transit systems, the system that would transport a specified volume of passengers within specified standards such as travel comfort, reliability etc., with the least cost for a specified distance, would then be selected as the appropriate system for that volume. To make the travel distance the same, physical boundaries will have to be defined for each system.

It is anticipated that a comparison between a bus-AHS and a conventional bus system with a dedicated lane would be relatively “pure” in the sense that almost everything will be the same except for the cost. The exception may be that at high traffic volumes, a bus-AHS may be able to provide a level of service that cannot be achieved by a conventional bus system. A relatively “pure” comparison between a truck-AHS and conventional truck operations on a dedicated lane could also be accomplished.

A comparison between a bus-AHS system and a light-rail system is not as “pure”. There are aspects, such as the quality of ride, seating comfort etc., that will most likely differ between the two alternatives. Similar issues could arise in the comparison of truck-AHS versus the inter-modal rail conventional alternative. The inter-modal rail option could be very different in terms of the quality of service that is experienced by a shipper.

For the simple comparisons, i.e., where the comparison is relatively “pure,” the outcomes should be fairly clear and easy to interpret. Three outcomes are possible in such a comparison:

- The automated alternative is the most cost-effective over the entire domain.
- The conventional alternative is the most cost-effective over the entire domain.
- The automated alternative is the most cost-effective over part of the domain and the competing alternative is most cost-effective over the remainder of the domain.

It is anticipated that some costs will not be readily quantifiable because it is impossible to do so or beyond the scope of the next phase of the project. They will only be discussed and not quantified. For example, in the case of the light rail system, it will offer the benefit (or lower cost) of generating less local mobile-source air pollution than conventionally powered buses. It is beyond the scope of the next phase of the project to estimate air pollution. The light rail system may also offer a more comfortable ride than buses, but this is impossible to quantify in terms of reduced costs. When considering such benefits the following outcomes are possible:

- The automated alternative is the most cost-effective over the entire domain and offers additional benefits.
- The conventional alternative is the most cost-effective over the entire domain and offers additional benefits.

The above outcomes do not offer conceptual difficulty when making a decision about which alternative of the pair would be the most desirable, but the following outcomes can offer some difficulty:

- The automated alternative is the most cost-effective over the entire domain but the conventional alternative offers additional benefits.
- The conventional alternative is the most cost-effective over the entire domain, but the automated alternative offers additional benefits.

A further complication is introduced when the benefits and costs are viewed only from the societal viewpoint, as is proposed for this project, and not also from the stakeholders' perspective. The

viewpoint taken in the project is the societal viewpoint. Ideally, projects that employ public funds should all be evaluated from this point of view before other viewpoints are considered. This does not take into account to whom the costs accrue. For instance, when considering other points of view, such as what a freight shipping company might have, the issue of cost allocation becomes pertinent. Trucks are often not allocated the full cost burden of providing the road, and their shipping rates will include only the costs that they will incur. In the case of a rail system, it is more likely that the rates will include the full cost of the track. The way in which the respective two shipping companies will view the costs will not only depend on which costs they have to bear, but also how they finance their operations and how costs are accounted for. In U.S. accounting practice, costs are accounted for according to accounting rules, which consider costs differently from the way a conventional benefit-cost analysis would account for costs. A shipping company would also consider an increase in net revenues or profits as the major reason for investing in new technology. Since the benefits, from a societal point of view, are not necessarily proportional to net revenues or profits, there would not necessarily be a one-to-one correspondence between the investment decisions from the societal point of view and the business point of view.

Given the available time and the anticipated difficulty of obtaining information on the internal business practices of shipping companies, it is proposed that a full-blown analysis of the benefits and costs accruing to different stakeholders not be conducted. Instead, it is proposed that the differences in costs and benefits to the various stakeholders be identified and quantified as far as the information from the societal-based analysis will allow. If some bus or truck automation concepts are demonstrated to be more cost-effective than the conventional alternatives from the societal perspective, then a worthy future research topic would be a more thorough investigation of the concepts from stakeholders' perspectives, possibly with direct participation from some freight forwarders.

## **11.6 Cost Estimation**

To enable the comparison of the costs of the AHS concept versus the non-AHS alternative, it will be necessary to bring the costs onto the same basis. Because of the basic approach proposed, i.e., to consider real costs, this would entail eliminating taxes, financing cost etc. from the amounts. The comparison should also be made on the same time basis, i.e., equivalent annual amounts or present worth. It is anticipated that using equivalent annual amounts would be the more convenient. The cost has to be estimated over a period of time corresponding to the useful life of the project or at least until the future costs would not matter because of the effect of discounting future costs to the base year or converting the costs to equivalent uniform annual amounts.

When dealing with a benefit-cost analysis of alternative systems and comparing their costs, growth in traffic volume introduces some complexity. The amount of growth has to be determined, ideally from a demand analysis and it is not a given that two alternative systems will experience the same future demand. Since the demand will be treated as a parameter and will be varied to assess the effect of different traffic volume levels on cost, it does not appear realistic to predict growth levels and would seem more appropriate and conceptually simpler to assume a zero growth factor.

Costs for transportation systems generally fall into the following categories:



- System planning and design costs
- Construction, rehabilitation and other infrastructure capital costs
- System maintenance costs
- Administration and system operating costs
- Vehicle operating costs
- Travel time costs
- Accident costs

Accident costs will not be considered, since the operating concepts will not be adequately understood to enable reliable prediction of the frequency and severity of accidents. As stated before, external costs such as environmental costs will not be considered. The proposed approach is to discuss them where appropriate, but not quantify them.

The costs can be further categorized as follows:

- One-time fixed costs;
- One-time costs that occur infrequently;
- Costs that occur frequently and are associated with the traffic volume.

One-time costs are costs such as system planning, design and construction costs that are a function of the geographic extent of the system as well as the capacity that has to be provided. These costs can occur at different times during the life of the project, but are usually associated with capacity or the geographical extent of the system.

Rehabilitation costs occur infrequently and are a function of the extent of the system and the amount of wear, which is usually a function of the traffic volume. These costs occur at irregular intervals and are distinct from maintenance costs, which occur with regular frequency.

System maintenance costs occur continuously and grow over time as a function of the system extent and traffic volume. System administration, system operating, travel time and vehicle operating costs are also associated with the traffic volume. The latter costs can contain vehicle purchase costs, but these costs can also be considered as capital costs.

As stated before, to compare alternative systems that are functionally the same, it is necessary to have the same number of passengers transported over the same distance. For this purpose, the system should be bound geographically so that everything outside the system would be common to the options being compared. The part of the system inside the boundaries would then show up the differences in the performance of the alternatives and consequently the differences in cost. The system has to be large enough so as to be able to arrive at meaningful averages. On the other hand, the system has to be as small as possible to facilitate efficiency in estimation.

Existing systems will be used as a basis for the analysis. This will add realism to any discussion and will also lead to a more meaningful determination of differences in cost than a wholly imagined system would. For instance, in the case of the AHS-Truck, the availability of space in the median for the addition of an exclusive lane will make a system more affordable and feasible

than having to add road space in an alternative manner. However, the existing system will be simplified significantly to make the analysis feasible within the available resources. The systems that will be used as a basis for the comparisons will be further discussed in subsequent sections of this report.

Different volume levels will have to be selected. A logical starting point may be the current traffic volumes for the existing systems. The unit of traffic would be either passengers or containers.

The major sources of cost differences for each set of comparisons will be discussed in the following sections.

## **12. SYSTEM BOUNDARIES AND SOURCES OF SIGNIFICANT COST DIFFERENCES FOR COMPARISON AMONG ALTERNATIVE URBAN BUS SYSTEMS**

### **12.1 Automated Busway (ABUS) versus Light Rail**

The physical system chosen as a basis is the part of the Santa Clara Valley Transportation Authority (VTA) light rail system north of the downtown area. The authors consider this part of the system to be reasonably representative of light rail systems. See Figure 3 for a schematic description of the system.

The boundary of the system will exclude the feeder and distribution system, which in this case would be buses or automobiles. The transfer and wait portion of bus passengers (transferring to the light rail) will be included inside the system so that the cost associated with the extra time taken can be estimated.

There will probably be a difference in the access time between an ABUS system and a light rail system. People who would be using the automobile mode because they do not wish to transfer to the light rail may shift to the ABUS because of the absence of a mode transfer. The result would be a difference in access time as well as a difference in the demand for the line-haul portion of the trip (on the dedicated lane or the light rail line). To determine this mode shift would require demand modeling and make the cost comparison very complex. This is considered beyond the scope of this project. As stated above, only the line-haul portion and the wait and transfer time to the light rail will be considered in the next phase of the project. The demand will be assumed to be the same for both alternatives.

The transfer time of persons accessing the system from the automobiles will be omitted since it will be assumed that it would be the same for both the ABUS and light rail systems. There will be a difference in the waiting times for the two systems, because of the difference in frequency of service for the two systems. It is assumed that the light rail trains will have a lower frequency because of the higher capacity. The effect of the passengers accessing the system from the automobiles will be taken into account insofar as they would affect the capacity and concomitant costs of the part of the system within the boundaries.

There will be a difference in the costs associated with providing the track or way for the two systems. This cost will include the planning, design, construction, maintenance and system

operating costs. Right-of-way costs should also be considered here. Planning, design and construction costs are often lumped together. A related cost component is the cost of major rehabilitation of the way over the course of its useful life. These costs are more akin to construction costs than to maintenance costs that are incurred on a more routine basis. Maintenance costs would also be different for the two systems. Also, the introduction of rail in an area, where roads dominate, requires additional expertise that may also increase costs. This would, however, be difficult to quantify.

Administration costs and system operating costs have some fixed elements and some elements are a function of the size of the system. These costs are related to the management and offices, salaries and benefits, transportation supervision (dispatchers, inspectors etc.), office expenditures (heat, light, telephone, rentals etc.), building and fixed plant expenditures, support services (promotion, legal, audit, purchasing and taxes. Since only a part of the complete transit system will be considered (the remainder of the bus service and purchased transportation will not be considered), it will be difficult to separate out the differences in these costs that could be attributed to using the light rail versus the ABUS. These costs will therefore be considered to be common to both systems.

Vehicle operating costs consist of operator wages and benefits and vehicle-related costs. These costs will be fundamentally different for the two systems, because of the difference in the vehicle types and capacity, the number of vehicle-miles traveled, the number of vehicle-hours operated as well as the number of operators needed. The maintenance costs for automated buses will likely be higher because of the higher vehicle complexity.

The assumption will be made that the travel time for passengers on the line-haul section will be the same for both systems. There will be differences in the travel times resulting from differences in the passenger travel times because of the elimination of the transfers from feeder buses for the ABUS and from the difference in frequency of service.

## **12.2 AHS-Bus versus Conventional Bus on Dedicated ROW**

The physical system chosen as a basis is again the part of the VTA light rail system route north of the downtown area. Figure 7 summarizes the basic trip concept for conventional bus on a dedicated lane with provision for passing a stalled bus; Figure 8 summarizes the basic trip concept for conventional bus on a dedicated lane but without provision for passing a stalled bus. Figure 9 depicts the basic geometry for a road consisting of two regular (mixed-traffic) lanes and a bus lane implemented on a dedicated lane next to the median. (More space will be needed if regular shoulders are required.) Figure 10, however, depicts the geometry of a conventional road consisting of three regular (mixed-traffic) lanes.

There would be a great deal of similarity between the two systems, but there are differences that will give rise to differences in costs. It should be noted that the roadway for the AHS-Bus may be narrower and related costs will be lower than the corresponding costs for the dedicated bus lanes because of more accurate lane-keeping by AHS vehicles. It is readily possible to obtain a rough estimate from existing design theory to obtain an estimate of the reduction in road width and the reduction in roadway surface area. The structural cost of the pavement may also be lower, because of more efficient construction resulting from less “wander” of the vehicles.

The operating costs for the two systems should be approximately the same, except for the difference in cost arising from the reduced labor cost because there will not be drivers on all buses all the time. There may also be reduced fuel consumption for the ABUS because of reduced wind drag resulting from close following, although this may not be significant at low operating speeds. There may also be a difference in vehicle operating cost because of the difference in the utilization of vehicles. There will be additional cost to automate the ABUS, but according to researchers at PATH, this cost is insignificant compared to the overall cost of the vehicle. Similar to the comparison between automated bus systems with light-rail systems, the maintenance costs for automated bus systems will likely be higher than their conventional-bus counterparts.

A possible negative source of travel time for passengers is the waiting time for the bus “trains” to form up. This should be considered together with other positive factors, e.g., integrated mainline operations with local collection-distribution.

### **13. BENEFIT-COST ELEMENTS FOR COMPARISON BETWEEN TRUCK-AHS AND CONVENTIONAL ALTERNATIVES**

#### **13.1 AHS-Truck Versus Conventional Lanes**

The system boundaries were chosen so as to have a Truck-AHS system that would be long enough to allow for several of the access points to the system and also to make the comparison with intermodal rail possible. Issues related to the latter comparison will be discussed in a later section.

Two basic systems have been identified to possibly serve as a basis for the comparison. The I-10 between Los Angeles and El Paso in Texas is the preferred system because it is a good alternative for the rail system between Los Angeles/Long Beach Harbors and El Paso. The alternative system is the I-5 and the I-10 between Sacramento and Colton. The choice of the two systems will be further discussed in a later section. See Figure 15 for a schematic description of the two systems.

The AHS-Truck system will have major access points at approximately every 100 miles, but this interval should be reviewed when the final system for comparison is designed. It is anticipated that it will be necessary to construct assembly and disassembly areas at the major access points.

Additional road surface will have to be constructed to accommodate the AHS-Truck system. The additional road surface will consist of space for a breakdown lane and space for a separator from normal traffic. The least expensive way to add additional lanes is usually to add them in the median of the freeway, if there is adequate space. A separator should also be provided between the opposing traffic streams for safety reasons. If space is not available to add the extra lanes in the median, then the infrastructure for the Truck-AHS will have to be provided by:

- Taking away some of the space now allocated for conventional traffic.
- Double-decking the existing roadway.
- Adding space on the outside of the existing roadway.

- Constructing a completely new roadway.

The first option may be politically infeasible because of the difficulty presented by taking away space from existing users. This option is reminiscent of the failure of attempts in the 1970s to convert conventional lanes to HOV lanes. It would, however, avoid problems associated with acquiring additional right-of-way.

Double decking the freeway may be costly and may currently be unacceptable to the public because of the fear of failure during earthquakes. However, in future, this option may become acceptable, especially if rising congestion levels become unacceptable and leads to a change in the public's priorities. This option avoids the issue of having to acquire additional right-of-way.

Adding space on the outside is generally very costly, because it involves major redesign and construction of interchanges. Acquisition of additional right-of-way is also costly and may be politically infeasible in urban areas. See Figures 11, 12, 13 and 14 for schematic descriptions of the basic trip concept and basic geometry of a truck-AHS. The basic trip concept for truck travel on conventional mixed-traffic lanes is depicted in Figure 19.

For the conventional system, it may be necessary to construct additional lanes if future traffic volumes would require it. In this event, the same problems may be encountered as in the case of the Truck-AHS. However, the space required for a conventional lane is less than the space required for the Truck-AHS because it is not necessary to add a breakdown lane or a separator.

For this comparison, it is anticipated that there will be differences in the cost of the infrastructure required for the two alternatives and that infrastructure cost for the AHS-Truck will probably exceed the corresponding cost for the conventional freeway for the same volume of traffic. The added cost would consist of providing, maintaining and operating the additional road space as well as the added cost for the assembly and disassembly areas.

There will be a difference in vehicle operating costs between the two systems. It is anticipated that the driver cost for the Truck-AHS system will be less than for the conventional system, because of using fewer drivers to drive the trucks over the line-haul sections. However, the trip lengths for the AHS-Truck will be longer because there will be fewer access points to the freeway for the AHS-Truck, which will result in overall longer trip lengths for the containers and increased driver costs for the access portion of the trip. Drivers may also have to wait at the assembly areas for a truck to drive after disassembly, which will be an added cost for the Truck-AHS.

Because the trucks using the AHS system will be traveling longer distances to the access points, vehicle-related costs such as vehicle depreciation etc. will increase. However, there is evidence that fuel use for the Truck-AHS will be less because of the decrease of wind resistance when the trucks are in a train with short headways between the individual trucks (4). There will also be an added cost for outfitting the trucks to enable them to be a part of the train, but again, according to researchers at PATH, this is not significant.

It is anticipated that there will be additional travel time for the Truck-AHS because of the longer distances traveled and the delays at the assembly and disassembly points. It is difficult to say at this juncture whether the travel times on the line-haul sections will be greater or less for the Truck-AHS. This will depend upon the proportion of trucks using the AHS lane. For instance, if

only a small proportion will be using the AHS lane, then the remaining lanes may become congested with resulting higher travel times for vehicles using those lanes. The differences in travel times will also change for different levels of traffic, because the effects of increased volume is anticipated to be different for the two alternatives.

The pavement maintenance/rehabilitation cost of a highway depends heavily on the amount traffic it carries. The difference in this cost between adding a truck-AHS and adding a conventional mixed-use lane is expected to be significant.

### **13.2 Truck-AHS Versus Dedicated Truck Lane**

The proposed base system is the same as the ones proposed for the previous comparison. The system boundaries can in this case be more “pure” than would the case of comparing the Truck-AHS versus the intermodal rail option, since the beginning and end of the corridor can be exactly the same. There are, however, other problems that arise and could make it difficult to compare the two systems on an equal basis. These difficulties are related to the design of the access and exit points for the Truck-AHS versus those for the trucks on the dedicated conventional bus lane.

If the dedicated truck lane were also placed closest to the median (similar to the concept outlined for the AHS-Truck), with some physical separation from the remainder of the traffic, then placement of the entrances and exits would present similar problems to those presented by the Truck-AHS. It is conceivably easier to design the option with the dedicated truck lane with more frequent exits and entrances, if the truck lane were placed closer to the right-hand side of the direction of travel and if other traffic were allowed to weave through the truck lane. For the purpose of this study, however, the assumption will be made that the access points will be similar to those of the AHS-Truck

There will be differences in infrastructure-related cost, both with regard to capital and maintenance costs. The space required for the dedicated lane for the AHS-Truck may be less because a narrower lane will be required because of the improved lane-keeping. There will be a cost increase for the assembly areas for the AHS-Truck.

Since fewer drivers will be needed for the AHS-Truck, the driver cost should be lower and there could be a decrease in fuel usage because of close convoying. On the other hand, there will be increases in travel time because of the time taken to assemble the truck trains.

See Figures 11, 12, 13 and 14 for schematic descriptions of the basic trip concept and basic geometry of a truck-AHS. The basic trip concept and basic geometry for a dedicated truck lane are depicted in Figures 16, 17 and 18. The principal difference between the two systems depicted in Figures 16 and 17 is the side on which the dedicated truck lane is relative to the traffic direction. These Figures should be compared to their truck-AHS counterparts.

### **13.3 AHS-Truck Versus Intermodal Rail**

Historically, rail systems have been more competitive over longer distances, i.e. in excess of 500 miles. Obviously the length of the system could favor one or the other. To gain insight into this

issue, it would be useful to define a system with a length of approximately 500 miles. Moreover, the comparison should be made in a corridor where intermodal rail is already in operation. This will make cost comparisons more realistic. However, there are some major complicating factors that force a simplification of this comparison given the resources available for the comparison.

Finding rail routes and truck routes that are comparable is difficult. The rail systems are generally old systems with terminals in central urban areas and it would be difficult and very artificial to conceive a truck terminal at the same location. If the truck terminal were placed elsewhere, access costs would differ and the lengths of the line-haul portions could also be different. This could be partially overcome by defining a rail system and a road system with the same lengths, but different terminal locations. One problem with this approach is that the terminal access costs would not be exactly the same and the costs would be less for the AHS-truck option, because access outside Central Business District (CBD) areas would generally be less costly. It is conceivably possible to substitute a highway on a rail route, but estimating costs for this comparison would also be outside the scope of this project.

A major barrier to an accurate comparison of costs is that cost data for inter-modal rail in a specific corridor are proprietary and it is therefore impossible to estimate the real cost of inter-modal rail in a specific corridor.

In order to arrive at a comparison that is tractable, an approximate approach to the comparison is proposed. First, assume that the two industries share a common ratio between the actual cost of trucking versus the actual shipping rate. Since shipping rates for both industries are in the public domain and the actual cost of trucking is known with reasonable accuracy, this assumption enables a very rough estimation of the actual cost of the rail industry. The cost of inter-modal rail can be determined by multiplying the shipping rate for inter-modal rail by the ratio of the shipping cost for the truck alternative divided by the shipping rate for trucks. When interpreting the results, allowance should be made for the fact that distortions will be present because of accounting and business practices as well as the allocation of fixed costs. This ratio-based estimate is not expected to be very accurate, but this approach does offer a solution, given the limitations of available resources and the unavailability of certain data. The cost of intermodal rail transportation can then be estimated by determining the rates per kilometer, based on an existing intermodal rail section, and applying it to the corridor selected for comparison.

When carrying out this comparison, it is not necessary to have a rail and truck route that are exactly comparable, since it is only the relative cost of the shipping rates that are considered. It does make the comparison more realistic though when the corridor, used for comparison, is one where competition between trucking and intermodal rail does take place.

Based on the above discussion, it is proposed that the rail system be defined as the Union Pacific section between Sacramento and Colton. A comparable road system would be the combination of I-5 and I-10 between the same two terminals. However, the information provided by Union Pacific on their website does not currently indicate that intermodal rail is being operated on any section of their network in California. The only solution to finding costs would be to determine a rate per kilometer for the section between Hutchinson, Kansas, and Chicago, Illinois.

For the comparison, it will be necessary to determine the full cost of the AHS-Truck system. This will comprise all costs related to the additional road space, access and the terminal areas as well as all costs related to operations.

## 14. CONCLUSION

The performance period of this one-year project was intended to synchronize with the 2003 Demo in such a way that the findings could be used as input to the 2003 Demo effort. Among the information needs for the 2003 Demo is benefit-cost comparisons between automated urban bus operations and its conventional public-transit alternatives and between inter-city truck-AHS and its conventional freight-transportation alternatives. The conventional public-transit alternatives include light-rail systems and busway systems. We compared some aspects of the implementation of automated bus operations to their counterparts of an existing light-rail system in California; we also compared the automated bus operations to a conventional busway with respect to similar aspects. The conventional freight-transportation alternatives include addition of a conventional lane (to accommodate all vehicle types), addition of a truck lane, addition of an exclusive AHS truck lane (of three different configurations), and intermodal rail.

Due to the complexity of the issues involved in developing and evaluating bus-truck AHS and the size of the proposed budget, the scope of research was limited. The research work involved development of system design options, development of operating concepts and then identification of some benefit-cost elements for a more detailed benefit-cost analysis in the future. The focus was on those major cost-benefit elements that differ significantly among the alternatives. (Some of the actual numeric estimates were beyond the scope of this research, but will be a subject of the Phase II of this project to be conducted in the 2002-2003 PATH fiscal cycle.) Concepts were developed and evaluated for transportation corridors only. Only a limited number of essential aspects of operating concepts were addressed in detail while the rest, e.g., safety and technological feasibility, are addressed in a perfunctory manner. Demand was considered as a parameter, rather than to be derived based on demand modeling.

We reviewed literature and developed operating concepts for both urban bus automation and inter-city truck automation. We also selected a small number of most promising operating concepts for urban bus automation and inter-city truck automation, both with variations and intermediate steps.

On urban bus automation, we selected one unprotected automated busway system (ABUS) for city operations and two operating concepts for automated bus operations on or along a freeway. All or a subset of these three concepts can be integrated to form other operating concepts. We also identified issues for further feasibility and benefit-cost studies. In general, we believe that the proposed ABUS system is particularly promising. Critical issues yet to be resolved include the safety of operating automated buses at low to medium speeds within dedicated but unprotected right-of-way on city streets, particularly the safety issues resulting from the absence of a driver on the trailing buses of a small closely-spaced bus convoy.

On truck automation, we selected two operating concepts for a protected inter-city truck-AHS, an open system and a closed system. The open system accommodates any properly equipped truck while the closed system can be used by only the tractors and even the trailers operated by selected AHS haulers. To demonstrate the deployability of these concepts and explain “how to get



there from here,” we described promising steps leading from the current transportation systems to the proposed systems.

A truck-AHS, if eventually realized, will be a revolution in freight transportation. A key ingredient of a truck-AHS is a dedicated truck-lane. A key position of the authors is that a dedicated truck-lane must exist before transportation agencies and the general public will commit to or even begin to accept the concept of truck automation. More precisely, a truck-lane alone must be able to provide sufficient benefits to justify its dedication or construction, without the help of the potential further benefits to be generated by truck automation. This position is motivated by the tremendous amount of risk involved in a commitment to a truck-AHS when much uncertainty exists about its possible eventual deployment. Physically separated truck-lanes that accommodate Longer Combination Vehicles may hold the key to successful deployment of truck-lanes as well as to successful deployment of a truck-AHS later on. The benefit of the proposed inter-city truck-AHS hinges upon its length. Urban freeways at many major metropolitan areas are already heavily congested. Unused existing right-of-way is scarce, and competition for it is fierce. If two inter-city truck-AHS segments cannot be connected through such a metropolitan area or via a bypass so that automated inter-city trucking is disrupted at such a metropolitan area, the potential benefit of such a truck-AHS may be drastically reduced.

We identified key benefit-cost elements of these operating concepts for a more detailed benefit-cost analysis in the future. The focus was on those major cost-benefit elements that differ significantly among the alternatives defined earlier as the scope of this project. Detailed benefit-cost analysis will be the focus of Phase II of this project.

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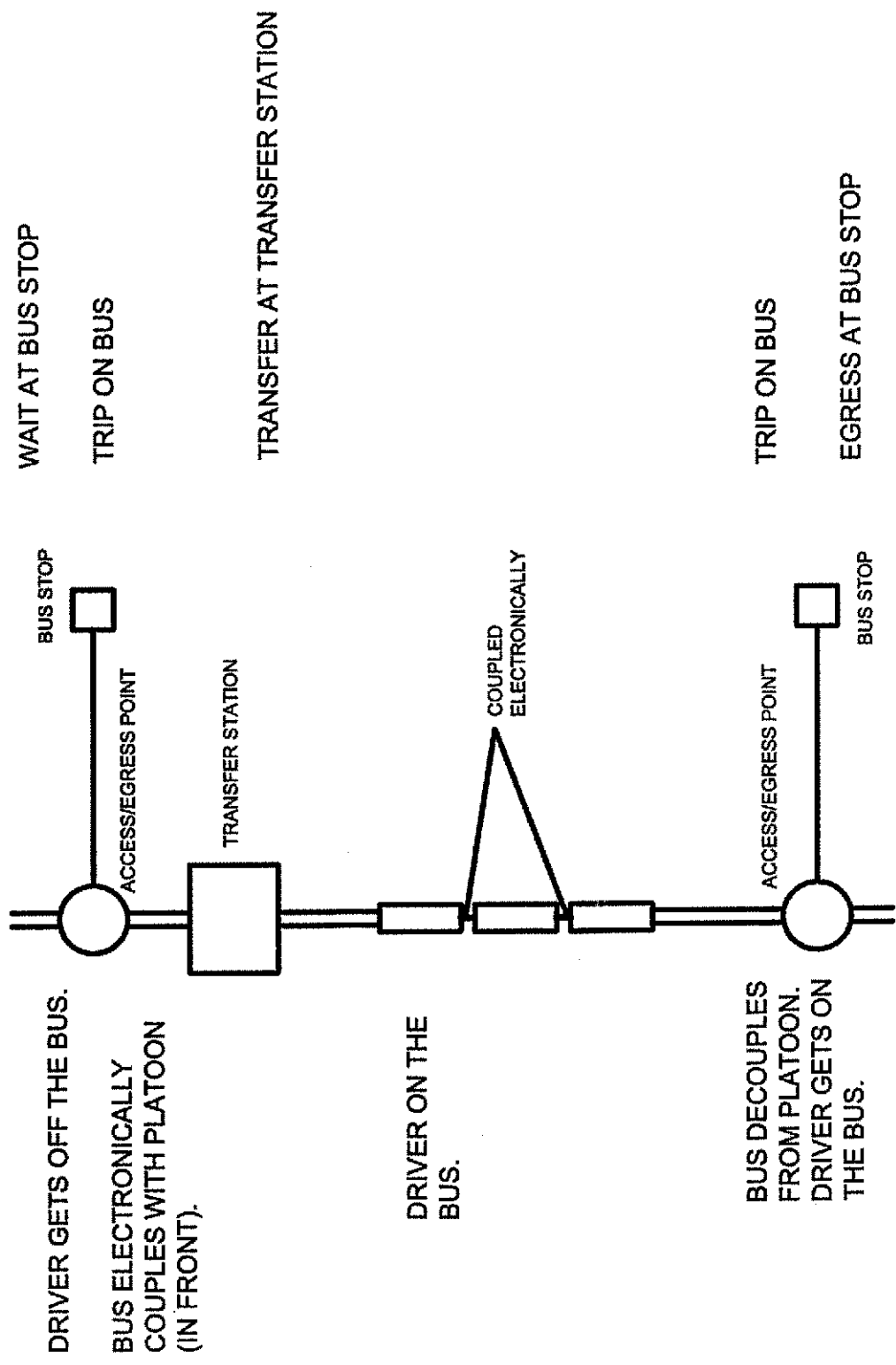


FIGURE 1. BASIC TRIP CONCEPT FOR ABUS.

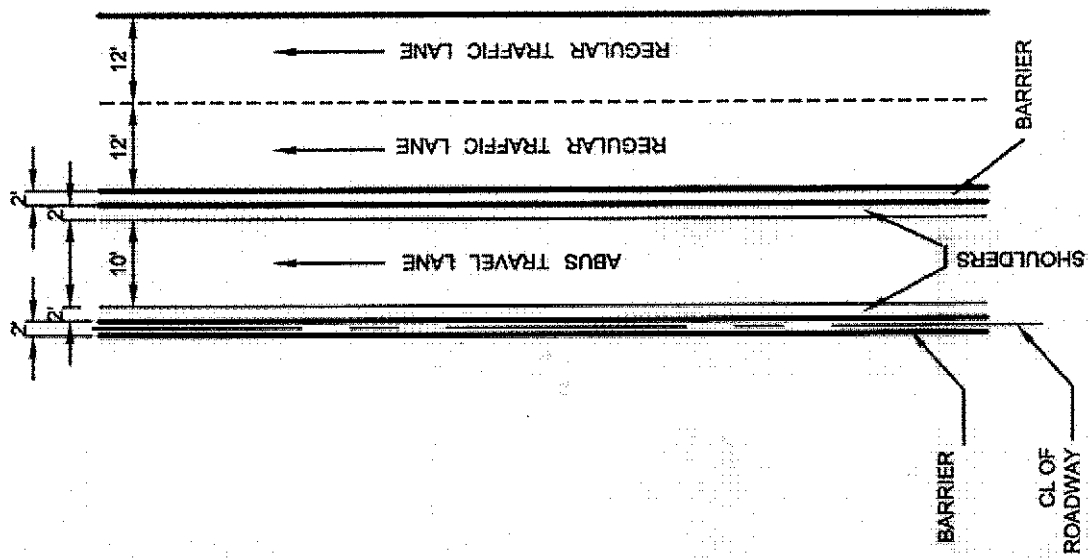


FIGURE 2. BASIC GEOMETRY FOR ABUS ON DEDICATED LANE CONFIGURATION.



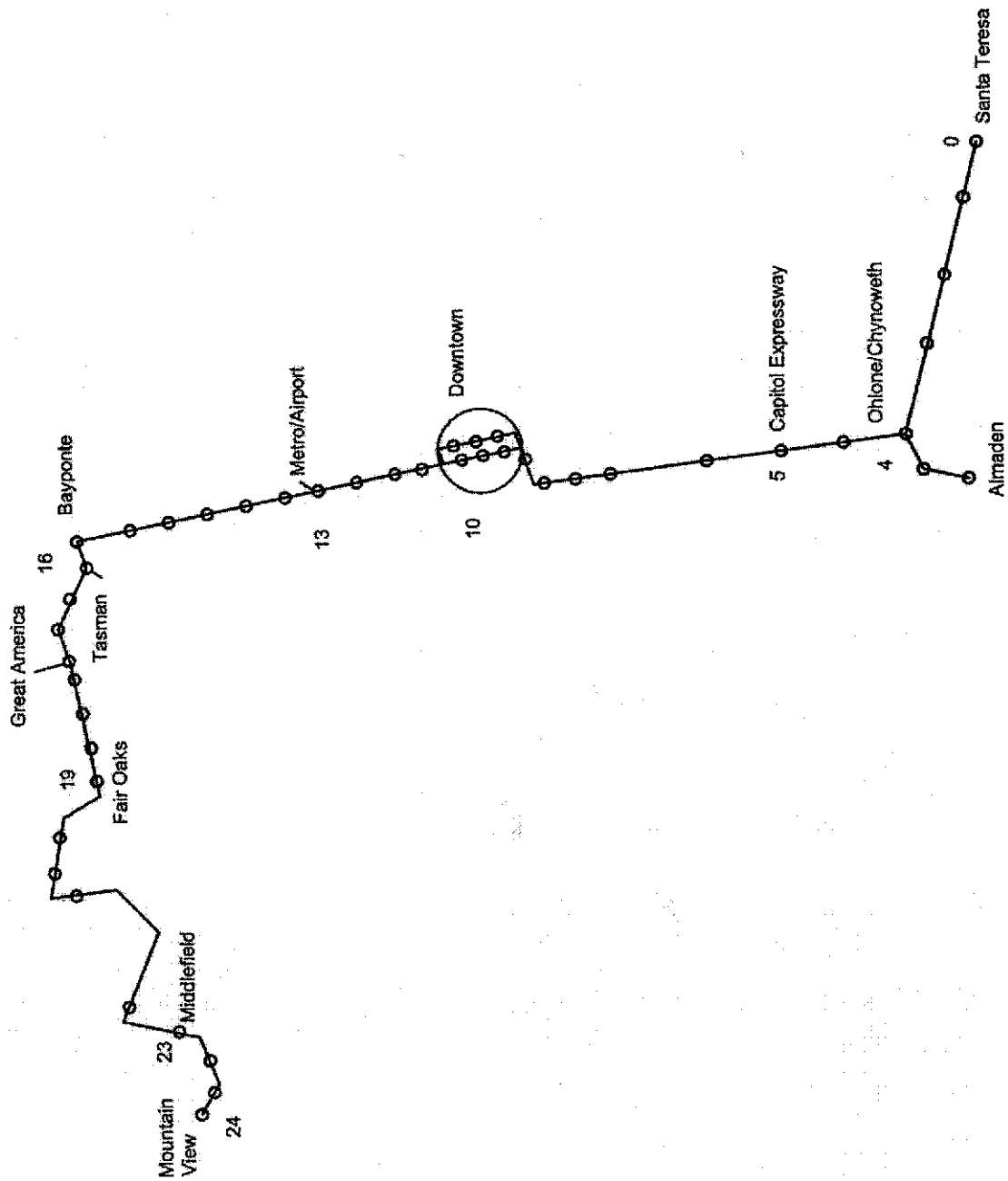


FIGURE 3. SANTA CLARA LIGHT RAIL SYSTEM (VTA).

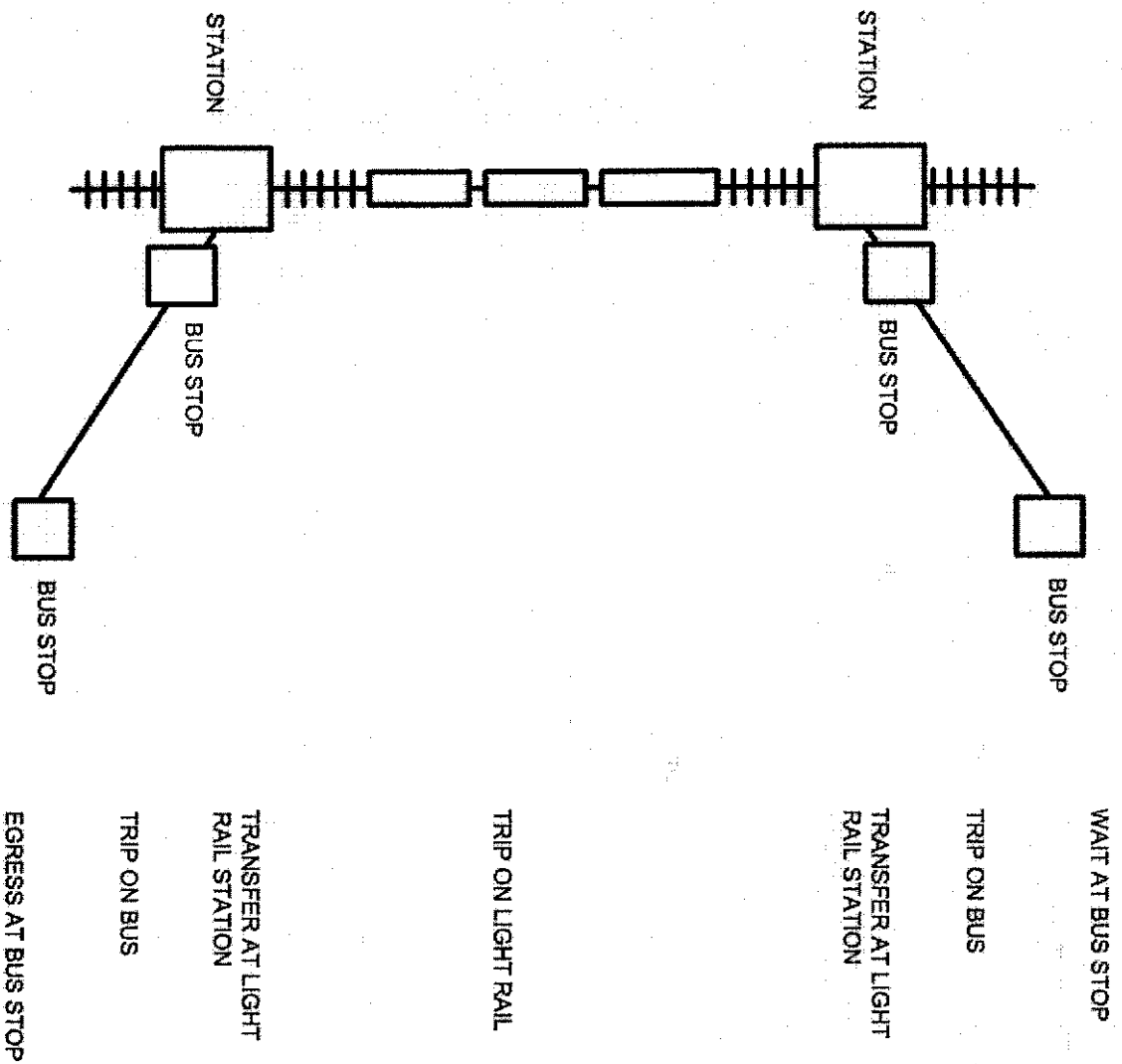


FIGURE 4. BASIC TRIP CONCEPT FOR LIGHT RAIL.

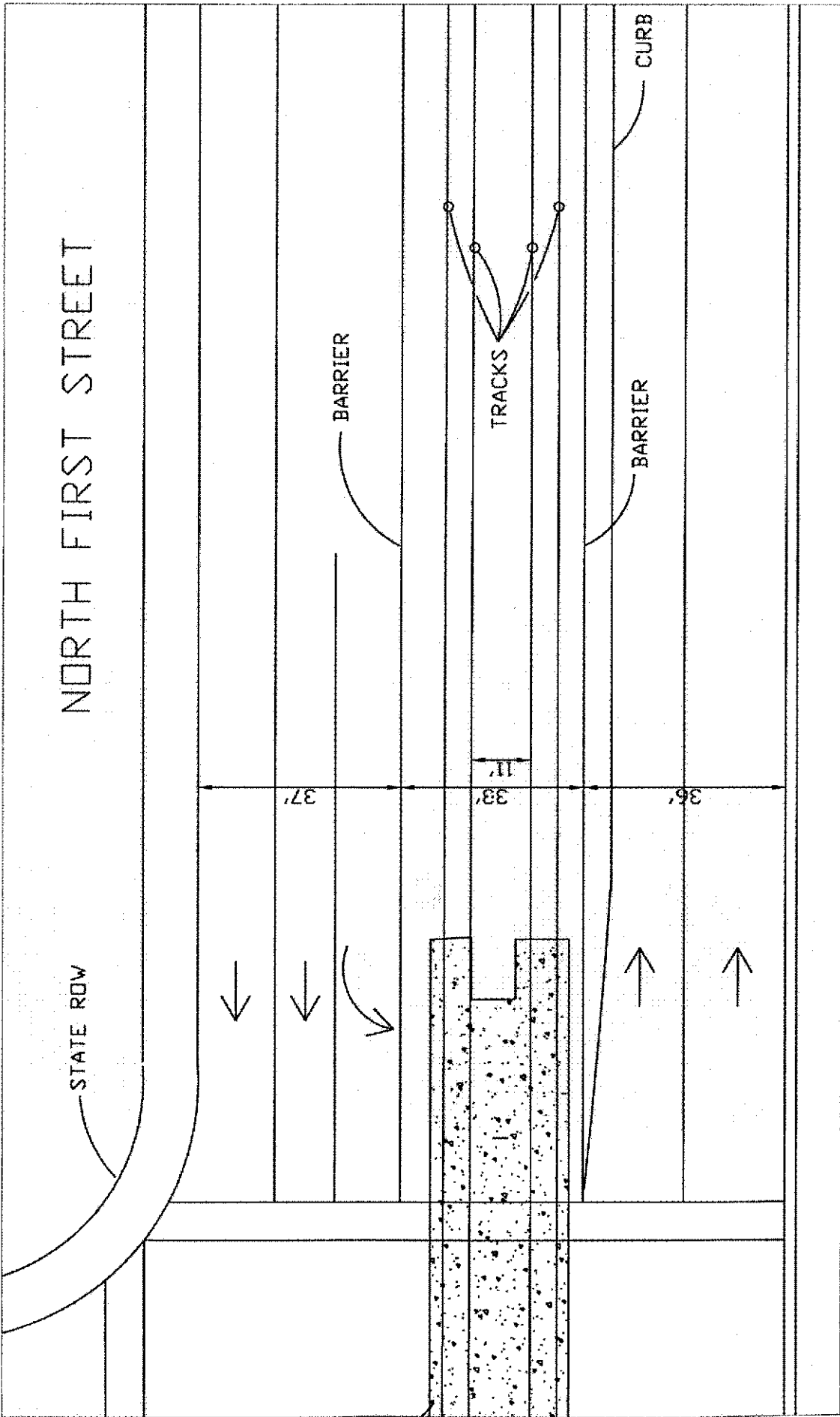


FIGURE 5. LIGHT-RAIL OPTION (FIRST AND SKYPORT).

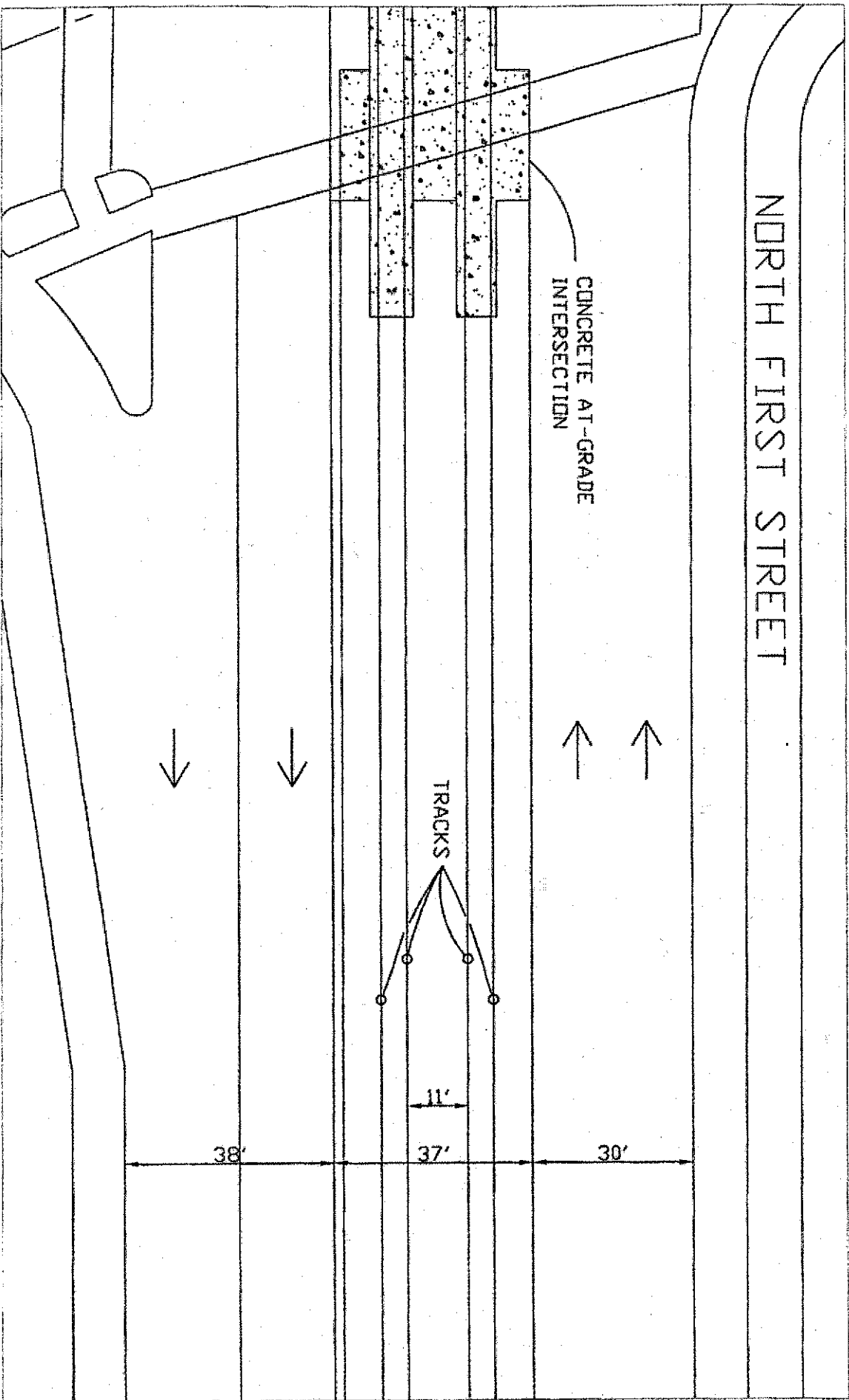


FIGURE 6. LIGHT-RAIL OPTION (BROKOW AND FIRST).

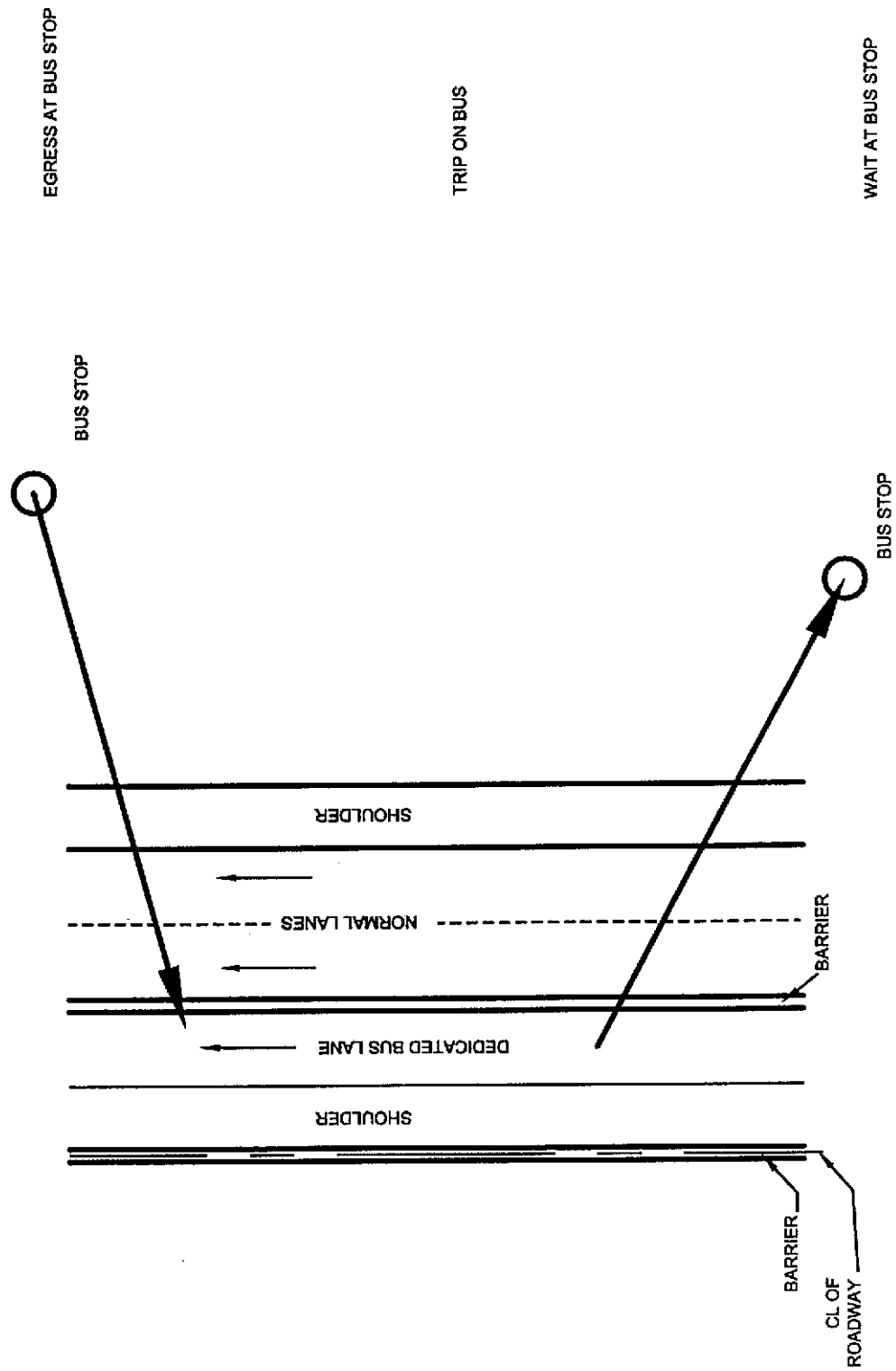


FIGURE 7. BASIC TRIP CONCEPT FOR BUS ON DEDICATED LANE (WITH PROVISION FOR PASSING A STALLED VEHICLE).

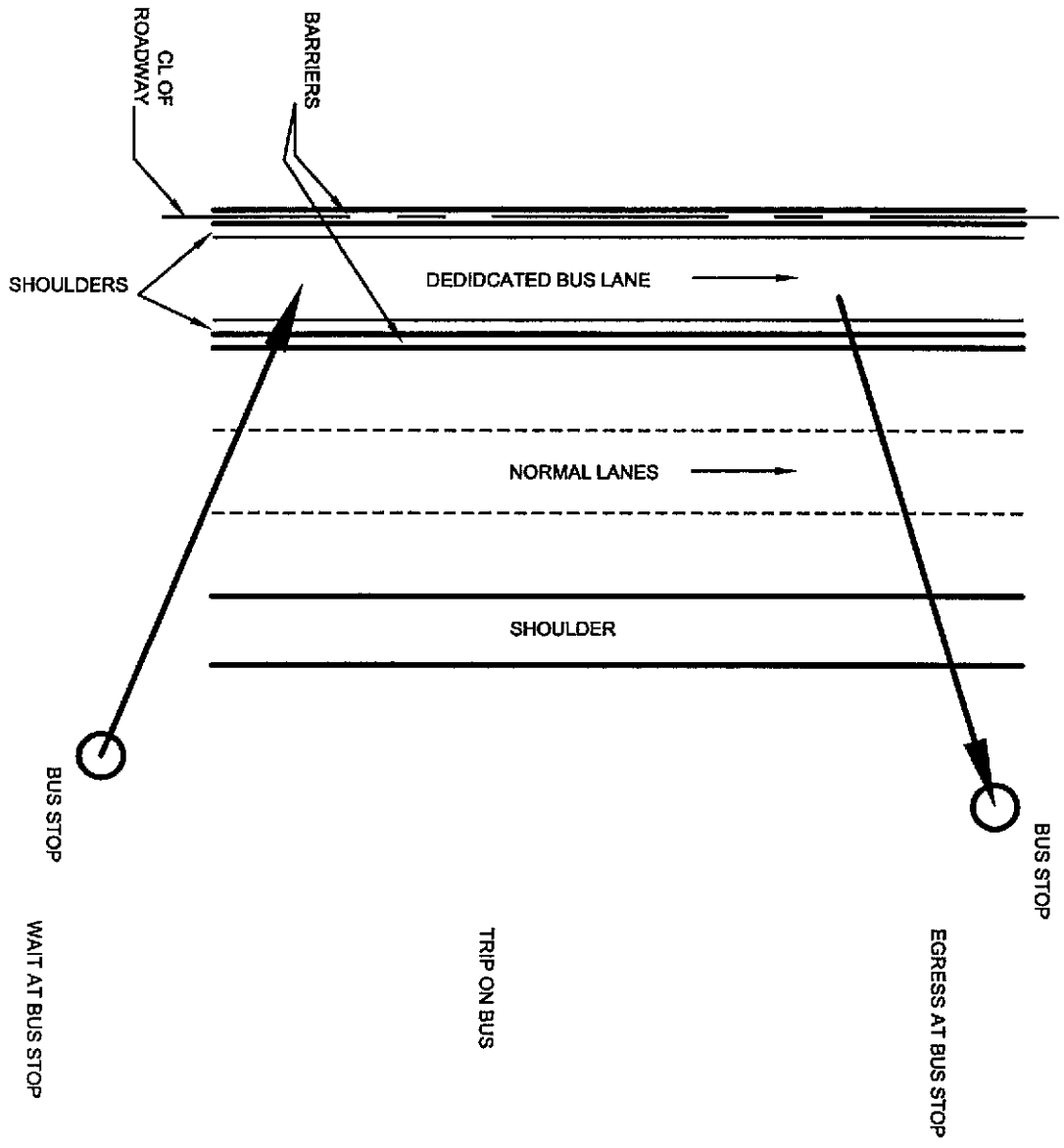


FIGURE 8. BASIC TRIP CONCEPT FOR BUS ON DEDICATED LANE (WITHOUT PROVISION FOR PASSING A STALLED VEHICLE).

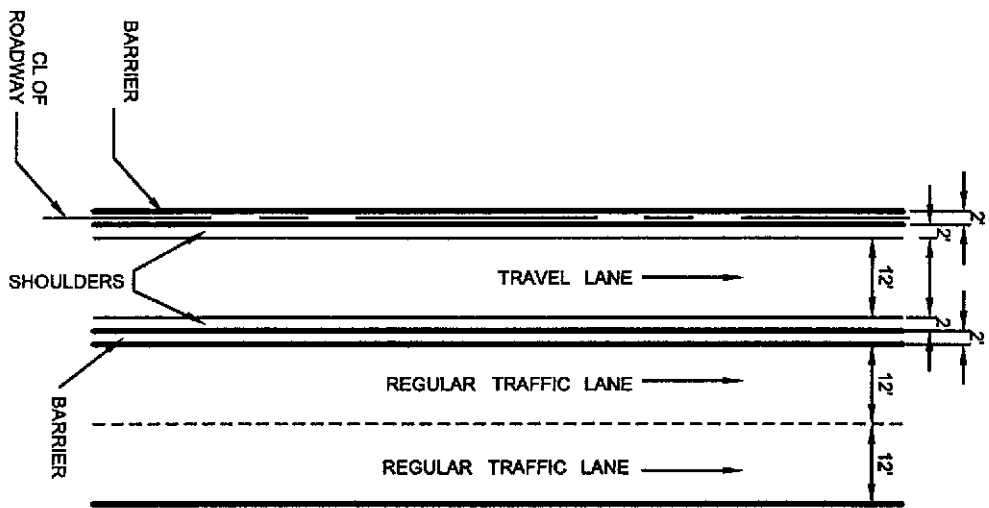


FIGURE 9. BASIC GEOMETRY FOR CITY BUS ON DEDICATED LANE CONFIGURATION.

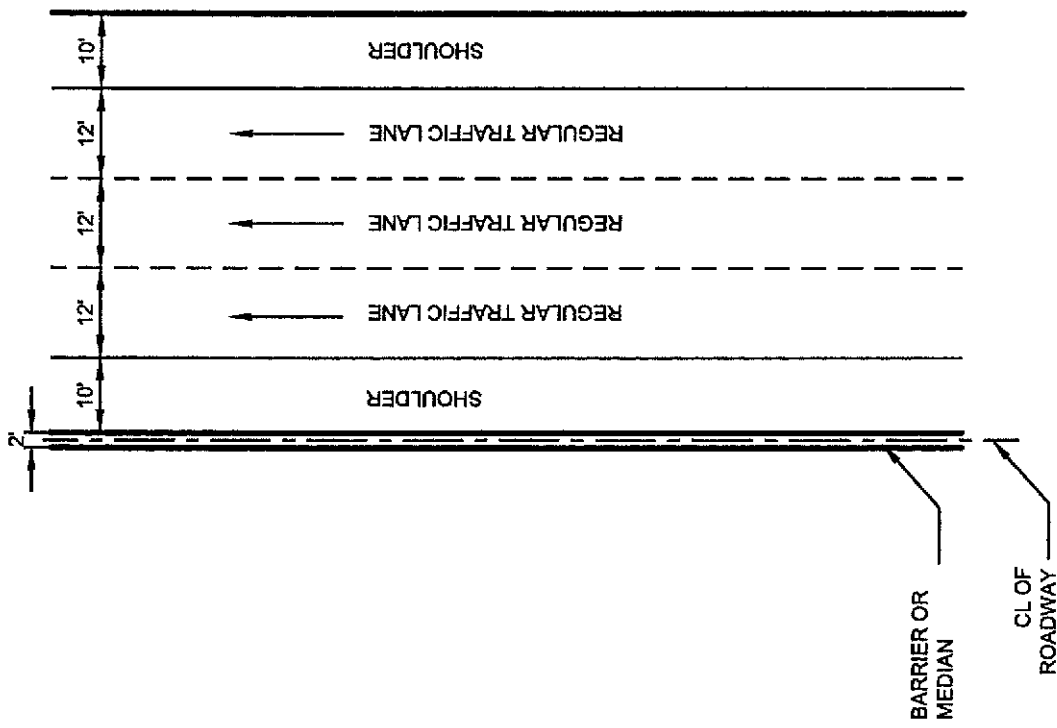


FIGURE 10. BASIC GEOMETRY FOR MIXED TRAFFIC-LANE CONFIGURATION.



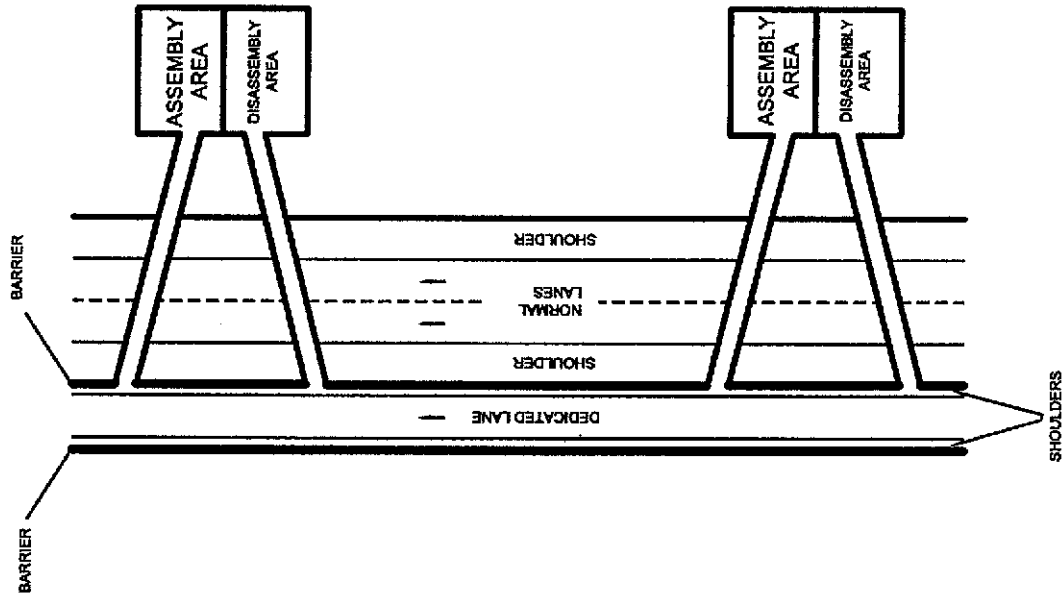


FIGURE 11. BASIC TRIP CONCEPT FOR TRUCK-AHS ON DEDICATED LANE (LEFT-SIDE CONFIGURATION).

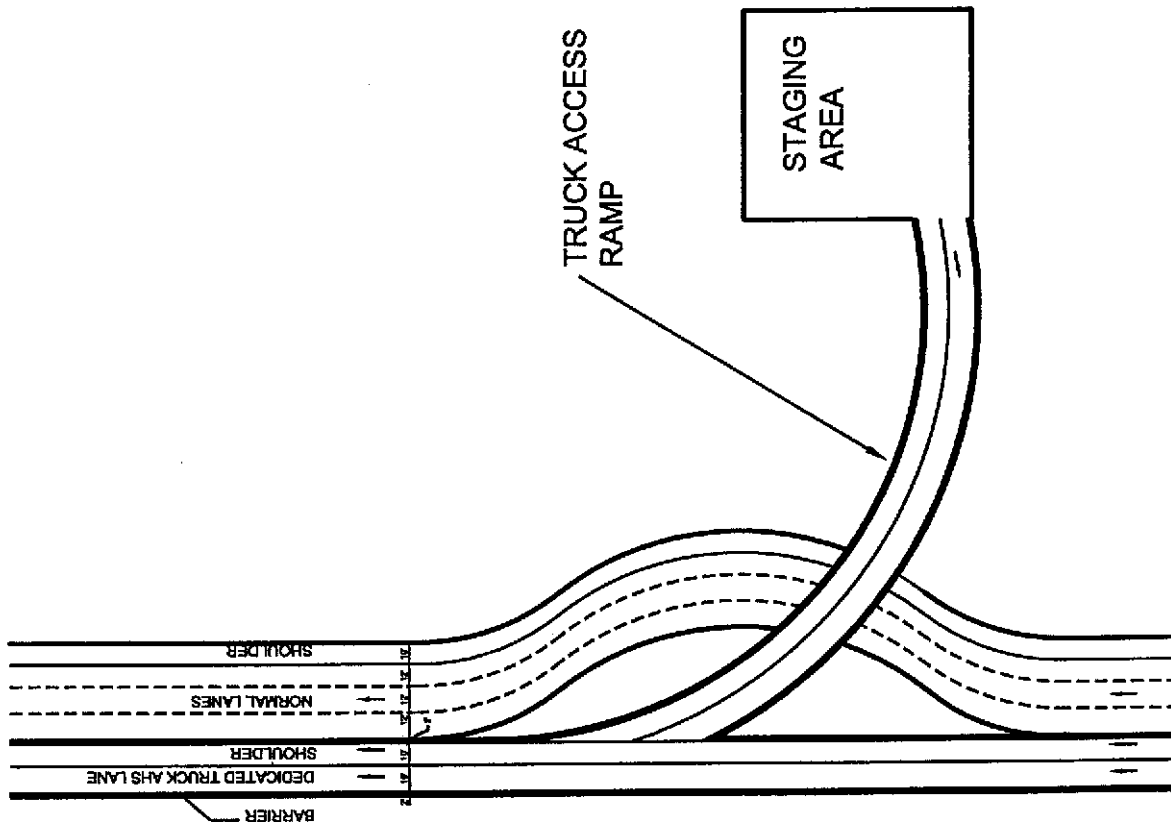


FIGURE 12. BASIC TRIP CONCEPT FOR TRUCK-AHS ON DEDICATED LANE (LEFT-SIDE CONFIGURATION).

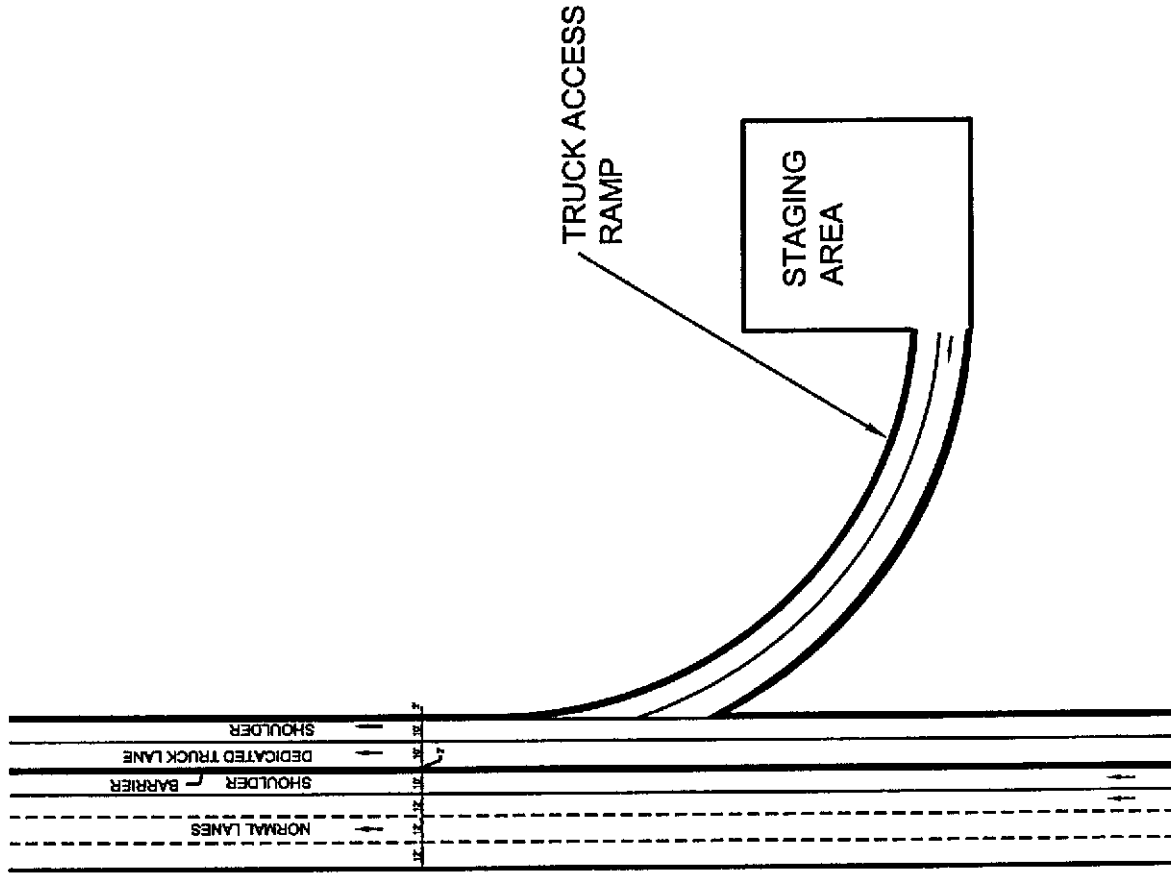


FIGURE 13. BASIC TRIP CONCEPT FOR TRUCK AHS ON DEDICATED LANE (RIGHT-SIDE CONFIGURATION).

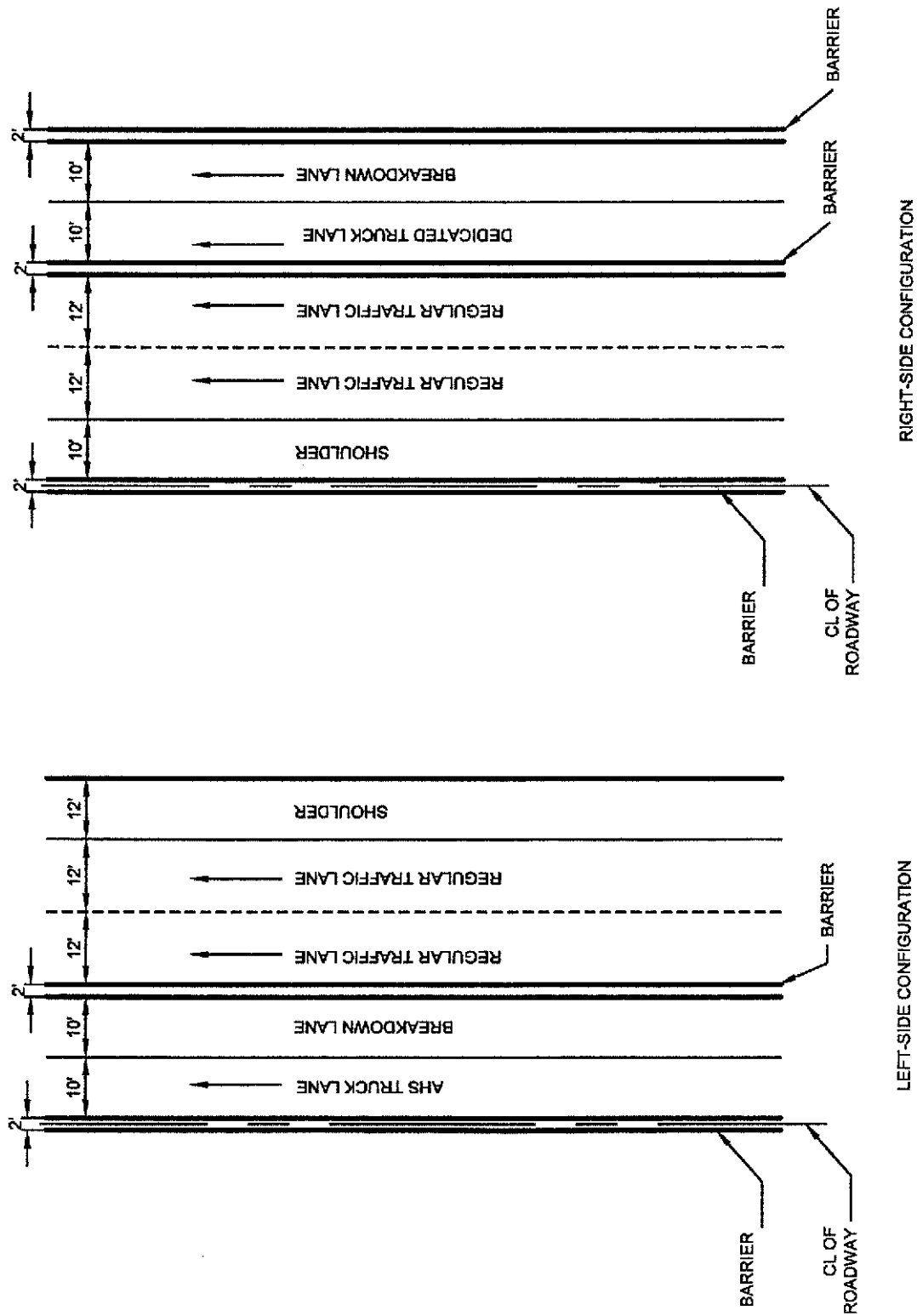


FIGURE 14. BASIC GEOMETRY FOR TRUCK AHS CONFIGURATIONS.

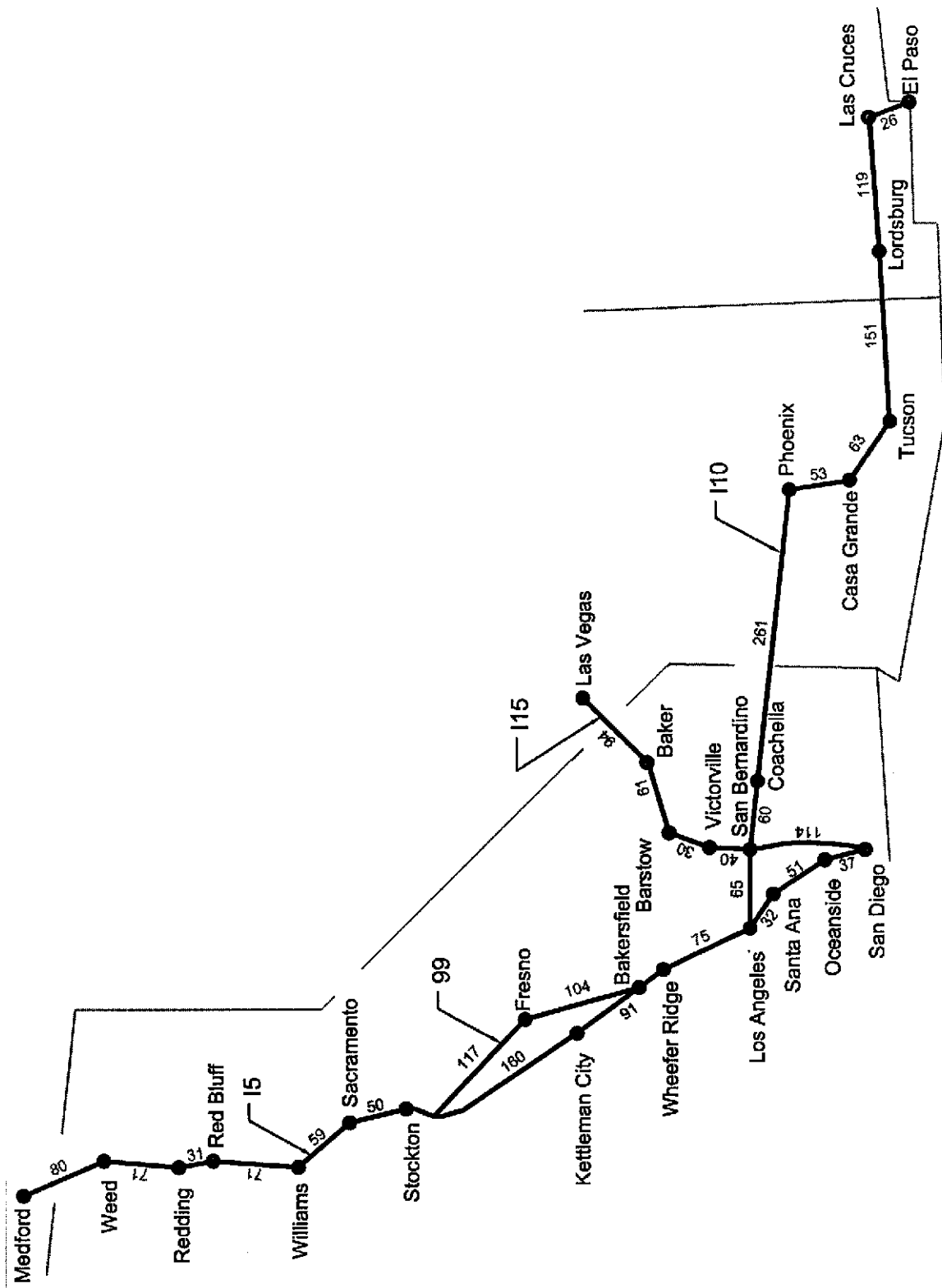


FIGURE 15. INTERSTATES I5, I10, AND I15.

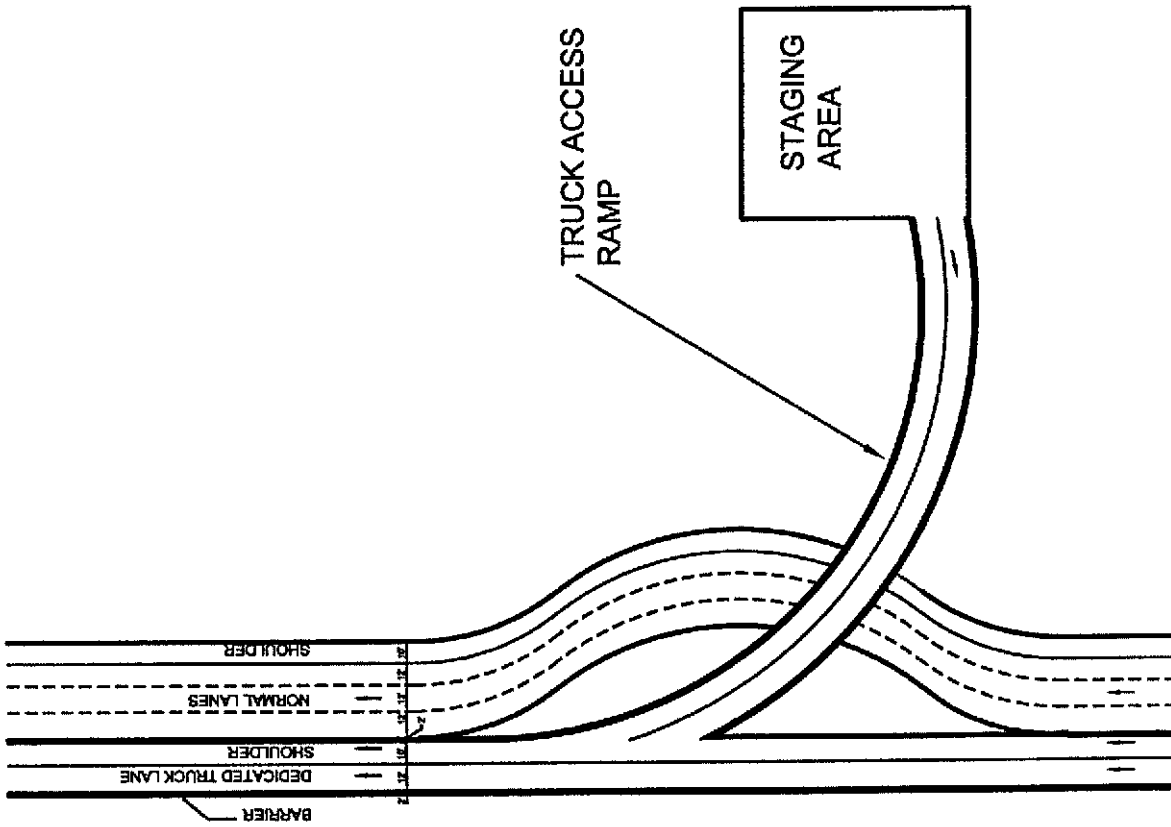


FIGURE 16. BASIC TRIP CONCEPT FOR TRUCK ON DEDICATED LANE (LEFT-SIDE CONFIGURATION).

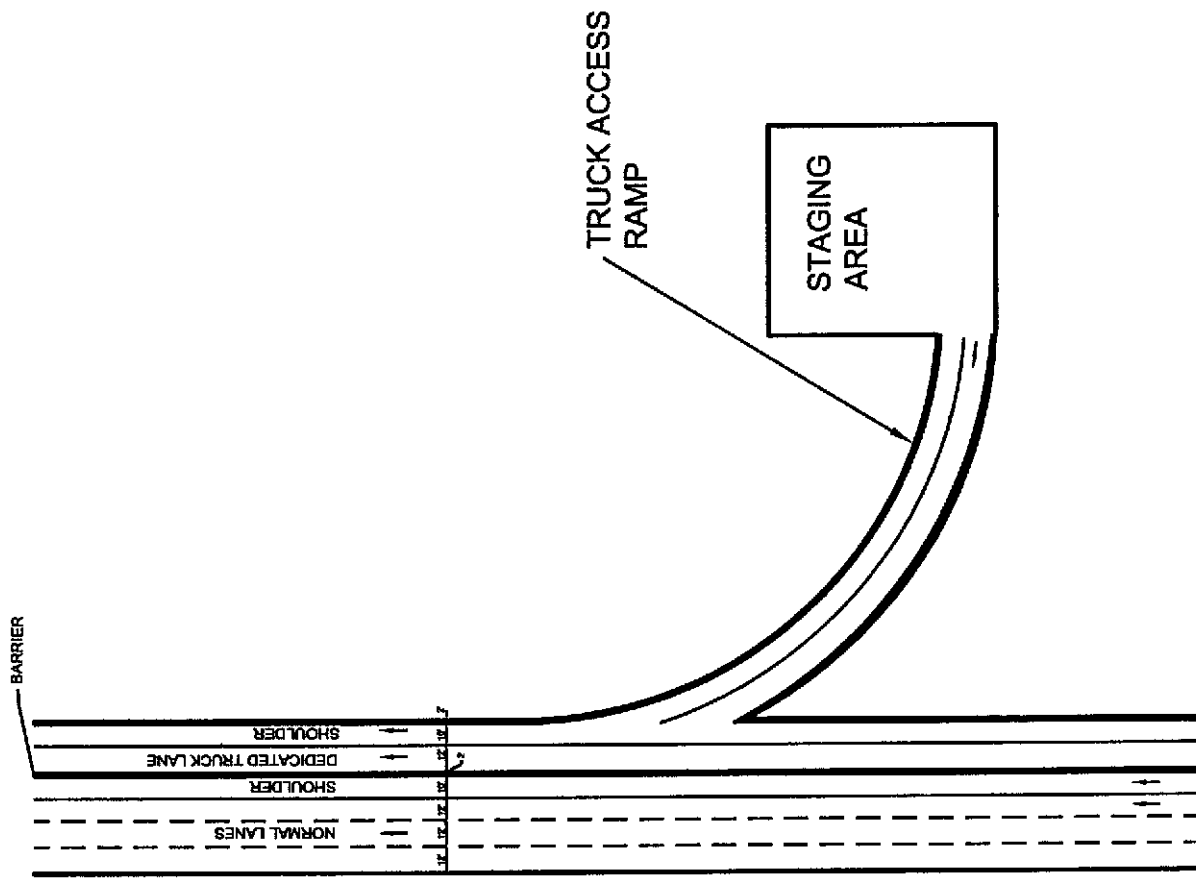


FIGURE 17. BASIC TRIP CONCEPT FOR TRUCK ON DEDICATED LANE (RIGHT-SIDE CONFIGURATION).

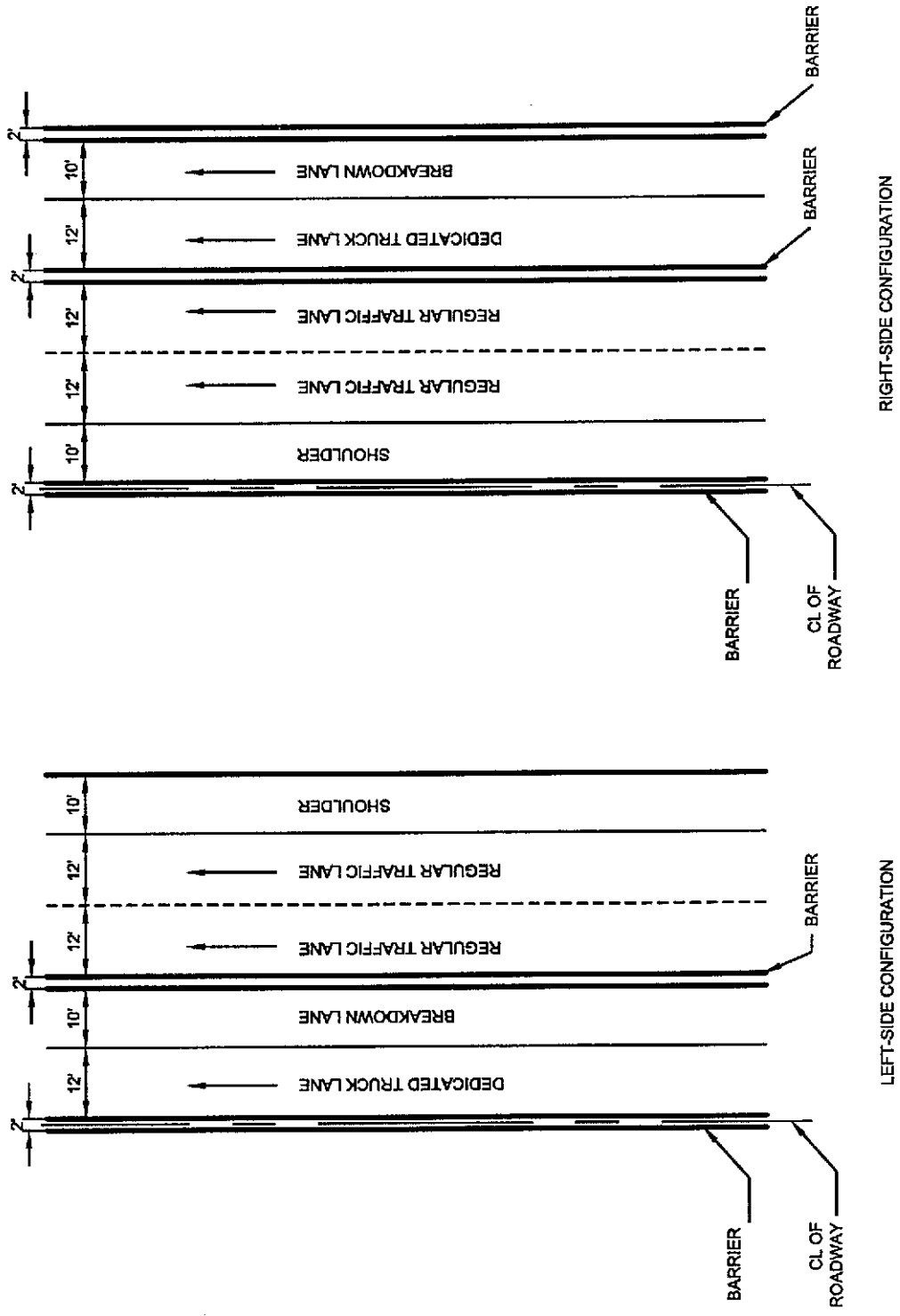


FIGURE 18. BASIC GEOMETRY FOR TRUCK ON DEDICATED LANE CONFIGURATIONS.



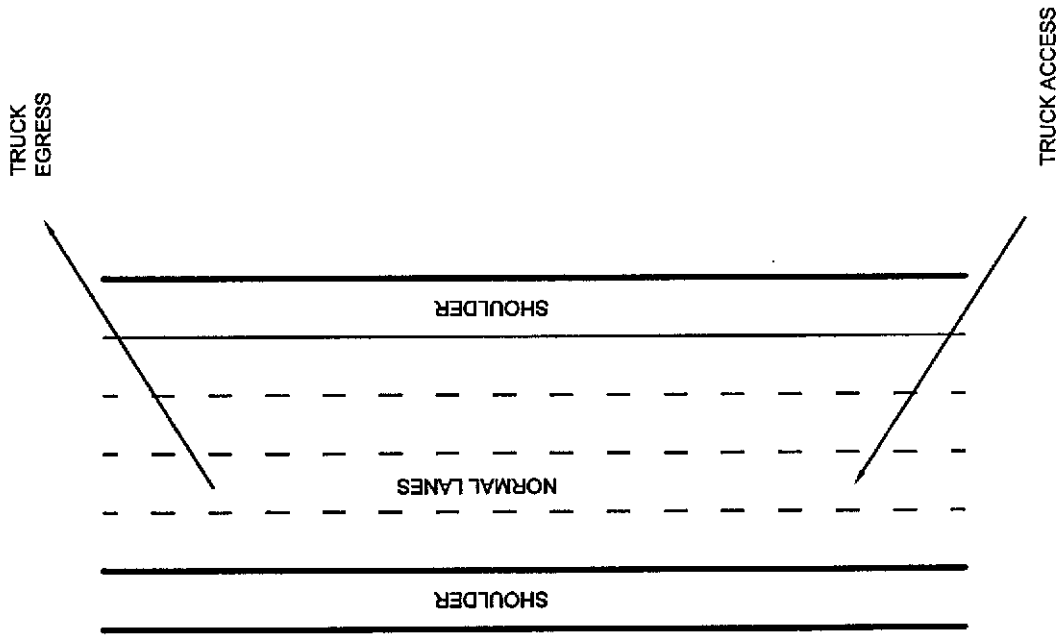


FIGURE 19. BASIC TRIP CONCEPT FOR TRUCK -- MIXED TRAFFIC.