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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 been funding a one-year research project entitled "Definition And Evaluation of Bus And Truck Automation Operations Concepts," proposed by the authors. This report summarizes the results of the research project achieved during the first six months. During those six months, 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 deployment 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 an operating concept 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 operating 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."

DEFINITION AND EVALUATION OF BUS AND TRUCK AUTOMATION OPERATIONS CONCEPTS

H.-S. Jacob Tsao and Jan L. Botha

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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 seeks 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 utilizes and builds 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 is 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 urban bus-AHS 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 compare some aspects of the implementation of a bus-AHS to their counterparts of an existing light-rail system in California; we also compare a bus-AHS 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 is limited. The research work involves development of operating concepts first and then identification of some benefit-cost elements for a more detailed benefit-cost analysis in the future. The focus is on those major cost-benefit elements that differ significantly among the alternatives. (Some of the actual numeric estimates are beyond the scope of this research, but will be a subject of possible follow-on studies for the 2001-2002 PATH RFP cycle.) Concepts are developed and evaluated for transportation corridors only. Only a limited number of essential aspects of operating concepts are addressed in detail while the rest, e.g., safety and technological feasibility, are addressed in a perfunctory manner. Demand is considered as a parameter, rather than to be derived based on demand modeling.

During the first six months of this 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 an operating concept for a protected inter-city truck-AHS. 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.

An Unprotected Urban Automated Busway System (ABUS)

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

TABLE 1: A Four-step Deployment Sequence Toward the Proposed ABUS system

Step	Main Features	Main Benefits	Main Traffic Issues
1 Conventionl Busway (with sufficient right-of-way)	• Bus operations on light-rail right-of-way	• Same bus for line-haul and collection/distribution	• Scattered buses disturbing surrounding traffic
1' Busway with Automation to Enable Bus Operations on Narrow Righ-of-way	• Automated precision turning/automated precision lane-changing • Automated lane-keeping • Automated bus-following • Automated precision docking (if desired)	• Same bus for line-haul and collection/distribution • Automation enabling busway operations on narrow right-of-way	• Scattered buses disturbing surrounding traffic
2 Manual Bus Convoying Through ITS	• Clustering buses to reduce disturbance via ITS technologies	• Reduction of disturbance to surrounding traffic due to signal preemption or priority	• Possible excessive disturbance as demand grows
3 Automated Closely-spaced Convoying (An ABUS)	• Automated closely-spaced convoying • Automated precision turning/automated precision lane-changing, automated lane-keeping,	• Reduction of disturbance to surrounding traffic due to signal preemption or priority	• Safety

	automated vehicle-following and precision docking if not already implemented		
4 Driverless Bus-following (Another ABUS)	• Absence of driver on trailing buses	• Reduction of labor cost	• Safety

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 leave the bus at the first bus-AHS station along the route after driving the bus manual 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 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. Automation technologies, particularly the lateral vehicle control technologies, may actual be required for the realization of such service concepts on urban freeways with little right-of-way to spare for such transfer stations.

A Protected Inter-city Truck AHS

The proposed Protected Inter-city Truck AHS and the proposed deployment steps are summarized in the following table.

TABLE 2: A Eight-step Deployment Sequence for the Proposed Truck-AHS

Step	Main Features	Main Benefits	Main Issues
1. Market Acceptance of Advanced Warning Technologies for Trucks	• Range sensing and frontal collision warning • Vision-based Lane-departure warning	• Use on and off highways • Safety • Technology maturation • Price drop	• Market acceptance
2. Market Acceptance of (Non-Simultaneous Use of) Hands-off and Feet-off Automation Technologies for Trucks	• Feet-off highway operations • Hands-off highway operations • Only one of the two features can be activated at any time.	• Driver comfort due to partial automation	• Possible abuse on city streets • Ability of the driver to react to unexpected events by interfering or overriding partial automation • Market acceptance
3. Public Acceptance of Truck-Lane Dedication	• Construction or dedication of a truck lane on the left or the right-hand side	• Higher freight throughput	• Acceptance by the general public • Amount of toll charge • Possible protest by the rail industry
4. Public Acceptance of a Physically Separated Truck Lane on Freeway Median with LCVs Allowed Through New Legislation	• Isolated truck lane on or near median • Staging areas at selected locations • Ramps from and to the truck lane from the leftmost conventional lane • Operation of LCVs allowed only in the truck lane and the staging areas to increase trucking productivity	• Safety due to less mixing of light and heavy vehicles • Significantly higher productivity of the driver and the equipment as well	• Public acceptance of the separate truck lane on the median • Legislative acceptance of allowing LCVs on the truck lane • Amount of toll charge • Possible protest by the rail industry • Potential for complete blockage by a single disabled truck, unless the

			combined width of the truck lane and the shoulder is sufficiently wide to allow lower-speed passage through the incident area • The provision of passing lanes if different cruising speeds are allowed. • Flow hindrance by trucks with slower cruising speeds if otherwise.
5. Automated Driving in Mixed Traffic on the Truck Lane	• Installation of magnetic markers or other "active" markers on the truck lane • Simultaneous hands-off and feet-off driving supported • Longitudinal mixing with manually driven trucks • Vehicle-to-vehicle and vehicle-to-infrastructure communication required for all trucks using the truck lane to ensure safety in traveling and merging	• Redundancy in lateral and higher safety guidance • Comfort for (trained) driver of automated trucks	• Safety of automated driving • Safety of mixing on mainline • Safety of merging between automated and manual truck traffic
6. Automated Truck Lane Accessible Only From Staging Areas	• Exclusive use by automated trucks, including automated LCVs • Closure of the ramps from and to	• Higher safety for mainline operations due to the homogeneity of traffic (of trucks only)	• Demand sufficiency to justify the dedication of truck lane to the exclusive use by

	the leftmost conventional lane • Access to the truck lane in the median only from the staging areas at selected locations.	• Higher merging efficiency due to the homogeneity.	automated trucks only. • Amount of toll charge • Modal-change overhead (between the conventional trucking and AHS-trucking)
(The sequence for the following two steps may vary.) 7. Automated Convoying With no Driver on Trailing Trucks of a Convoy	• Truck convoying • Driverless operations for trailing trucks (tractor plus trailers) • AHS Hauler for hire or scheduled AHS Hauler service (like an automotive, without freight of its own)	• Significantly higher driver productivity as well as equipment productivity	• Safety of driverless operations of the trailing trucks • Modal-change overhead (between the conventional trucking and AHS-trucking) • Amount of toll charge • Possible protest by the rail industry
8. Closely-spaced Convoying	• Closely-spaced truck convoying, which mimics a train • A "train system" with trucks	• Better fuel efficiency • Higher throughput • Tightly clustered trucks leaving more space between convoys for safer and more efficient merging	• Safety • Amount of toll charge • Possible protest by the rail industry

The remaining effort of this research will be focused on identification of key benefit-cost elements of the operating concepts for a more detailed benefit-cost analysis in the future. The focus will be on those major benefit-cost elements that differ significantly among the alternatives stated earlier.

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 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) is a more promising concept than its automobile counterpart, 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. The principal investigator actually 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 has been funding a research project entitled "Definition And Evaluation Of Bus And Truck Automation Operations Concepts," proposed by the authors. This report summarizes the results of this research project achieved during the first six months. 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. Sections 4 and 5 summarize the operating concepts selected for urban bus automation and for inter-city truck automation. To facilitate comparison, schematic descriptions of these concepts are given together with those for the conventional counterpart in later sections. Sections 6 and 7 summarize their deployment sequences. Concluding remarks are given in Section 8.

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
- Evaluation:
  - Cost and Benefit:
    - A focus on monetary costs and benefits or, when this is not possible, a pseudo-measure for monetary values
    - A focus on major elements impacting monetary cost and benefit: electronics costs for the infrastructure improvement assumed to be negligible, when compared to the total cost of roadway modification or construction
  - Technology: functional specification for the required technology, without any study of technology feasibility (e.g., automatic self-diagnostic capability on vehicle; capability of roadside safety check of vehicle; the possible infrastructure support needed to identify vehicles that need to communicate with one another for safe merging)
  - 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

A simple high-level cost-benefit comparison among these alternatives

A simple high-level comparison of benefits and costs relative to alternative systems will be ultimately performed. The objective of this analysis would be to determine traffic volume and pattern thresholds for implementing bus AHS.

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

A simple high-level cost-benefit comparison among these alternatives

A simple high-level comparison of benefits and costs relative to alternative systems will be ultimately performed. The objective of this analysis would be to determine traffic volume and pattern thresholds for implementing truck AHS.

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 an 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.

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 BUs System (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 around 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 5. 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 the basis of the operating concept and then point out possible new or better services that can be offered by an urban ABUS over a corresponding light-rail system, followed by a brief benefit comparison between the bus-AHS and the light-rail system. An operating concept for a bus-AHS intended for possible implementation on dedicated and protected right-of-way along the median of a freeway, as a simplified operating concept from the ABUS operating concepts proposed in this Section, will be proposed in Section 6, in the context of deployment of ABUS and bus-AHS.

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. The system operates on right-of-way that is commonly required of a light-rail system and serves the line-haul function. Since the access to the right-of-way is not controlled and the system is intended for implementation on city streets, this system is not an automated HIGHWAY system. We will refer to this system as an Automated Busway (ABUS) or an ABUS system. 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. Buses form closely-spaced platoons, 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 ABUS. The flexibility offered by buses extends beyond local passenger collection and distribution. For example, passenger transfer between platoons serving different routes is made possible at a station; a bus can merge with or break off from a platoon at an access or egress location or at a station. Also, passenger transfer can be made within a platoon, which may consist of buses serving different routes. 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.

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 platoon with a driver on the lead bus at least and with an upper limit on the length of platoon (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 platooning (i.e., organizing buses into clusters) will be advantageous. Note that such platooning requires much coordination among different buses and bus routes. Also, such platooning 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 platoons of reasonable length form is an important task. The necessary coordination goes beyond the physical separation of the buses in a platoon.
- Closely-spaced platooning:
  - ♦ The shorter the distance between two buses in a platoon, 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 platoon, 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 platoon 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 platoon is electronically coupled and platoon control must be able to react to sudden braking without causing any intra-platoon collisions.
  - ♦ It turns out that platooning in this situation is critical, but the motivation is completely different from what originally motivated the concept of closely-spaced platooning - 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 platoon or joining a waiting platoon at a station; driver getting off the bus and waiting for an exiting bus .
- Automated exiting out of a platoon (from any position of the platoon) 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 platoon, 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 platoon.
- The presence of a driver on the lead bus of a platoon 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 platoon) in a transfer station for special actions, e.g., for longer stay of a bus at the station (than the platoon), 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 platoon leader to watch out for possible safety hazards for the whole (short platoon) 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 platoon enabling the driver of the lead bus to monitor platoon.
- 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 laight-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.
- 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 platooning, 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-platoon transfers, not just inter-platoon transfers: A transfer at a station may be between two buses in the same platoon, involving no waiting for another platoon.
- 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 platoon, 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.

5. AN OPERATING CONCEPT FOR A PROTECTED INTER-CITY TRUCK AHS ON A FREIGHT CORRIDOR

5.1 The Basis of the Operating Concept

Like the operating concept for an ABUS proposed in the previous section, the proposed inter-city truck AHS combines the strengths of a freight rail system with those of a truck system and formulates a new system concept that offers new and/or better services. The truck-AHS operates on the right-of-way that is required of an inter-city freeway, e.g., in the median. 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. The operations of such a truck-AHS can be thought of as a rail system where rail cars are replaced by (self-propelled) trucks and physical linkages are replaced by electronic linkages. Trucks form closely-spaced platoons, mimicking a freight train, so as to require only one driver on-board the lead truck and hence to significantly reduce labor cost, to capitalize on reduced wind-drag for fuel efficiency (Ulmer, 1999), and to increase capacity. The trucks serve not only line-haul sections but also collect and distribute freight off the truck-AHS. The flexibility offered by trucks extends beyond local freight collection and distribution. For example, a truck can merge with or break off from a platoon easily at an access or egress location or at a station. In the new system, the lead trucks, with or without any freight of its own, can be operated by a company offering the service of hauling (self-propelled) trucks (with freight) on the AHS, and the tractors of the trucks hauled could be owned by the company but rented or leased to the freight-forwarders or shippers. More details about the operating concept are itemized below. Note that the proposed concept also works on right-of-way that is commonly required of a railroad.

5.1.1 Normal Operations:

5.1.1.1. Normal Mainline Operations

- One single lane in each direction, 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. (On grades, an additional climbing lane may still be required.)
- Automated lateral and longitudinal control (hands-off and feet-off).
- Platooning, with a driver on the lead truck at least and with an upper limit on the length of platoon. The lead truck of a platoon has a driver. The driver is responsible for detecting debris ahead on the lane or other non-nominal 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. An operational issue with this requirement is that when or before the lead truck of a platoon departs the mainline, arrangements must have been made so that upon the departure, the new lead truck has a driver on-board.
- Closely-spaced platooning: The shorter the distance between two trucks in a platoon, the less wind-drag on both trucks. Achieving this may require new research.
- Platoon consolidation (from two into one) while moving: no simultaneous consolidation of three or more platoons into one, at least for initial deployment.

5.1.1.2 Normal Access and Egress Operations:

- For a point-to-point implementation, the operations at the two end points (or “terminals”) may be complex if the AHS is to provide reasonable throughput. Large areas for assembly and disassembly may be required. The complexity of assembly/disassembly operations for more general implementations depends on access/egress demand. Terminal design is a worthy and interesting research topic.
- Platooned entry.
- “Tagging along” by an entering platoon or truck onto the end of a mainline platoon (optional at least for initial deployment stages). This feature may reduce much disturbance to mainline traffic (Hall et al. , 2001).
- Platoon splitting into two while moving: without splitting, the whole platoon would have to exit the mainline to let the exiting trucks leave the platoon.
- “Simultaneous splitting and exiting” (optional at least for the initial deployment stages): a member truck in the middle of a platoon splits away from the platoon as it exits the mainline, which may significantly reduce the disturbance to the mainline traffic at egress locations.

5.1.2 Operations Related to Non-nominal Events (Issues and Solutions)

- Difficulty in replacing human cognitive ability and adaptability: driver of the platoon leader to watch out for possible safety hazards for the whole platoon.
- Difficulty in obstacle detection by machines: performed by the driver on the lead truck.
- Reliability requirement for minimizing failure rate and probability of lane blockage: Standards for fleet maintenance can and will have to be developed.
- Safety of closely-spaced convoying: Organizing trucks of different characteristics into different platoons to minimize probability and severity of intra-platoon collision, e.g., braking capability, total weight, etc..
- Disabled truck: 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). If a disabled truck blocks the travel lane, the traffic may be able to get around the disabled truck using the shoulder at a

lower speed than the normal speed limit before the disabled truck is removed. Otherwise, a speedy removal of the disabled truck from the travel lane and the truck AHS becomes a critical issue.
- Difficulty in providing check-in function and infrastructure at entrances to minimize failure rate on AHS: standardized fleet maintenance.

5.1.3 Liability

- Liability issues: no issue if all trucks in a platoon are operated by the same company (either by the same shipper, forwarding company or the "AHS hauler"). Negotiation among operators participating in a platoon will require minimum public-sector responsibility.

5.1.4 Deployment

- How to utilize more fully a truck-AHS when there are not enough fully-equipped trucks: Conventional truck-lane construction first, with automation requirement fully considered; mixed traffic (conventional trucks and automated trucks) accommodated for transition to all-automated-truck operations before sufficient amount of truck usage can be achieved, but allowed with partial automation or with toll.
- Safety of mixed traffic: Cooperation protocol between automated and less-equipped trucks must be developed to ensure safe mixing, particularly for entry into and exit from the AHS. A manually-driven truck must be equipped with communication capability to negotiate with automated trucks and the driver must follow the protocol.
- How to build up a population of AHS-equipped trucks before opening the AHS: features useful off AHS; see discussion under bus-AHS.

5.2 New Services

- A brand-new service type is made possible: Analogous to railroad companies hauling (forwarding) train cars containing freight of their customers. The platoon leader can be a tractor hauling no freight of its own but serving as the leader of a platoon. Such a company may be called an "AHS hauler". Note that the tractors of the trailing trucks may be provided by a shipper, a forwarder, or by an "AHS hauler."

5.3 Benefits

5.3.1 Major Benefits over Current Truck Operations

- Labor saving due to driverless operations of the trailing trucks. (Much of the trucking industry's objection to weight-and-size and work-hour limitations has to do with labor cost.)
- Fuel saving due to reduction of wind-drag for both a lead truck and the trailing trucks.

5.3.2 Major Benefits over Current Rail Operations

- The operating concept offers much more flexibility because no modal change is involved between line-haul operations and local collection and distribution.
- Assembling and disassembling self-propelled trucks (without any tracks) is much more flexible than entraining and detraining rail cars on tracks or loading and unloading trailers on and off railroad flat cars..

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

6.1 INTRODUCTION

We propose several operating concepts for Automated BUs Systems (ABUS) as part of a four-step sequence toward an end-state. Variations of the four-step sequence are also proposed to accommodate the possible varying degrees of right-of-way availability. These 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. These concepts are 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. One bus-AHS concept intended for possible implementation on dedicated and protected right-of-way along the median of a freeway is 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.

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. 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. The new operating concept is proposed for operations in the same urban setting, and, therefore, we refer to it as an Automated BUsway System (ABUS). We propose several ABUS concepts. 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 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 6.2 through 6.6 address several ABUS operating concepts while Section 6.7 describes the bus-AHS operating concept. Section 6.2 summarizes the ABUS concepts as well as a four-step deployment sequence toward the concepts while Section 6.3 through Section 6.6 discuss in more detail possible implementation issues associated with deploying the four steps. Concluding remarks are given in Section 6.7.

6.2. 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.

6.2.1 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.

6.2.2 The Four Steps

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

<u>Step 1: A Conventional Urban Unprotected Busway</u>

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 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.

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

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. Such turning movements may require a significant amount of additional right-of-way at the intersections than what a light-rail system would require if the buses are to be manually driven onto or off the busway from the crossing street. (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.

<u>Step 2: A Busway with Manual Bus Convoying through ITS Technologies</u>

To 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 reduc 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.

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

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-space 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.

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

If safety permits, the trailing buses of a platoon may not require a driver. However, the lead bus of a platoon 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 platoons, 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 platoons serving different routes is made possible at a station; a bus can merge with or break off from a platoon at an access or egress location or at a station. Also, passenger transfer can be made within a platoon, 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

Step	Main Features	Main Benefits	Main Traffic Issues
1 Conventional Busway (with sufficient right-of-	• Bus operations on light-rail right-of-way	• Same bus for line-haul and collection/distribut	• Scattered buses disturbing surrounding

way)		ion	traffic
1' Busway with Automation to Enable Bus Operations on Narrow Righ-of-way	• Automated precision turning/automated precision lane-changing • Automated lane-keeping • Automated bus-following • Automated precision docking (if desired)	• Same bus for line-haul and collection/distribution • Automation enabling busway operations on narrow right-of-way	• Scattered buses disturbing surrounding traffic
2 Manual Bus Convoying Through ITS	• Clustering buses to reduce disturbance via ITS technologies	• Reduction of disturbance to surrounding traffic due to signal preemption or priority	• Possible excessive disturbance as demand grows
3 Automated Closely-spaced Convoying	• Automated closely-spaced convoying • Automated precision turning/automated precision lane-changing, automated lane-keeping, automated vehicle-following and precision docking if not already implemented	• Reduction of disturbance to surrounding traffic due to signal preemption or priority	• Safety
4 Driverless Bus-following	• Absence of driver on trailing buses	• Reduction of labor cost	• Safety

6.2.3 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.

6.3. IMPLEMENTATION ISSUES FOR THE FIRST STEP - UNCORRIDINATED 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.

6.3.1 Physical Barrier

Since buses on 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). The design of such barriers are important implementation issues.

6.3.2 Narrow Right-of-way

Due to the intense competition for right-of-way among different uses of urban roads, 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.

6.3.3 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.

6.3.4 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 issues 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.

6.3.5 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.

6.3.6. 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.

6.3.7 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.

6.3.8 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.

6.3.9 Air Pollution (to Downtown Pedestrians and Restaurant Patrons)

Some light-rail systems are electrified, and there is no air pollution. 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.

6.4. IMPLEMENTATION ISSUES FOR THE SECOND STEP - MANUAL BUS CONVOY THROUGH ITS

6.4.1 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 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.

6.4.2 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.

6.4.3 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.

6.5. IMPLEMENTATION ISSUES FOR THE THIRD STEP - AUTOMATED CLOSELY-SPACED BUS CONVOYING

6.5.1 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 platooning 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.

6.5.2 Safety

The safety of closely-spaced bus convoying is 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.

6.5.3 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.

6.5.4 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.

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

6.6.1 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.

6.6.2 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.

6.6.3 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.

6.6.4 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. These issues make a big difference in system and design requirements.

6.6.5 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.

6.6.6 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.

6.7. OPERATING CONCEPTS FOR BUS AUTOMATION ON OR ALONG A FREEWAY

This subsection proposes three 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. The third is a mixture of the first two.

6.7.1 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.

6.7.2 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.

6.7.3 An Integrated Concept

Note that the two concepts defined in Sections 6.7.1 and 6.7.2 can be integrated to form a third concept where sufficient right-of-way for accommodating two lanes of automated bus traffic is available for part of the freeway corridor, but not the whole corridor. These two concepts can be implemented according to the availability of right-of-way. 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.

6.8. 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.

7. A DEPLOYMENT SEQUENCE FOR THE PROTECTED INTER-CITY TRUCK AHS ON A FREIGHT CORRIDOR

7.1 INTRODUCTION

We developed operating concepts of an intercity truck-AHS in Section 5 (Tsao and Botha, 2001). This section focuses on the deployment of those concepts. We discuss the needs of the trucking industry in Section 7.2. These needs not only point to the potential of the proposed truck-AHS but also present clues for developing key steps of deployment. We capitalize on these needs while circumventing some critical problems, and develop a deployment sequence in Section 7.3 that, we believe, is plausible. We also discuss some key issues that may hinder the deployment in Section 7.4. The actual feasibility of the proposed intercity truck-AHS as well as that of the proposed sequence can only be assessed with further in-depth studies, which are beyond the scope of this paper. Concluding remarks are given in Section 7.5.

7.2. THE NEEDS OF THE TRUCKING INDUSTRY AND STAKEHOLDER CONCERNS: OPPORTUNITIES FOR AUTOMATION OF INTERCITY TRUCKING

In the literature on intelligent transportation systems, the potential of many advanced technologies for improving the performance of 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 needs of the customer of a truck-AHS and stakeholder concerns.

7.2.1 A Major Concern of the Long-haul Trucking Industry: Productivity

To limit safety hazards and damage to pavement, limits on weight, size and configuration have long been imposed on trucks (e.g., Transportation Research Board, 1982; Federal Highway Administration, 1998). Here, configuration refers to the number 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 48 feet or shorter), double (i.e., a tractor hauling two trailers of 28 feet or shorter). As the trucking industry tries to increase its productivity, longer truck combinations have been introduced, and many states in the nation have permitted their operations on selected highways and the access roads. These longer truck combinations have been referred to as "longer combination vehicles," or LCVs for short. Most notably among the LCVs are Rocky Mountain Double (i.e., a tractor, a 48-feet trailer and a 28-feet trailer), Triple Trailer

Combination (i.e., a tractor and three 28-feet trailers) and Turnpike Double (i.e., a tractor and two 48-feet trailers). Heavier trucks are more efficient because they use less fuel per pound than lighter 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.

To reduce the likelihood of driver fatigue and the associated safety hazards, limits on a driver's work hours have also been imposed. These limits obviously have a significant impact on the productivity of a driver and that of the equipment, and have been a subject of considerable debate. If the weight, size, configuration and work-hour limits can be relaxed, the productivity of a driver as well as that of the equipment can be increased.

Currently, no LCVs are allowed in California (State of California, 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., March, 2001). However, safety may actually be improved if LCVs are allowed only on a dedicated and physically separated truck lane and on exclusive staging areas.

Another major concern is the phenomenon called "off-tracking," which refers to the fact that rear wheels of a vehicle do not follow the same track as the front wheels around a curve in the road. A result is that the vehicle may encroach adjacent lanes, drive over curbs or go partly off the road. Safety as well as damage to the physical infrastructure becomes a concern. The issue of infrastructure damage will further be discussed later in Section 7.2.3.

A major advantage of the proposed truck-AHS is its ability to support flexible configurations, not only in terms of the number of trailers (or driverless trailing trucks) a human truck driver can haul but also in terms of the dynamic "configurability" of the trailers. This would certainly boost the productivity of a driver as well as that of the equipment significantly.

Another possible source of productivity increase is relaxed work-hour limits. The operating characteristics of a truck requires 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. For example, the stopping distance of a truck is significantly longer that of an automobile, and truck steering must be smooth to avoid jack-knifing. With the aid of automated driving and the physical separation of trucks from automobiles, a truck driver may be able to driver safely for longer hours than otherwise.

7.2.2 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 (Caltrans,1998a; Caltrans,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. (Although the

Consortium was conceived with highway automation as part of the solutions, the interest in highway automation seems to have weakened recently.)

Tsao and Rizwan (Tsao and Rizwan, 2000), in studying the air-express freight forwarding business recently, pointed out a “vicious cycle” regarding 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 forwarders 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.

7.2.3 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 University of Texas at Austin estimated that the damage done by one pass of a tractor-trail 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 the lane, because the automated guidance will decrease the amount of “wander” in the lane. Both of these characteristics of the AHS will allow more efficient design and construction of the pavement.

7.2.4 The Driving Public’s and the Transportation Agencies’ Concern About Safety and Consequent Throughout Impacts by 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 automobiles occurs, the safety consequences are likely severe. Moreover, the consequent impact on highway throughput may be drastic. This separation of truck traffic from the rest of the freeway traffic will likely be welcomed by not only the driving public but also the trucking industry.

On a truck-AHS, truck behavior, e.g., speed, may be regulated by the infrastructure. Regulating the speed of the trucks could lead to smaller deviations of the individual speeds from the average speed. Few accidents will result. Because trucks will also be removed from the rest of the traffic stream, the standard deviation of the speeds of the rest of the vehicles will also decrease, leading again to a decrease in 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.

7.2.5 Truck Manufacturers’ Inclination to Provide and Sell New Features

Truck manufacturers, like automobile manufacturers, tend to welcome technological innovations that will improve safety and comfort. They also tend to welcome technological innovations that will improve the fuel efficiency and driver productivity. However, note that 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, but may result in lower fuel efficiency. This goes to show the necessity to develop AHS operating concepts that would be sufficiently appealing to truck operators, from the perspective of productivity improvement.

7.3. A DEPLOYMENT SEQUENCE TOWARD THE PROPOSED TRUCK-AHS

We propose eight deployment steps toward the proposed inter-city truck AHS. Market Acceptance Steps, i.e., Steps 1 and 2, are independent of Public Acceptance Steps, i.e., Steps 3 and 4, and, therefore, these two groups of steps can proceed in parallel. Additional steps or more refined steps can be defined, and some of them will be addressed at the end of this section. A discussion of possible deployment sites follows.

7.3.1 A Possible Deployment Sequence

We believe that having a plausible implementation sequence is a big factor for the successful implementation of the truck-AHS. The sequence was therefore conceived to have initial steps which could be beneficial by themselves and could lead to the implementation of the end state.

Step 1: Market Acceptance of Advanced Warning Technologies for Trucks

Step 1.1: Develop and deploy radar-based, infra-red based or other range-sensors and frontal crash warning systems for trucks to use on conventional highway lanes as well as off highways.
Step 1.2: Develop and deploy vision-based lane identification and lane-departure warning systems for trucks to use on conventional highway lanes as well as off highways.

Step2: Market Acceptance of (Non-Simultaneous Use of) Hands-off and Feet-off Automation Technologies for Trucks

Step 2.1:

- Based on the systems developed and deployed in Step 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.)

Step 2.2:

- Based on the vision-based lane identification and lane-departure warning systems developed and deployed in Step 1.2, develop and deploy lane-keeping and other lateral vehicle control systems that enable hands-off driving.
- Disallow the simultaneous use of both the hands-off and the feet-off features, to prevent driver disengagement from driving tasks.

Step 3: Public Acceptance of Truck-Lane Dedication:

- Select an important and congested freight corridor where the benefits of automation will be evident. This issue will be further discussed in Section 7.3.2. It will be important to ascertain that the dedication of a lane will be physically plausible.
- Construct a new truck lane or dedicate an existing lane for each direction for exclusive truck use in or next to the median of the main freeway along the corridor.

Step 4: Public Acceptance of a Physically Separated Truck Lane on Freeway Median with LCVs Allowed Through New Legislation:

- Separate physically, for each direction, the lane on the median or the lane closest to the median from the rest of the freeway and dedicate that lane as the exclusive truck lane.
- Construct "staging areas" at selected locations off but adjacent to the selected freeway, and build access and egress ramps from and to these "staging areas".
- 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 the state of California, but we propose that they be allowed on dedicated and physically separated truck lanes).
- Allow entry into and exit from the truck lane (by singles but not doubles or triples) directly from and to the leftmost conventional lane, i.e., the conventional lane that is closest to the truck lane, at locations where the amount of traffic does not warrant a staging area plus a dedicated set of ramps and where such entry and exit can be made safely.
- Tolls can be collected electronically either at the interface areas, i.e., the on- or off-ramps, or at selected locations along the freeway.

Step 5: 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 enabling closely-spaced truck convoying eventually). (Note that closely-spaced truck convoying may render vision-based lane-keeping inoperable, particularly at night.)
- Support automated driving (i.e., hands-off and feet-off driving) in midst of manually driven truck traffic, but under the supervision of the truck driver, who is responsible for the safe operations of the truck.
- 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.)

Step 6: Automated Truck Lane Accessible Only From Staging Areas:

- Dedicate the truck lane to automated traffic only; disallow non-equipped trucks on the truck lane. (This dedication may experience resistance from operators of non-equipped trucks because their privilege will be taken away. As the population of equipped trucks increases to a level warranting a dedicated lane for automated trucks only, the support for higher productivity and higher fuel efficiency achievable only through the following two steps may be stronger than the resistance.)
- 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 moderate speed.

- Close the on- and off- ramps between the truck lane and the leftmost conventional lane.
- In addition to automated driving (i.e., hands-off and feet-off driving), truck-to-truck communication ensures safety and enhances ride quality on the mainline, 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).
- “Fitness” checking, if necessary, 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.)

The sequence for the following two steps may vary. In fact, either could be a predecessor for the other. In addition, they can be combined into one single step.

Step 7: Automated Convoying With no Driver on Trailing Trucks of a Convoy: Support automated convoying with no drivers required on any trailing truck (i.e., the tractor plus the trailers) of the convey.

Step 8: Closely-spaced Convoying:
Support closely-spaced truck convoying for those trucks that are adequately equipped, to achieve fuel savings.

These eight steps as well as their main features, main benefits and main issues are summarized in Table 2.

TABLE 2: A Eight-step Deployment Sequence for the Proposed Truck-AHS

Step	Main Features	Main Benefits	Main Issues
1. Market Acceptance of Advanced Warning Technologies for Trucks	• Range sensing and frontal collision warning • Vision-based Lane-departure warning	• Use on and off highways • Safety • Technology maturation • Price drop	• Market acceptance
2. Market Acceptance of (Non-Simultaneous Use of) Hands-off and Feet-off Automation Technologies for	• Feet-off highway operations • Hands-off highway operations	• Driver comfort due to partial automation	• Possible abuse on city streets • Ability of the driver to react to unexpected events

Trucks	• Only one of the two features can be activated at any time.		by interfering or overriding partial automation • Market acceptance
3. Public Acceptance of Truck-Lane Dedication	• Construction or dedication of a truck lane on the left or the right-hand side	• Higher freight throughput	• Acceptance by the general public • Amount of toll charge • Possible protest by the rail industry
4. Public Acceptance of a Physically Separated Truck Lane on Freeway Median with LCVs Allowed Through New Legislation	• Isolated truck lane on or near median • Staging areas at selected locations • Ramps from and to the truck lane from the leftmost conventional lane • Operation of LCVs allowed only in the truck lane and the staging areas to increase trucking productivity	• Safety due to less mixing of light and heavy vehicles • Significantly higher productivity of the driver and the equipment as well	• Public acceptance of the separate truck lane on the median • Legislative acceptance of allowing LCVs on the truck lane • Amount of toll charge • Possible protest by the rail industry • Potential for complete blockage by a single disabled truck, unless the combined width of the truck lane and the shoulder is sufficiently wide to allow lower-speed passage through the incident area • The provision of passing lanes if different cruising speeds are allowed. • Flow hindrance by trucks with slower cruising speeds if otherwise.
5. Automated Driving in Mixed Traffic on	• Installation of magnetic markers	• Redundancy in lateral and higher	• Safety of automated driving

the Truck Lane	or other "active" markers on the truck lane • Simultaneous hands-off and feet-off driving supported • Longitudinal mixing with manually driven trucks • Vehicle-to-vehicle and vehicle-to-infrastructure communication required for all trucks using the truck lane to ensure safety in traveling and merging	safety guidance • Comfort for (trained) driver of automated trucks	• Safety of mixing on mainline • Safety of merging between automated and manual truck traffic
6. Automated Truck Lane Accessible Only From Staging Areas	• Exclusive use by automated trucks, including automated LCVs • Closure of the ramps from and to the leftmost conventional lane • Access to the truck lane in the median only from the staging areas at selected locations.	• Higher safety for mainline operations due to the homogeneity of traffic (of trucks only) • Higher merging efficiency due to the homogeneity.	• Demand sufficiency to justify the dedication of truck lane to the exclusive use by automated trucks only. • Amount of toll charge • Modal-change overhead (between the conventional trucking and AHS-trucking)
(The sequence for the following two steps may vary.) 7. Automated Convoying With no Driver on Trailing Trucks of a Convoy	• Truck convoying • Driverless operations for trailing trucks (tractor plus trailers) • AHS Hauler for hire or scheduled AHS Hauler service (like an	• Significantly higher driver productivity as well as equipment productivity	• Safety of driverless operations of the trailing trucks • Modal-change overhead (between the conventional trucking and AHS-trucking) • Amount of toll

	automotive, without freight of its own)		charge • Possible protest by the rail industry
8. Closely-spaced Convoying	• Closely-spaced truck convoying, which mimics a train • A "train system" with trucks	• Better fuel efficiency • Higher throughput • Tightly clustered trucks leaving more space between convoys for safer and more efficient merging	• Safety • Amount of toll charge • Possible protest by the rail industry

Other features can also be supported, and the corresponding steps added. For example, trucks can be organized into platoons 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, with loads and grades considered.

7.3.2 Possible Deployment Sites

The I-freight corridor in Southern California, including I-710, SR60 and then I-10 (connecting the Los Angeles and Long Beach Harbors to the inland areas and the East Coast), 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. (22). 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). 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, we wanted to also consider long-haul freight corridors where the truck-AHS could also be a substitute for rail.

The I-10 freight 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. Second, most western states along I-10, including California, New Mexico and Texas, do not currently permit LCVs (i.e., longer combination vehicles). 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 benefit 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. 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 but heavy-traffic corridors carrying a large amount of such intermodal freight in the U.S., including the corridor leading from Long Beach, CA through I-10 to large cities and seaports along the way.

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.

7.4. POSSIBLE ISSUES AND SOLUTIONS ASSOCIATED WITH THE PROPOSED TRUCK-AHS AND THE PROPOSED DEPLOYMENT SEQUENCE

7.4.1 The Requirement of a Dedicated Truck Lane

Although truck lanes are common on freeway sections where the slope 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 for eventually deploying a truck-AHS);
- potential intense competition for right-of-way for passenger or transit vehicles in cities, unless truck by-pass can be constructed or existing beltways can accommodate the automated and dedicated truck traffic; (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. This is because 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.

7.4.2 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. Note that passing will be conducted on the convoy basis, and the required length of such a passing lane will be much longer than their conventional counterparts.

7.4.3 Possible Objection by the Railroad Industry and the Intermodal Rail Industry , Not Necessarily the General Multi-modal Transportation Industry

The world's first "containership," the Ideal-X, made its inaugural voyage from Port Newark, New Jersey on April 26, 1956. Since then, containerization has become a dominant mode for ocean carriers for decades. 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. 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. 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 explains why the strength of intermodal rail was in the market of dry-van (i.e., non-refrigerated) truck-load traffic between major cities more than 700 miles apart. More precisely, intermodal service accounted for 70% of that market (Daniel Smith et al., 1990).

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 (Daniel Smith et al., 1990). However, the reality was that, even in the over-500-mile market segment, intermodal rail accounted for less than 20% of the market (McKenzie et al., 1989).

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 a 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. The only major manufacturer of such bi-modal trailers was RoadRailer, and it estimated that the breakeven mileage was 400-500 miles, and that, for higher mileages, RoadRailer would become more competitive than trucking (McKenzie et al., 1989). Despite this estimation, this bi-modal service has not become a significant component of the intermodal rail service.

If an intercity truck-AHS is eventually built, it must be able to significantly improve inter-city trucking. Moreover, it may also be able to significantly improve long-haul as well as short-haul 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 does provide and has provided competitive advantages to the (intermodal) rail industry. However, the effort involved in raising the vertical clearance is likely to be by far less than the public-sector effort required to implement a truck-AHS.

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 (APC), CSX/Sea-Land and Burlington Northern Worldwide (BN Worldwide). 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 benefit and become attractive for these companies. Deployment of an inter-city truck-AHS will likely be not only an engineering issue, but also a major political and public-policy issue.

To close this discussion on the possible competition between AHS-trucking and intermodal rail, we like to point out that comparing the cost and benefit between the mode of AHS-trucking and the mode of intermodal rail may not be a relevant question. Intercity AHS-trucking will not be pursued if it is not cost-effective with respect to conventional trucking. But, as long as it is cost-effective with respect to conventional inter-city trucking, it will likely be competitive with respect to intermodal rail. Therefore, the key question is whether inter-city AHS-trucking is cost-effective than conventional inter-city trucking. In determining cost-effectiveness or competitiveness, all relevant measures of effectiveness must be considered, including service quality.

7.4.4 Tolls

The amount of possible toll charge is an important issue for a truck-AHS because the benefit depends on the amount of traffic using the truck-AHS, and the amount of traffic using the truck-AHS depends on the amount of toll charge. As discussed earlier, it also may have serious implication on the long-standing competition between the trucking industry and the intermodal rail industry. It is clear that the toll charge plays a role in the possible diversion of freight traffic from the intermodal-rail mode to AHS-trucking.

7.4.5 A New Mode of Freight Transportation, Although a "Dual Mode"

The proposed operating concept of a truck-AHS introduces a possible new mode of transportation, e.g., the driverless mode of trucking (for the trailing trucks in a truck convoy). Despite the many improvement possibilities for trucking efficiency, truck operations involving the truck-AHS may be bi-modal. As in any multi-modal transportation, e.g., intermodal rail, modal transfer between conventional trucking and AHS trucking may be involved, e.g., assembly and disassembly of LCVs, and the efficiency of the modal transfer may become an issue. However, AHS-trucking and conventional trucking may well constitute a "dual-mode" that requires little "transfer overhead." Nevertheless, operational concepts must be developed in sufficient detail and the modal transfer must be sufficiently efficient.

7.4.6 Safety and Liability, to be Studied Carefully

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.

7.4.7 Partnering with the private sector

Deploying the proposed truck-AHS concept 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 private-public partnership.

7.5 CONCLUSION

In Section 7, we discussed the needs of the trucking industry, proposed a deployment sequence for an inter-city truck-AHS and point out key issues for implementing the sequence. The feasibility of the truck-AHS and that of the proposed sequence is a worthy subject for future research.

8. CONCLUSION

We have completed Task 1 through Task 6, and the project is on schedule. We believe that the operating concepts developed for urban bus automation and inter-city truck automation are promising. The promises have been demonstrated by the proposed deployment sequences. Possible issues yet to be resolved have also been pointed out. They reveal some worthy future research subjects. In the next six months, our research work will be focused on identification of key benefit-cost elements of these operating concepts for a more detailed benefit-cost analysis in the future. The focus will be on those major cost-benefit elements that differ significantly among the alternatives within the scope of this project.

REFERENCES AND BIBLIOGRAPHY

Al-Ayat, R., and Hall, R.W., "A conceptual approach for developing and analyzing alternate evolutionary deployment strategies for Intelligent Vehicle/Highway Systems," PATH Working Paper 94-5, 1994.

Al-Kadri, M., Benouar, H., and Tsao, H.-S.J., "Intermediate Automation Concepts for Evolution toward Automated Highway Systems," Transportation Research Record No. 1651, 1998.

Bagby, J.W., and Gittings, G.L., “Litigation Risk Management for Intelligent Transportation Systems,” ITS Quarterly, Spring-Summer, 1999.

Baum, H. and Schulz, W.H., “Economic Evaluation of CHAUFFEUR,” Proceedings of the 4th World Congress on Intelligent Transportation Systems, Berlin, Germany, 1997.

Borodani, P., Carrea, P., and Gortan, L., “Short headway Control of Trucks on Motorways: the CHAUFFEUR Project,” Proceedings of the 4th World Congress on Intelligent Transportation Systems, Berlin, Germany, 1997.

Caltrans (1998a), 1998 California Transportation Plan: Statewide Goods Movement Strategy, Office of the Director, California Department of Transportation, Sacramento, California, October,1998.

Caltrans (1998b), 1998 California Transportation Plan: Transportation System Performance Measures (Final Report), Office of the Director, California Department of Transportation, Sacramento, California, August,1998.

California PATH, “White Paper: Development of BRT Evaluation Tools and Techniques,” submitted to the Federal Transit Administration in response to the FTA’s interest, 1999.

Carey, G. N., Viggiano, S. M., and Gardner, L., “The development of a guided bus system : the Eugene/Springfield experience,” Institute of Transportation Engineers. Meeting (68th : 1998 : Toronto, Ont.). Annual meeting papers, Institute of Transportation Engineers, Washington DC.

Chen, C.-Y. and Litkouhi, B., “Technological Challenges in the Development of AHS,” ITS Journal, Vol. 4, No. 1-2, pp. 81-100, 1998.

DeMarco, V. R., “Dual-Mode System Development Program of the Urban Mass Transportation Administration,” Proceedings of International Conference on Dual Mode Transportation, Washington, D.C., 1974; Transportation Research Board Special Report No. 170, **:** Transportation Research Board, National Research Council, Washington, D.C..

Federal Highway Administration, Comprehensive Truck Size and Weight Study, U.S. Department of Transportation, 2000.

Federal Transit Administration, “Issues in Bus Rapid Transportation,” U.S. Department of Transportation, FTA, Office of Research, Demonstration and Innovation, 1998.

Hall, R.W., “System Configurations: Evolutionary Deployment Considerations,” Chapter 4 of Automated Highway Systems, P.A. Ioannou (editor), Plenum Press, New York, pp. 49-71, 1997.

Hall, R.W., Nowroozi, A., and Tsao, H.-S.J., "Entrance Capacity of an Automated Highway System,” to appear in *Transportation Science*, 2001.

Hall, R.W. and Tsao, H.-S. J. "Automated Highway System Deployment: A Preliminary Assessment of Uncertainties", Chapter 16 of Automated Highway Systems, P.A. Ioannou (editor), Plenum Press, New York, pp. 325 - 334, 1997.

Hall, R.W., and H.-S. J. Tsao "Capacity of Automated Highway Systems: Merging Efficiency," Proceedings of American Control Conference, Albuquerque, New Mexico, June, 1997, pp. 2046-2050.

Hall, R.W., Thakker,V., Horan, T.A., Glazer, J., and Hoene, C., Automated Highway System Field Operational Tests for the State of California: Potential Sites, Configurations and Characteristics, California PATH Research Report UCB-ITS-PRR-97-45, 1997.

Hanson, M. and H.-S.J. Tsao, "Leveraging Exogenous Events for the Deployment of Automated Highway Systems," Proceedings of The Third World Congress on Intelligent Transportation Systems, Orlando, Florida (1996).

International Conference on Truck Weight and Size Limits, Canada, 1989.

Kawamura, K., Commercial Vehicle Value of Time and Perceived Benefit of Congestion Pricing, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of California, Berkeley, 1999.

Lankard, T.L., and Lehrer, J., "Big Trucks, Big Trouble ? – Long Combination Vehicles Could Mean Greater Risks on California Roads", Westways, Vol. 91, No.6, Auto Club of Southern California, 1999.

March, J.W., "DOT's Comprehensive Truck Size and Weight Study – A Summary," Public Roads, March/April 2001 Issue, Turner-Fairbank Highway Research Center, 2001.

McKenzie, D.R., North, Mark C., and Smith, D.S., Intermodal Transportation – The Whole Story, Simmons-Boardman Books, Inc., Omaha, Nebraska, August, 1989.

Michael, J.B., Godbole, D.N., Lygeros, J., and Sengupta, R., "Capacity Analysis of Traffic Flow Over a Single-Lane Automated Highway System," ITS Journal, Vol. 4, No. 1-2, pp. 49-80,1998.

Ran, B., Johnson, S., Leight., S, and Tsao, H.-S.J., "Traffic Analysis for Highway-to-Highway Interchanges on Automated Highway Systems: Congestion in Absence of Dedicated Ramps", Transportation Research Record 1588: Planning and Administration; Highway Operations, Capacity, and Traffic Control, pp. 145-151, 1997.

Riva, P. and Ulken, U., "CHAUFFEUR Tow-Bar: the Vehicle Based System Architecture," Proceedings of the 4th World Congress on Intelligent Transportation Systems, Berlin, Germany, 1997.

Schulze, M., "CHAUFFEUR, the European Way towards an Automated Highway System," Proceedings of the 4th World Congress on Intelligent Transportation Systems, Berlin, Germany, 1997.

Sengupta, R., Godbole, D. and H.-S.J. Tsao, "Concept Definition of an Infrastructure-Supported Automated Highway System," Proceedings of The Third World Congress on Intelligent Transportation Systems, Orlando, Florida,1996.

Shladover, S.E., “Review of State of Development of Advanced Vehicle Control Systems (AVCS),” International Journal of Vehicle Mechanics and Mobility, Vol. 24, pp. 551-595, 1995.

Smith, Daniel S. (Principal Investigator), Double Stack Container Systems: Implications for U.S. Railroads and Ports, Research Report FRA-RRP-90-1, Federal Railroad Administration, June, 1990.

South Australia. Dept. of Transport, Guided bus rapid transit : proceedings, international seminar, Adelaide, South Australia, 1988.

State of California, California Vehicle Code, Section 35000, Division 15. California Legislative Counsel, Sacramento, California, 2001.
(http://www.leginfo.ca.gov/.html/veh_table_of_contents.html)

Stevens, W.B., “Evolution to an Automated Highway System,” Chapter 7 of 4 of Automated Highway Systems, P.A. Ioannou (editor), Plenum Press, New York, pp. 109-124, 1997.

Transportation Research Board, An Investigation of Truck Size and weight Limits: Panel Review of Final Report (including comments made by major stakeholders, e.g., American Trucking Associations, American Automobile Association, Environmental Defense Fund), Office of the Secretary, U.S. Department of Transportation, UR 26, June 1982.

Tsao, H.-S. J., " A Framework for Evaluating Deployment Strategies for Intelligent Transportation Systems", Intelligent Transportation Systems Journal (ITS Journal), Vol. 6, pp. 141-173, 2001.

Tsao, H.-S. J. (1998a), "From the Guest Editor," Special Issue of the ITS Journal on Automated Highway Systems, Vol. 4, Nos:1-2, 1998.

Tsao, H.-S.J. (1998b), "An Axiomatic Approach to Developing Partial Automation Concepts for Deployment of Automated Highway Systems and Partial Invocation of Vision-Based Lane-Keeping and Adaptive Cruise Control," *Transportation Research Record*, No. 1651, 1998.

Tsao, H.-S. J. (1998c), "The Role of Air Cargo in California's Goods Movement,", UCB-ITS Research Report UCB-ITS-RR-98-7, University of California at Berkeley, Institute of Transportation Studies, Sept. 1998.

Tsao, H.-S. J. (1995a), "Traffic Control for Automated Highway Systems: A Conceptual Framework", Transportation Research, Part C, Vol. 3, No. 4, pp. 227-246, 1995.

Tsao, H.-S. J. (1995b), "Stage Definition for AHS Deployment and an AHS Evolutionary Scenario", Intelligent Vehicle Highway Systems Journal, Vol.2(4), pp. 359-382, 1995.

Tsao, H.-S. J. (1995c), "A Staggered-Diamond Design for Automated/Manual-HOV Highway-to-Highway Interchangesand Constraints on AHS Design for Accommodating Automated Highway Change", Intelligent Vehicle Highway Systems Journal, Vol.2(3), pp. 281-292, 1995.

Tsao, H.-S. J. (1995d), "Constraints on Initial AHS Deployment and the Concept Definition of a Shuttle Service for AHS Debut", IVHS Journal, Vol. 2(2), 159-173, 1995.

Tsao, H.-S.J. and Botha, J.L. (2001), “Operating Concepts for Urban Bus Automation and Inter-city Truck Automation,” to be presented as the IEEE ITS Conference to be held in August in Oakland, California and to be published in the Conference Proceedings.

Tsao, H.-S. Jacob and Rizwan, Asim, The Role of Intelligent Transportation Systems in Intermodal Air Cargo Operations,” Research Report UCB-ITS-RR-2000-5, Institute of Transportation Studies, University of California, Berkeley, 2000.

Tsao, H.-S. J. and Hall, R.W., "A Probabilistic Model for AVCS Longitudinal Collision/Safety Analysis", Intelligent Vehicle Highway Systems Journal, Vol.1, No. 3, pp. 261-274, 1994.

Tsao, H.-S. J., Hall, R.W., and Chatterjee, I., "Analytical Models for Vehicle/Gap Distribution on Automated Highway Systems", Transportation Science, Vol. 31, No. 1., pp. 18-33, 1997.

Tsao, H.-S. J., R.W. Hall and S.E.Shladover, "Design Options for Operating Automated Highway Systems", Proceedings of Vehicle Navigation & Information Systems Conference (Oct. 1993).

Tsao, H.-S. J.,, T.A. Plocher, W.B. Zhang, and S.E. Shladover, "Human Factors Design for Automated Highway Systems: Second Generation Scenarios", draft US-DOT FHWA Report, under FHWA Contract No. DTFH61-91-C-00100, (Jan. 14, 1994).

Tsao, H.-S.J., Hall, R.W., Shladover, S.E., Plocher, T.A. and Levitan, L.J., "Human Factors Design of Automated Highway Systems: First Generation Scenarios,” US-DOT FHWA Report FHWA-RD-93-123 (1993).

Tsao, H.-S. J. and Ran, B., "Driver Intelligence Replacement in a Decision-Oriented Deployment Framework for Driving Automation", Proceedings of The Third World Congress on Intelligent Transportation Systems, Orlando, Florida (1996).

Ulmer, Berthold, “CHAUFFEUR: From Concept to Realization,” 3rd International Workshop on Vehicle-Highway Automation, Toronto, Canada, Nov. 11-12, 1999.