Assessment of the Applicability of Cooperative Vehicle-Highway Automation Systems to Freight Movement in Chicago

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ABSTRACT

This paper reports on a performance assessment of the application of cooperative vehicle-highway automation systems (CVHAS) to freight movements in the metropolitan Chicago area. Cooperative vehicle-highway automation systems are systems that provide driving control assistance or fully automated driving and are based on information about the vehicle's driving environment that can be received by communication from other vehicles or from the infrastructure, as well as from their own on-board sensors. A new truck-only roadway facility is proposed to serve a selected set of intermodal rail yards, industrial parks and points-of-entry to the region. Besides a baseline alternative against which to measure the impacts of CVHAS technology applications, we selected four additional operational concept alternatives with which we performed comparative analyses against the baseline, calculating both benefits and costs. Our evaluation showed that all of the alternatives are economically viable and CVHAS technologies are able to help improve the performance of the intermodal freight system. We recommend one of the alternatives for further investigation, which is a conventional truck-only roadway open to all trucks before 2015 and then upgraded to an automated highway open only to automated trucks. This case study and its findings can help provide a better understanding of the benefits from using CVHAS technologies and provide evidence of applicability to stimulate broader interest in CVHAS.

KEY WORDS

Cooperative Vehicle-Highway Automation Systems, Applicability Assessment, Freight Movements, Truck-Only Roadway

INTRODUCTION

Freight movement by heavy trucks is growing at a faster rate than the movement of people by passenger cars, as are the costs associated with the congestion and safety problems encountered by trucks. The highest-density truck traffic typically occurs in large metropolitan areas that also have the highest-density automobile traffic, compounding the problems of both. Opportunities exist for using cooperative vehicle-highway automation systems (CVHAS) to improve the efficiency and safety of movement of both passenger cars and heavy trucks, but for a variety of reasons the implementation on heavy trucks is likely to be feasible earlier than on passenger cars (Shladover, 2001). For example, maturing technologies can be used more safely by professional drivers on professionally maintained vehicles than by the general public on vehicles that may not be maintained at all, and costs of the technologies are a smaller percentage of total vehicle costs. The opportunities to benefit from using CVHAS technologies are best understood by use of site-specific case studies, in which specific transportation problems of specific localities can be addressed. This paper addresses a case study for the Chicago metropolitan region, the hub for freight movement in the United States. The Chicago Area Transportation Study (CATS) is the Metropolitan Planning Organization (MPO) for the six-county region of northeast Illinois that includes Chicago.

Vehicle-highway automation systems vary from simple warning systems to fully automated highway systems. Figure 1 shows a schematic view of the range of possible operating concepts, considering the two key dimensions of the degrees of automation and of cooperation and Table 1 describes and defines each class of these systems. Cooperative vehicle-highway automation systems are part of this spectrum of systems providing driving control assistance or fully automated driving, based on information about the vehicle's driving environment that can be communicated from other vehicles or from the infrastructure, as well as from their own on-board sensors.

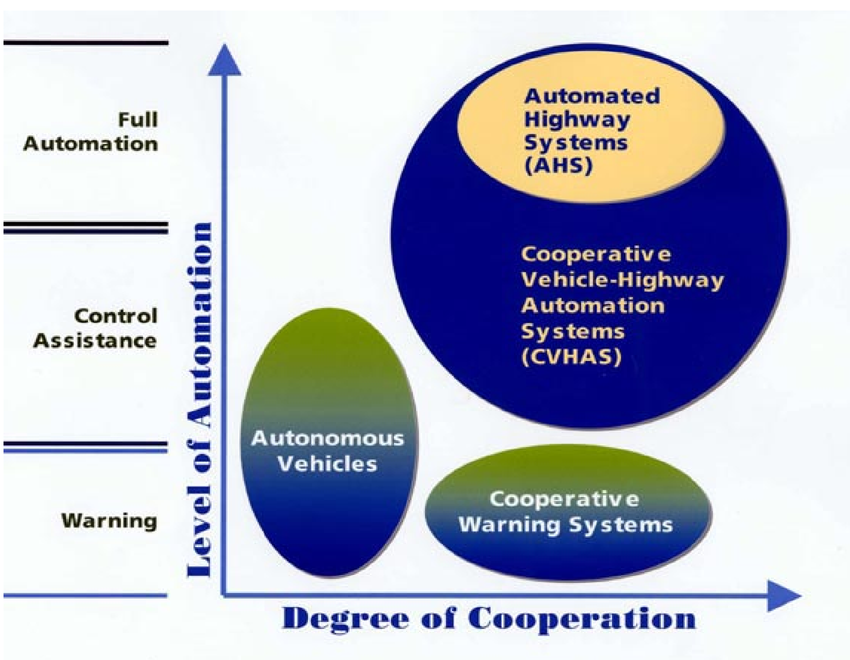

FIGURE 1 CVHAS Technology Characteristics

TABLE 1 Vehicle-Highway Automation Systems

TERM	DEFINITION
Warning	Audible, visible or haptic cue to alert driver to a potentially unsafe condition
Control assistance	Automatic control of a portion of the driving function to assist the driver by relieving workload (e.g., adaptive cruise control) or to enhance safety (e.g., collision avoidance braking)
Full automation	Completely automatic control of driving, relieving the driver of responsibility for driving functions
Autonomous vehicles	Vehicles that derive all their information about the environment from their own on-board sensors, without communication to or from the infrastructure or other vehicles. By analogy to human drivers, the autonomous vehicles can “see”, but they cannot “talk” or “listen” to others
Cooperative warning systems	Warning systems that can receive information about the vehicle’s driving environment by communication from other vehicles or from the infrastructure, as well as from their own on-board sensors
Cooperative vehicle-highway automation systems (CVHAS)	Systems that provide driving control assistance or fully automated driving, based on information about the vehicle’s driving environment that can be received by communication from other vehicles or from the infrastructure, as well as from their own on-board sensors
Automated highway systems	Systems that provide fully automated driving (which is only possible on separated, protected lanes), based on information about the vehicle’s driving environment that can be received by communication from other vehicles or from the infrastructure, as well as from their own on-board sensors

In our study of intermodal freight movements in metropolitan Chicago, we provide quantitative analyses of both the benefits and costs associated with application scenarios of CVHAS technologies compared with non-CVHAS scenarios. Generally, the benefits are expected primarily in terms of traffic congestion mitigation, travel time savings, fuel consumption and pollutant emission savings, and savings of capital costs of constructing roadway facilities. Primary cost factors include construction of truck-only roadways, annual operation and maintenance costs, and CVHAS equipment purchase and installation costs. These analyses can shed light on system operating concepts, system designs, and benefits and costs to stakeholders. They can form the basis for making technical decisions, refining design trade-offs, showing more general CVHAS benefits, and providing direct evidence of applicability to stimulate further interest in CVHAS.

The remainder of this paper consists of an introduction to CVHAS technologies under consideration followed by the background information on freight movements in the Chicago area. After these, we present a discussion of the selection of the alignments that formed the backbone network of nodes and links, that is, rail yards, industrial parks, and regional points of entry and their interconnecting roadways and the operational concepts for which we conducted a comparative evaluation of benefits and costs. The subsequent two sections consist of the core of the paper, presenting the impact analysis and cost-benefit analysis. We offer conclusions and recommendations in the last section.

CVHAS TECHNOLOGIES

The CVHAS technologies under consideration include automatic steering, speed, and spacing control and operation of trucks in either two- or three-truck platoons (diminishing returns with respect to productivity set in for platoons longer than three trucks (NAHSC, 1997). Under automatic steering control, trucks stay centered in the traveling lane. For automatic speed and spacing control, trucks are not operated under manual speed control and so can be operated at closer inter-truck distances. Table 2 describes attributes associated with each of these automatic functions.

TABLE 2 CVHAS Attributes

	AUTOMATIC STEERING	**AUTOMATIC SPEED & SPACING CONTROL**
TECHNOLOGIES	• Roadway “magnetic marker” sensors • Vision/optical sensing • Electronically controlled steering actuator	• Forward ranging sensors (radar or laser) • Electronic control of engine and brakes • Vehicle-vehicle data communication
BENEFIT OPPORTUNITIES	• Ability to operate truck in narrower lanes, saving right-of-way and construction costs • Enabling operations in locations too narrow for conventional trucks • Smoother lateral ride quality • Reduced driver stress	• Enhanced capacity using truck platoons • Smooth ride quality • Reducing fuel use and emissions
INCREMENTAL COST GENERATORS	• Electronically-controlled steering actuator • Lateral position sensing system • Reference markings along vehicle lanes	• Sensing and communication devices • Electronic brake control actuators

We considered two levels of right-of-way restrictions for CVHAS operation for trucks: mixed-traffic operations, and trucks completely segregated from other traffic. In mixed traffic, trucks would operate on city streets (or freeways) with general traffic, just as they do presently, interacting with other motor vehicles, bicyclists, and pedestrians, but here the only attainable benefits from CVHAS technologies are potential (and hard to quantify) safety improvements from collision warning systems. For fully segregated truck lanes, only trucks are permitted access, resulting in no interaction with regular traffic, including no cross-street intersections. The lane would be barrier-separated and access would be via dedicated ramps or specified entrances. Benefits include the allowance for maximum control over operation, ensured reliability, regulation of travel time, safe operations, and the potential for high-capacity operations. There is, however, a high infrastructure cost that would be fully allocated to truck service and not amortized for other shared uses. Within the segregated truck lane environment, a further distinction can be made between truck lanes that are usable by all trucks and truck lanes that are restricted to CVHAS-equipped trucks (Miller et al., 2002).

BACKGROUND OF FREIGHT MOVEMENT IN THE CHICAGO AREA

Chicago is the hub for freight movement in the United States, in part because of its importance as a manufacturing and distribution center, but to a greater extent because it is the one place where all the eastern and western U.S. railroad lines, as well as two Canadian railroads, converge. Chicago is the preferred pass-through city for a majority of railroad freight traffic traveling between the eastern and western U.S. These movements are costly in terms of time, labor, freight-handling facilities, and impacts on all other surface travel in the Chicago region. Innovations that could facilitate freight movement within the region, especially among its major origins and destinations, have the potential to realize major economic benefits.

The Metropolitan Planning Organization (MPO) for northeastern Illinois is the Chicago Area Transportation Study (CATS), which has periodically conducted travel surveys of the motor carrier industry. The Intermodal Advisory Task Force (IATF), one of 11 CATS Task Forces, has served as the principal medium for freight transportation input to CATS since 1994. Members of IATF represent railroad companies, the trucking industry, freight-forwarding companies, intermodal associations, shippers, and other institutional stakeholders.

Goods movement in Chicago is a competitive, customer-driven and 24-hour-a-day business activity. The freight/goods movement industry is a significant piece of Chicago's economic profile, accounting for approximately 6% of the gross regional product in 1996, of which intermodal, i.e., rail-highway and vice versa, exchanges comprise approximately 1%.

In 1981, Chicago was a major transfer point for trailers between individual railroads carrying partial-or completely-cross country trailer-on-flatcar (TOFC) shipments. Rail transfers for TOFC shipments were handicapped by the high volume of trailer traffic at interchange points, a multiplicity of ramps, rail congestion, and difficulty maintaining a sufficient number of flatcars, so these shipments were transported by trucks either to their final destination (the consignee) or to another ramp for continued transportation by rail. To address the increased traffic congestion due to truck use on Chicago roads, the Federal Railroad Administration (FRA) commissioned a study (FRA, 1981) at that time to investigate the feasibility of constructing a private intermodal terminal roadway to serve the growing volume of truck traffic as well as to determine the benefits of having the roadway itself.

That study demonstrated the feasibility of an exclusive roadway in terms of the physical ability to construct the facility largely on then available rail right-of-way (ROW) to connect 10 of to 12 major intermodal yards studied at the time and in terms of the demand for intermodal interchange. The study location was an area approximately 4.7 miles wide by 7.5 miles long. The total cost of the 18.9-mile intermodal roadway in 1979 dollars was estimated to be $33.3 M including construction, right-of-way, and relocation costs, however, there was never any implementation beyond the study.

SELECTION OF ALIGNMENT AND CONCEPT OF OPERATIONS

The 1981 study focused on cross-town interchange truck movements; however, since then, there has been an effort by rail companies to decrease the volume of such truck movements, and there has been growth in truck movements between other forms of network nodes as producers and attractors of trips, such as warehouse concentrations, industrial parks, and regional points-of-entry on the national highway system. Current intermodal freight movements are increasingly container-on-flatcar (COFC), whereas in 1981 the movements were TOFC. Also, since 1981, several of the rail yards have closed while new ones have opened, resulting in a considerably larger geographical layout of the area's intermodal yards and a change in intermodal freight flow patterns, combined with more limited right-of-way availability. For example, some segments in the 1981 study are now used by the Chicago Transit Authority's Orange Line.

We employed a systematic approach to determine the alignment for the proposed truck-only facility (roadway). Initially, based on information from CATS about the current state of the northeastern Illinois intermodal freight system, we identified a set of major intermodal rail yards, industrial parks/warehouse concentrations and points-of-entry to the region on the national highway system that the facility would serve. We then created connections among these nodes, making use of presumed surplus and available rail/highway ROWs.

To identify candidate intermodal freight nodes that could benefit the most from application of dedicated truck lanes, both with and without use of CVHAS technologies, we considered four market categories:

- Market #1: Rail yard to rail yard
- Market #2: Rail yard to/from industrial parks/warehouse concentrations
- Market #3: Rail yard to/from cordon points-of-entry
- Market #4: Movements to/from and between points-of-entry, industrial parks and warehouse concentrations (including the truck trips through the region)

Volumes of cross-town rubber-tire yard-to-yard interchange traffic, i.e., Market #1, have been decreasing for the past twenty years and this trend is very likely to continue, though Market #1 is unlikely to disappear entirely. Moreover, the interchange traffic generated from two new yards, Joliet (BNSF), and Global III Rochelle (UP), will primarily be steel-wheeled to eastern railroad yards. *Therefore, in contrast to the 1981 study, the purpose of the proposed facility is not only to serve Market #1, but also Markets #2 - #4.*

There were a large number of such nodes to draw from. We used as primary selection criteria the following: (1) major trip generators and attractors in terms of largest volumes of truck movements, (2) representation of both western (UP and BNSF) and eastern (CSX and NS) U.S. railroads, and (3) a few rail yards along the pathways formed among the primary nodes and cordon points-of-entry as well as (4) consultation with CATS and Chicago-area intermodal freight stakeholders.

Based on these criteria and regional site visits, with significant input from CATS and the intermodal freight stakeholder committee, we developed two types of node-link combinations to investigate: short- and long-term alignments (Figure 2). The short-term alignment provides direct access or connection to:

- Rail Yards (63rd, 47th/51st, Corwith, Cicero, Global II, Bedford Park, and Willow Springs)
- Industrial Parks (Northlake)
- Cordon points-of-entry (Chicago Skyway/Indiana State Line in the southeast and I-94 North)

The long-term alignment consists of the short-term alignment plus the recently-opened Rochelle and Joliet rail yards and the Cordon points-of-entry on I-88 (@ Rochelle) and I-55 (@ Joliet), and associated routes linking them with the short-term alignment (See dotted lines in

Figure 2). The lengths of the short- and long-term alignments are 44.5 and 145 miles, respectively. Truck volumes in and out of Rochelle and Joliet as well as their impact on overall regional goods movement are currently not well documented and it is likely to take a few years for travel demand to and from these new facilities to become clearly evident. Moreover, capacity changes along nearby interstate routes that are already programmed (in CATS' Long Range Plan) must be accounted for. For all these reasons, we focused our analyses on the short-term alignment, for which there was more complete data.

The short-term network consists of a truck-only facility primarily on presumed surplus and available rail ROWs, either adjacent to existing tracks or in air rights, and is identified in Figure 2 by nine segments, representing connections among the major selected nodes.

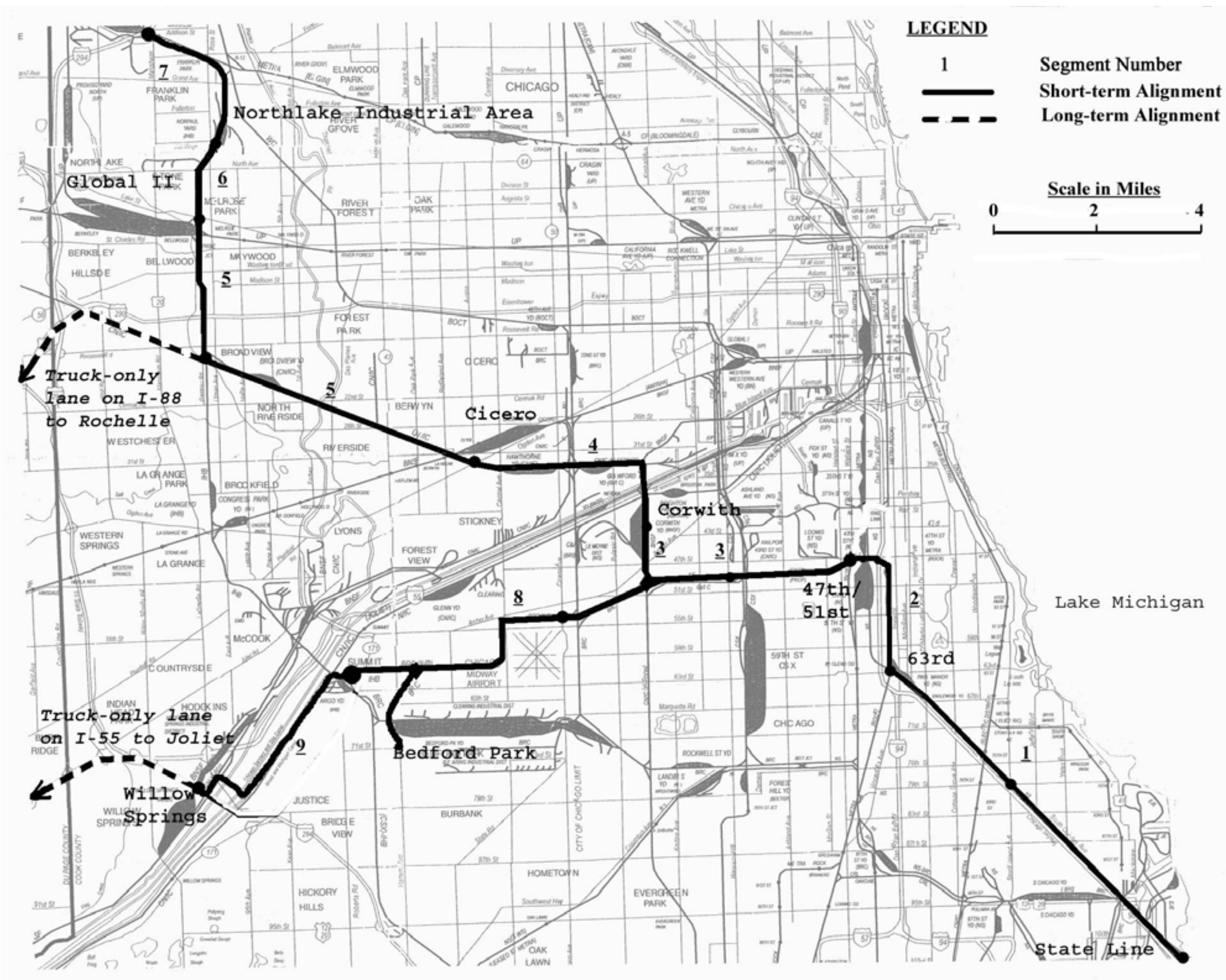

FIGURE 2 Selected Short and Long Term Alignments

In addition to a baseline case with no new truck lanes and an alternative with new truck lanes using only conventional technologies, against which to measure the impacts of CVHAS technology applications, we selected three additional CVHAS operational concepts for evaluation, for a total of five:

1. Baseline concept (do nothing, no CVHAS technologies, no truck-only facility)

2. Truck-only facility without CVHAS technologies, open to all trucks
3. Truck-only facility with CVHAS technologies (automatic steering) for equipped trucks only
4. Truck-only facility with CVHAS technologies (automatic steering, automatic speed and spacing control with two- or three-truck platoons if warranted) for equipped trucks only.
5. Truck-only facility without CVHAS technologies open to all trucks before a certain year to-be-determined and after that converting the facility to be an automated truck-way (automatic steering, speed and spacing control with two- or three-truck platoons)

It should be noted that prior to the to-be-determined year when Alternative 5 is converted to be fully automated, Alternative 5 is equivalent to Alternative 2. This study has not directly addressed the financing and governance models that could be used to facilitate deployment of new truck facilities, but future work should consider how a new entity could be created to acquire both vehicles and infrastructure and recoup the initial investment by lease-back payments from users.

IMPACT ANALYSIS

The major purpose of the analyses was to assess each CVHAS operational concept for use in the Chicago freight market. More precisely, we attempted to evaluate the impacts of each alternative, and investigated whether the positive impacts outweighed the negative impacts, and then recommended the most promising alternative for a further investment or engineering study.

The primary areas where the impact of CVHAS technology implementation could be experienced and benefits derived are in the areas of (1) traffic and congestion mitigation and travel time benefits and (2) safety, with benefits in the reduction of crashes, injuries, injury severity, property damage, loss of use of trucks, and fatalities; and (3) reduced fuel consumption and pollutant emissions. The impact analyses were performed at a macroscopic level.

Traffic Impacts

As the new truck-only facility provides an alternative truck route in the impacted area, some trucks will divert from their current routes to the new facility and experience time savings. Moreover, the trucks and passenger cars that continue to use existing routes will also enjoy time savings due to congestion mitigation. CATS ran its travel forecasting models, with input from the project team, to estimate traffic impacts of the proposed truck-only roadway on the Chicago regional traffic flow pattern.

The CATS travel forecasting-models represent the classical “four-step” process of trip generation, distribution, mode choice, and assignment, developed and improved upon since 1956, now built upon EMME/2 and ARC/INFO. Due to limited resources and the study’s macroscopic nature, only a time-of-day traffic assignment procedure was performed, meaning that the analysis reflects only the impacts of rerouting traffic, but not the induced demand effects of redistribution. CATS’ time of day assignment procedure incorporates features such as multiclass and capacity constrained equilibrium assignment. It splits into eight time periods the final highway trip table from the iterated process. Separate assignments estimate highway vehicle-miles and travel speeds for eight time periods during the day, and results of the separate period assignments are accumulated into daily volumes.

In the CATS models, the original truck trip generation was based on an older truck survey that does not reflect a trend towards more heavy trucks and more light trucks, with decreasing numbers of medium-sized trucks. CATS has recently assembled a Year 2002 intermodal heavy-duty truck O-D matrix, including 21 intermodal rail yards, 8 points-of-entry to the CATS region along the national highway system and 14 industrial park/warehouse concentrations (Rawling and Iris, 2003). The original heavy-duty truck trip table in the CATS models was adjusted by raising trip production rates for any traffic analysis zone that contains an intermodal ramp, thereby increasing the heavy truck trip table by 25% overall.

Tolling is one of the key factors affecting the overall traffic impacts in the region and the financial feasibility of the proposed facility. There exist several toll roads in northeastern Illinois, such as the Skyway, I-94/I-294 Tri-State Tollway, I-90 Northwest Tollway, I-355 South Tollway, I-88 between I-294and Rock Falls. It is a complex exercise and well beyond the scope of the study to determine an appropriate toll rate that maximizes socio-economic benefits and maintains a promising financial sustainability. A toll of $1.25 was applied at Segments 1, 3, 4 and 7 (see Figure 2 for segment numbers), to match the current toll level of state tollways. The toll rate we set is less than that on the Skyway and is comparable to those on the I-94/I-294 Tri-State Tollway. The Skyway has the highest single charge for any toll road in the state ($1.20 per axle), and a 5-axle truck would pay $6.00 for a single trip (7.8 miles, $0.77 per mile). The Tri-State charges tolls according to vehicle class. The average tolls per axle are somewhat different for different locations. For example, a 5-axle truck from Indiana to Northlake would pay $5.00 via the Tri-State Tollway. In our toll scenario, toll-collecting locations would be on Segments 1, 3, 4, and 7, and a toll of $1.25 should be paid each time a truck passes any of them, that is, if a truck travels from Indiana to Northlake via the new facility, it would pay $5.00 in total (32.5 miles, $0.15 per mile), the same it would pay if traveling via the Tri-State Tollway.

Table 3 presents truck facility performance results for the analysis of Alternative 2 at Year 2005, including daily vehicle volume (bi-directional), vehicle-miles-traveled (VMT), vehicle-hours-traveled (VHT) and average travel speed (mph) for defined segments. Table 4 presents network statistics for the private auto class of vehicles and the heavy truck class. VMT on all facilities includes freeways and expressways, while VMT on freeways and expressways (including the proposed truckway) is presented separately. One can be subtracted from the other to find VMT for only non-freeway/expressway facilities. VHT can be manipulated the same way.

We conclude that the capacity of one truck lane in each direction (Alternative 2) is adequate for the predicted truck traffic in Year 2005. The traffic volumes for Alternatives 3 and 4 would be lower than those in Table 3, because it takes time and money for the industry to equip their trucks with the CVHAS technologies. In the absence of a specific demand model for the adoption of these new technologies, we assumed levels of market penetration at the beginning of the project, of 15% for automatic steering in Alternative 3 and 10% for automatic steering, automatic speed and spacing control in Alternative 4. With the assumed market penetrations, traffic prediction for Alternatives 3 and 4 can be easily calculated.

By referring to the historic annual growth rates of intermodal truck movements in the Chicago area: 3.7% from 1978 to 1996, 5.6% from 1996 to 2000 and the annual growth rate of VMT by trucks in Illinois: 1.5% from 1997 to 2002, we predicted future growth rates for traffic volumes on the new facility as 2% from 2005 to 2015 and 1% from 2016-2025. Consequently, in Alternative 2 traffic volumes of several segments of the facility will be beyond their capacities in 2015, and thus a second lane in each direction would be added on these segments by that time.

TABLE 3 Truck Facility Daily Statistics for Alternative 2 in Year 2005

Segment #	Volume in Vehicles	Vehicle Miles Traveled	Vehicle Hours Traveled	Average Travel Speed
1	10,484	83,872	1,557	54
2	13,974	41,921	953	44
3	10,385	51,923	853	61
4	10,012	40,046	616	65
5	12,543	100,347	1,827	55
6	10,014	15,021	235	64
7	7,381	22,143	319	69
8	6,578	49,334	726	68
9	4,821	21,693	304	71

TABLE 4 Network Statistics with Toll Scenario in Year 2005

	VMT		VHT	
	All Facilities	Free/Expressway	All Facilities	Free/Expressway
Private Auto No-build	159,644,571	40,545,003	7,319,636	1,325,469
Private Auto Build w/Toll	159,635,502	40,826,589	7,268,434	1,323,007
Difference	-0.0%	0.7%	-0.7%	-0.2%
	All Facilities	Free/Expressway	All Facilities	Free/Expressway
Heavy Truck No-build	6,741,155	4,264,104	204,843	94,617
Heavy Truck Build w/Toll	6,765,553	4,367,236	196,986	91,325
Difference	0.4%	2.4%	-3.8%	-3.5%

Alternative 5 was designed as more deployment-staging oriented. According to the traffic prediction for Alternative 2, the year of transforming the truck-only facility to automated operation would be 2015. We expect that the cost of CVHAS equipment will be reduced significantly by then, as described in the next section. Therefore, it is safer to assume the market penetration of CVHAS-equipped trucks is 80% in 2015. Furthermore, a second lane will not be needed in Alternative 5 because fully automated operation in two- or three-truck platoons can increase hourly link capacity significantly (Michael et al., 1998).

In summary, with the traffic impact analysis results, we finalized the operational concept alternatives as follows:

- Alternative 1
    - Baseline concept (no CVHAS technologies, no truck-only facility).
- Alternative 2
    - Truck-only facility without CVHAS technologies, open to all trucks;

    - One standard 12-foot lane in each direction before Year 2015, and a second lane added on Segments 1-6 by Year 2015.
- Alternative 3
    - Truck-only facility with CVHAS technologies (automatic steering) for equipped trucks only;
    - One 10-foot lane in each direction. Automatic steering control makes it possible for equipped trucks to follow lanes very accurately. For maximum-width trucks of 9 feet, lanes need only be 10 feet wide rather than the standard 12 feet.
- Alternative 4
    - Truck-only facility with fully automated CVHAS technologies (automatic steering, automatic speed and spacing control with two- or three-truck platoons if warranted) for equipped trucks only;
    - One 10-foot lane in each direction.
- Alternative 5
    - Truck-only facility without CVHAS technologies before Year 2015;
    - At Year 2015, upgrading the facility to be an automated truck-way (automatic steering, speed and spacing control with two- or three-truck platoons);
    - One standard 12-foot lane in each direction.

In each of these cases, the truck lanes are accompanied by a shoulder lane to provide space to store any failed vehicles, to ensure that a single failed truck does not block the entire facility.

Safety Impacts

For a truck-only facility with CVHAS technologies, safety-related benefits stem from the separation of truck/non-truck traffic and the technologies as well. Traffic safety statistics show that a significant majority of two-vehicle crashes involving trucks and another vehicle, approximately 74%, are caused by drivers of the other vehicles, who make maneuvers that trucks are not able to respond to (NHTSA, 2003). The CVHAS collision warning technologies will no doubt reduce some kinds of crashes and result in some safety-related benefits. However, sufficient data are not available at this time to support quantitative estimates of the safety benefits, so those are not included here.

Fuel Consumption/Emission Impacts

Combinations of on-road and wind tunnel tests have shown that operating trucks in automated close-formation platoons can save 15%-20% of fuel consumption when they are cruising at highway speeds, compared to operating at the same speeds individually (Bonnet and Fritz, 2000). The automated trucks would maintain those high speeds continuously on the automated lane. Additionally, there are fuel savings because trucks on urban arterials experience stop-and-go traffic rather than higher-speed cruising. This effect has been quantified in research at the University of California at Riverside that has measured fuel consumption of a representative mix of modern Class-8 trucks (produced from 1998-2004), loaded to a gross vehicle weight of 60,000 lb., of about 5.5 miles per gallon when the truck is cruising at constant speed of 60 mph. Driving in congested traffic at an average speed of 30 mph leads to a decline to 4 miles per gallon. Following a California Air Resources Board driving cycle that includes a lot of stop-and-go cycles and an average speed of 18 mph, leads to a further decline to about 3.6 miles per gallon. These effects are illustrated in Figure 3.

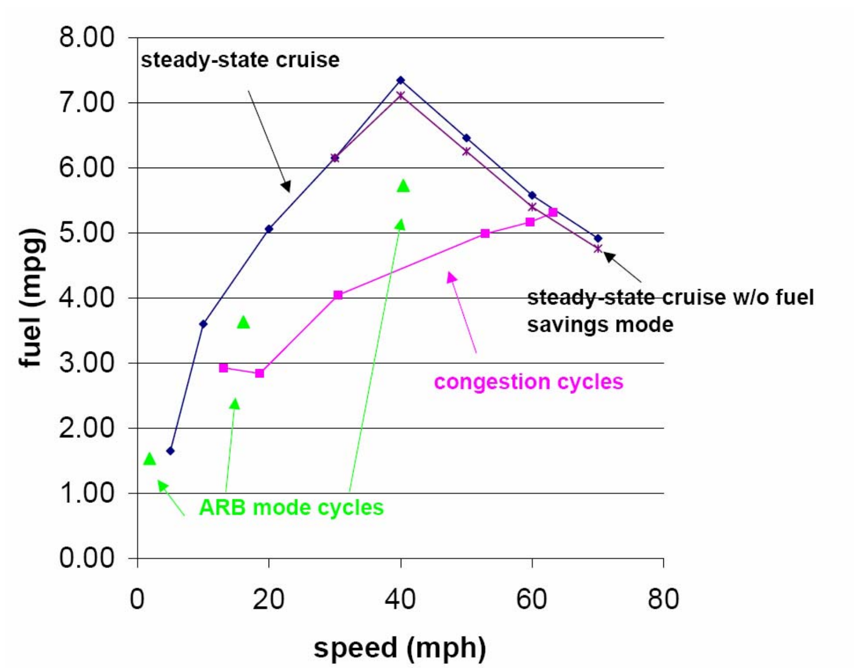

FIGURE 3 Fuel consumption of trucks (Source: Barth and Scora, 2004)

The same drag reductions producing fuel savings also contribute to reducing emissions from trucks. Carbon dioxide (greenhouse) gas reductions are directly proportional to fuel consumption reductions. The contributions for regulated pollutants are the subject of current experiments and are not yet known for heavy diesels of the types used in trucks, although they have been found to be substantial for the Otto-cycle engines used in passenger vehicles.

The proposed facility may also reduce emissions from trucks and other vehicles resulting from congestion mitigation. However, in this study, we did not examine these impacts but rather leave it to subsequent environmental studies. Note that integrating emissions costs into the cost-benefit evaluation does not have a major impact on project feasibility (Lee, 2000).

COST-BENEFIT ANALYSIS

This section presents a cost-benefit analysis (CBA) for the alternative operational concepts. The CBA period was 20 years (2005 – 2025). As recommended by the Office of Management and Budget, an annual discount rate of seven percent was used in the CBA.

Cost Estimation

The costs associated with each alternative were calculated, considering the following primary cost categories:

- Construction costs of truck-only roadway
- Right-of-way costs

- Annual facility operation and maintenance cost
- CVHAS equipment and installation costs (facility)
- CVHAS equipment and installation costs (in-vehicle units)

Construction Costs

The statistical data available from Illinois Department of Transportation show that the inflation-adjusted (Year 2002 price) costs per lane mile for major Chicago area highway engineering and construction projects are $6.9 M (1991 Elgin-O'Hare); $6.7 M (1992 Kennedy reconstruction); $7 M (1993 Tri-State add-lanes/reconstruction) and $7.1 M (1999 Stevenson reconstruction). These projects, involving reconstruction of heavily-used highways while open for public use, were considerably more complex than the proposed creation of new truck lanes on lightly-used or vacant ROWs.

Based on site visits to the proposed alignment and the above data, we estimated unit roadway construction costs for each specific segment, ranging from $1.5 M per lane-mile to $6.5 M per lane mile, depending on their ROW conditions. In each segment, certain number of bridges with different lengths may be needed, for example, to cross the Calumet River, the Dan Ryan Expressway, railroad trestles, canals or local streets. Therefore, we also determined a unit bridge construction cost as $20 M per lane mile, but with the special exception that the high-clearance bridge needed over the Calumet River would cost $60 M per lane mile. Table 5 presents unit construction cost for each segment at Interstate standard (12-foot lane).

TABLE 5 Unit Construction Cost Estimation of Truck-Only Facility

Segment #	Length (mile)		Unit cost ($ million per lane mile)	
	Highway	Bridge	Highway	Bridge
1	7.8	0.2	1.5	60
2	2.7	0.3	1.5	20
3	4.7	0.3	2.0	20
4	3.9	0.1	6.5	20
5	7.9	0.1	6.5	20
6	1.4	0.1	6.5	20
7	2.9	0.1	6.5	20
8	6.4	0.1	6.5	20
9	5.2	0.3	5.0	20
Total	42.9	1.6	-	-

As aforementioned, with automatic steering control, lane width could be reduced to 10 feet. Moreover, conventional highway alignments are based on drivers' sight distances at expected operating speeds. Automated vehicles are not subject to the same kinds of limitations, so it is possible to accommodate tighter curves and sight lines otherwise unacceptable for conventionally driven vehicles. With these considerations, we assumed the unit construction costs of roadways and bridges would be reduced eight percent and five percent, respectively, when calculating total construction costs for alternatives with automatic steering and full automation.

Right-of-way costs

The cost of industrial space (land alone) in Chicago-Cook County averages $3.93 per square foot ($42.30 per square meter) net (Enterpriz Cook County, 2003). We estimated the width of ROW requirement for each alternative. Multiplying the ROW width by the unit cost and total length yielded the total ROW costs. For Alternative 2, although a second lane in each direction would be added in the future, the ROWs were assumed to be purchased at the beginning of the construction. Therefore, the width of ROW for Segments 1-6 at Alternative 2 is 80 feet (2 feet barrier, 4 feet left shoulder, 2*12 feet lane, and 10 feet for the right shoulder in each direction). Consequently, the widths for Alternative 3, 4 and 5 are 52, 52, and 56 feet respectively.

Annual operation and maintenance cost of the proposed facility

Operation and maintenance (O&M) costs were calculated as a percentage of total project cost estimated at 3% - 4% of construction costs over a 20-year period (Sarakki Associates, 2003). For Alternative 3, 4 and 5 (after 2015), the O&M cost would be 10% -15% higher, because of maintenance of electronics and instruments and more frequent pavement rehabilitations. For Alternative 2 and 5 before 2015, the annual O&M costs were both $1.4 M. After then, they were $2.8 M and 1.6 M respectively. For Alternative 3 and 4, the annual O&M costs were $1.5 M and $1.6 M respectively.

CVHAS Equipment and Installation Costs (Facility)

Automatic steering and full automation need roadway reference markings, such as permanent magnets installed in the pavement so that vehicle positions can be measured relative to the markings. For new construction, the installation of these magnets should add about $5000 per lane mile. For retrofits into existing pavement, the cost of installation was assumed to be $10,000 per lane mile. Note that these costs will decrease over time as mass production techniques for magnet installation are developed.

For full automation, vehicle-roadway wireless communications will be also needed, and will probably be based on the next generation of dedicated short-range communications (DSRC) in the 5.9 GHz band. These devices are currently under development and are not yet commercially available, but it is likely that the roadside units will cost no more than $5000 each (and potentially much less than that with volume production in the long-term). One roadside unit will be needed at each on-ramp and off-ramp and then periodically along the automated lane, at a spacing of about 300 m.

Note that there may be other CVHAS facility requirements, such as a control center and its hardware and software. It is reasonable to assume that the traffic management and incident response functions for the automated truck facility will be handled at the existing regional transportation management center, together with the rest of the primary highway network. It may be necessary to provide an additional workstation at the center, specific to the automated truck facility, but the cost of this is likely to be very small relative to the other costs of the new facility and thus it is not explicitly computed in the analyses here.

CVHAS Equipment and Installation Costs (In-vehicle Unit)

It is key to recognize that the costs would be significantly different in the near term (when annual production of vehicles would only be in the hundreds) and the longer term (when it could be in the range of ten thousand). So the cost estimates presented in Table 6 were estimated under both assumptions. The costs are the incremental costs associated with the addition of CVHAS capabilities to trucks. In all cases, we have assumed modern trucks that already have electronically controlled engines and in-vehicle data buses. The underlying component technology on trucks is advancing for reasons unrelated to CVHAS, and it was assumed, based on discussions with the largest truck manufacturer in the world, that "by wire" actuation systems will be readily available on conventional trucks within the "long- term" planning horizon for this project.

TABLE 6 Cost Estimation for In-Vehicle Units

	Automatic steering control	
Cost generators	**Near-term unit cost ($1000)**	**Long-term unit cost ($1000)**
Steering actuator	2.5	0.5
Magnetic sensors	5	1
Computer and interfaces	5	1
Installation/integration	0.5	0.2
Sub-total	13	2.7
	Additional costs for full automation	
Forward ranging sensor(s)	2.5	0.5
Wireless communication	0.5	0.1
Brake actuation	5	1
Driver interface	1	Assume included
Installation/integration	1	0.3
Total	23	4.6

For calculating the costs of in-vehicle units for automatic steering control and full automation at 2005, we used the approximate near-term unit costs of $13 K and $25 K respectively while after 2015, we used the approximate long-term cost of $3 K and $5 K; Between Year 2005 and 2015, we applied a simple linear scaling down of the costs over time so that they continuously changed from the near-term cost to the lower long-term cost.

It was estimated from the CATS regional models that there would be 37,000 truck trips using the new truck-only facility at Year 2005. We assumed that there are, on average, two daily trips per truck, and therefore estimated a total of 18,500 trucks to be equipped.

For Alternative 3, the level of market penetration was assumed to be 15% of the trucks serving the routes under consideration in Year 2005, and would increase annually 15% more in the following three years and 10% more after that until reaching 80%, an assumed saturated level at Year 2010. Consequently, the number of equipped trucks would increase at the same rate as the market penetration grew, and after 2010, it would increase in the following years at the same growth rate as the traffic growth rate previously reported (Traffic Impacts Section) as 2% from

2010 to 2015, and 1% from 2015 to 2025. The assumed population growth of automatic steering equipped trucks is illustrated in Figure 4.

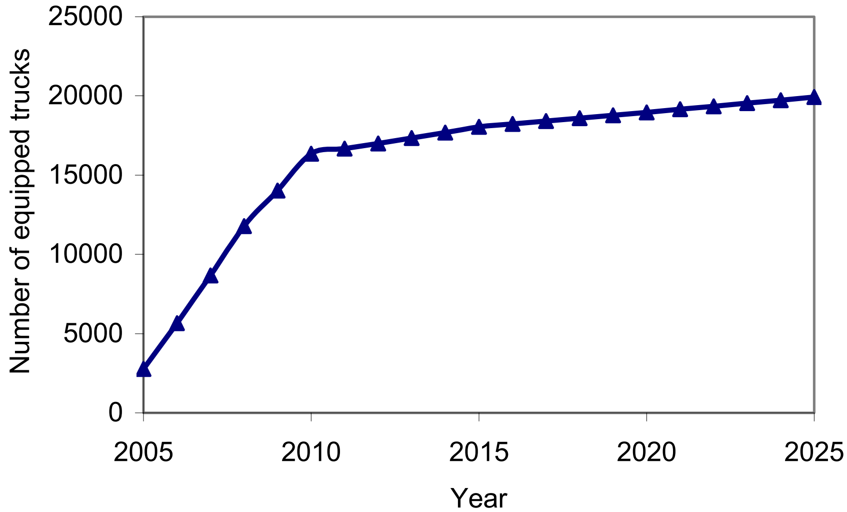

FIGURE 4 Assumed population growth of automatic steering equipped trucks

For Alternative 4, the level of market penetration was assumed to be 10% at Year 2005, and it would increase annually 15% in the following three years and 5% more after that until reaching 80% at Year 2013. The number of equipped trucks would increase at the same rate as the market penetration would grow, and after Year 2013, it would increase in the following years at the aforementioned traffic growth rates. The assumed population growth of full automation trucks is shown as Figure 5.

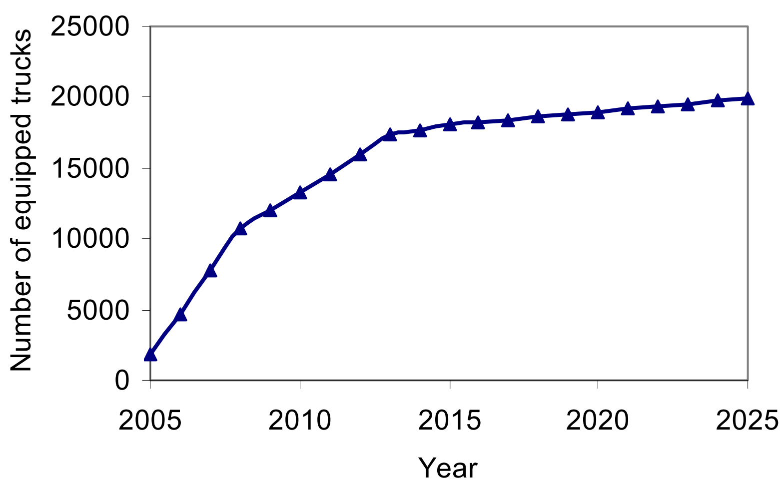

FIGURE 5 Assumed population growth of full automation trucks

For Alternative 5, the level of market penetration was assumed to be 80% at Year 2015, and the number of equipped trucks increased in the following years at the growth rate of 1%.

We assumed a 10-year truck life and thus included a replacement cost of in-truck equipment after the truck wears out.

Benefit Estimation

As aforementioned, we only considered benefits of travel time savings and reductions of fuel consumption. We did not consider the safety and environmental benefits discussed in the previous section as well as the reduced maintenance costs of surface streets.

Travel Time Savings

From Table 4, it can be calculated that, for Alternative 2 the total network travel time savings for passenger cars and trucks are 13,824,540 and 2,123,390 hours respectively at Year 2005. By applying the values of travel time $16 /hour for passenger cars recommended by FHWA (FHWA, 2000) and $65 /hour for heavy-duty trucks (based on discussions with CATS), we estimated the annual time saving benefits as US$ 221 M and $138 M respectively in Year 2005.

For the other alternatives, travel time savings were estimated by multiplying these values by the corresponding levels of market penetrations at Year 2005.We acknowledge that such linear scaling of time savings is not a realistic assumption, because the change of the total travel time of a network does not scale directly with the capacity it has. In fact, the linear scaling tends to underestimate the actual benefits. Therefore, it is safe to make this assumption in the sense that our conclusion about the cost-effectiveness of each alternative presented later will not be invalidated by relaxing this assumption.

Due to limited resources, we assumed the following trends for the timesaving benefits:

- For Alternatives 2 and 5 (before 2015), the corresponding benefits decreased at an annual rate of 5% in the following years, considering the growth of the traffic demand.
- For Alternative 3, the corresponding benefits increased annually at the same rate as the growth rate of market penetration before Year 2010 when the level of market penetration became saturated. After that, the benefits were assumed not to change.
- For Alternative 4, the corresponding benefits increased annually at the same rate as the growth rate of market penetration before Year 2013. After that, the benefits increased annually 2% from 2013 to 2015 and 1% from 2015 to 2025, considering the characteristics of automated operations.
- For Alternative 5 (after 2015), the corresponding benefits increased 1% annually from 2015 to 2025, considering the characteristics of automated operations.

Reduction of Fuel Consumption

Recall that there are two sources for the decrease in fuel consumption: avoiding stop-and-go traffic on urban arterials and aerodynamic drag reductions from automated close-formation platoons.

Based on the empirical data presented by Barth and Scora (2004), we estimated the reductions of fuel consumption of heavy-duty trucks due to avoiding stop and go traffic.

From Table 4, it can be calculated that with the introduction of Alternative 2, VMT of heavy-duty trucks on non-expressway/freeway facilities decreased by 78,734 miles while on expressway/freeway facilities it increased by 103,132 miles since the truckway was included in that class. The average travel speeds can also be calculated to be 23 mph and 46 mph on these two types of facilities, corresponding to the fuel consumption rates of 4.2 miles per gallon at ARB mode cycles and 6.6 miles per gallon at steady-state cruise without fuel savings mode. The unit price of diesel fuel was $1.50 /gallon (an average value taken over Chicago-area diesel prices obtained by means of an Internet search of the time of the analysis). Consequently, the annual fuel savings was estimated as $842,435 at Year 2005 for Alternative 2.

For the other alternatives, fuel cost savings were estimated by multiplying by the corresponding levels of market penetrations. Furthermore, we assumed the trends for fuel savings to be consistent with those used to estimate travel time savings.

In evaluating Alternatives 4 and 5, additional reductions were calculated by assuming 15% savings of fuel consumption due to automated close-formation platoons (Bonnet and Fritz, 2000). These savings also increased in the following years at the same growth rate of market penetration and traffic volume. The total savings were estimated as $ 41.7 M and $17.5 M for Alternatives 4 and 5 respectively.

Comparison of Costs and Benefits

The evaluation results for the alternative operational concepts are presented in Table 6 with entries expressed in present value (2003) terms.

TABLE 7 Evaluation Results of the Alternative Operational Concepts (Year 2003$)

	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Cost Components				
Construction costs	716,164,244	439,216,000	439,216,000	474,800,000
ROW costs	73,871,424	48,016,426	48,016,426	51,709,997
Annual O&M	21,941,915	17,391,021	18,550,423	15,544,330
CVHAS costs (facility)	0	445,000	1,638,342	1,665,700
CVHAS costs (vehicle)	0	165,038,739	300,196,641	40,259,968
Total	811,977,583	670,107,186	807,617,831	583,979,994
Benefit Components				
Travel time savings	2,938,473,072	2,185,796,310	1,931,338,450	2,981,926,571
Reduction of fuel consumption	6,893,874	5,128,039	46,257,595	24,505,307
Total	2,945,366,946	2,190,924,349	1,977,596,045	3,006,431,878

B/C ratio	3.63	3.27	2.45	5.15

In calculating the B/C ratios in Table 7, we assumed that the residual values of all the alternatives after 20 years (the CBA time period) were each zero. Because of limited levels of market penetration of CVHAS equipped trucks in Alternative 3 and 4, the truck-only facility was not fully utilized and thus these two alternatives are somewhat inferior to Alternative 2. It implies that, compared with the conventional truck-only lane (Alternative 2), the incremental costs of these alternatives outweigh the incremental benefits, causing an incremental B/C ratio that is less than one. However, note that the total costs of the CVHAS alternatives (3-5), including the vehicle costs, are all lower than the total costs of the truck-only facility without use of CVHAS technologies (Alternative 2).

Alternative 5 was evaluated as the best since it deployed CVHAS technologies at a later time, when the costs of the in-vehicle equipment were lower and the traffic volumes higher. The incremental CVHAS B/C ratio is 7.57 (Note that incremental B/C ratio was incremental benefits divided by incremental costs, compared with Alternative 2. We categorized cost savings as incremental benefits). Therefore, the deployment-staging issue is very important for a successful implementation of CVHAS. We recommended Alternative 5 for further investigation.

Sensitivity Analysis

The CBA presented above was based on many assumptions. Therefore it is necessary to perform sensitivity analyses relative to particular parameters in order to support the above conclusions. Because Alternative 5 was recommended for further investigation, we focused our attention on this operational concept and performed sensitivity analyses to test the reliability of the previous conclusion about it. We did not intend to determine which parameter or assumption the CBA presented above is most sensitive to.

We identified the factors that appeared to have significant impact on the evaluation outcome such as construction costs, CVHAS in-vehicle unit cost, and travel time savings. These factors are uncertain, and we performed the CBA based on our best estimate of the values of these factors. There is no doubt that any deviation from our estimate will affect the analysis outcome, and we thus conducted sensitivity analyses on these three factors. Other factors, such as annual discount rate and ROW unit cost will certainly affect the analysis outcome, but their influence was considered secondary here.

In order to investigate the impact of the uncertainty of these factors on the evaluation outcome, we determined ranges of values that these factors could assume in a conservative (pessimistic) manner:

- Construction costs
  The unit construction costs are presented in Table 5, which were determined by referring to the statistical data and conducting site visits. We assumed that the unit cost could be up to 20% lower or up to 100% higher.
- CVHAS in-vehicle unit costs
  The CVHAS in-vehicle unit costs are presented in Table 4.12. For calculating the costs of Alternative 5, we used the approximate long-term cost of $5K. Here we assumed that this cost could be increased to the approximate near-term unit cost of $25K or decreased to 20% less.

- Travel time savings
  A variety of parameters contribute to the uncertainty of travel time savings, such as the accuracy of predicted traffic volume, level of market penetration assumed, and value of travel time used. We did not differentiate their impacts but assumed that total travel time savings could be reduced by 67% or increased by 20%.

It can be found that in the worst possible scenario (two times the unit construction cost, $25K CVHAS in-vehicle unit cost, and one-third travel time savings), Alternative 5 would become economically unattractive because its B/C ratio would decline to 0.86. This warrants a further examination of the reliability and robustness of the B/C ratio estimate for Alternative 5. For this purpose, we performed a Monte-Carlo analysis to see how these three factors affect Alternative 5's B/C ratio, where unit construction cost, CVHAS in-vehicle unit cost, and travel time savings were assumed to be uniformly distributed within their varying ranges described as above, and they were independent from each other.

Figure 6 presents the B/C ratios resulting from the Monte-Carlo analysis, with a sample size of 2000.

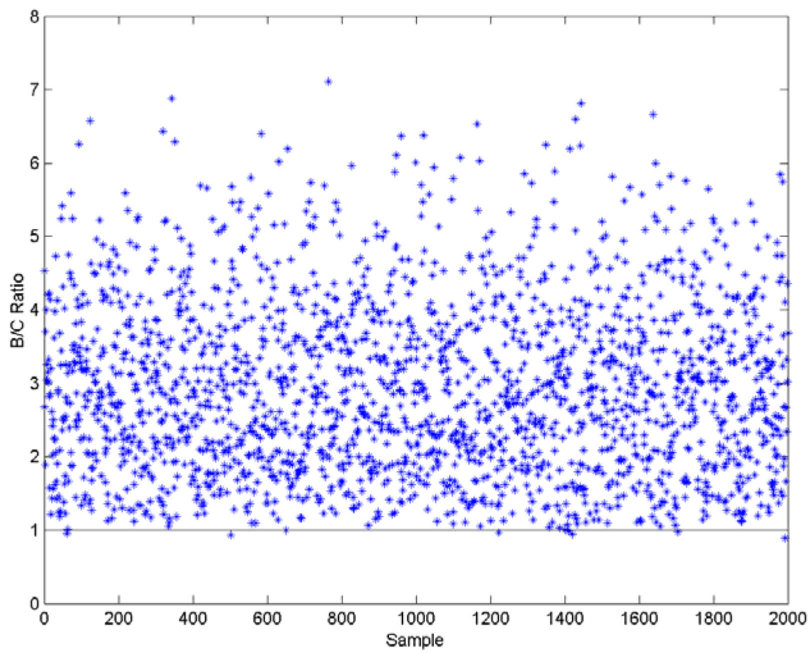

FIGURE 6 B/C ratios of Alternative 5 Compared to the Do-Nothing Alternative in the Monte-Carlo Analysis

It can be found that there were only eight cases over 2000 samples that the B/C ratio of Alternative 5 is less than one. We conducted a *t*-test to test the null hypothesis that "the B/C ratio of Alternative 5 is less or equal to one". The resultant *t*-statistic was 74.1. Even at the 0.1% significance level, with 1999 degrees of freedom, we rejected the null hypothesis. Therefore, the *t*-test shows that Alternative 5 is economically attractive, compared to the baseline case with no truck facility, and this conclusion is reliable and robust.

The above Monte-Carlo analysis validated the robustness of the B/C ratio estimate for Alternative 5 with respect to the do-nothing baseline. It is also of interest to show the comparison with conventional truck-only facility (Alternative 2) to highlight the difference based on use of CVHAS technologies, given that a truck-only facility is going to be developed. Therefore, we performed another sensitivity analysis to investigate the impact of the uncertainty on the incremental B/C ratio, compared to Alternative 2.

The major uncertain factors associated with the incremental B/C ratios were identified as below. Again, we determined ranges of values that these factors could assume in a conservative manner.

- Saving of construction costs
  One of major incremental benefits of Alternative 5 over Alternative 2 is the saving of construction costs because a second lane would not be added in Segments 1-6. However, this second lane might not be needed in Alternative 2 if actual traffic volume was much lower than predicted. We assumed this condition had a probability of 20%.
- CVHAS in-vehicle unit costs
  Similarly as above, we assumed that this cost could be increased to the approximate near-term unit cost of $25K or decreased to 20% less.
- Market penetration
  The level of market penetration would affect both incremental costs and benefits. For the estimation of Alternative 5, we used 80% at Year 2015. Here we assumed that this level could be increased to 90% or decreased to 50%.

A Monte-Carlo analysis was conducted to see how these three factors affect Alternative 5's incremental B/C ratio, where saving of construction costs was assumed to be binomially distributed, and CVHAS in-vehicle unit cost and market penetration uniformly distributed between their varying ranges described as above, and they were independent from each other.

Figure 7 presented the incremental B/C ratios resulting from the Monte-Carlo analysis, with a sample size of 2000.

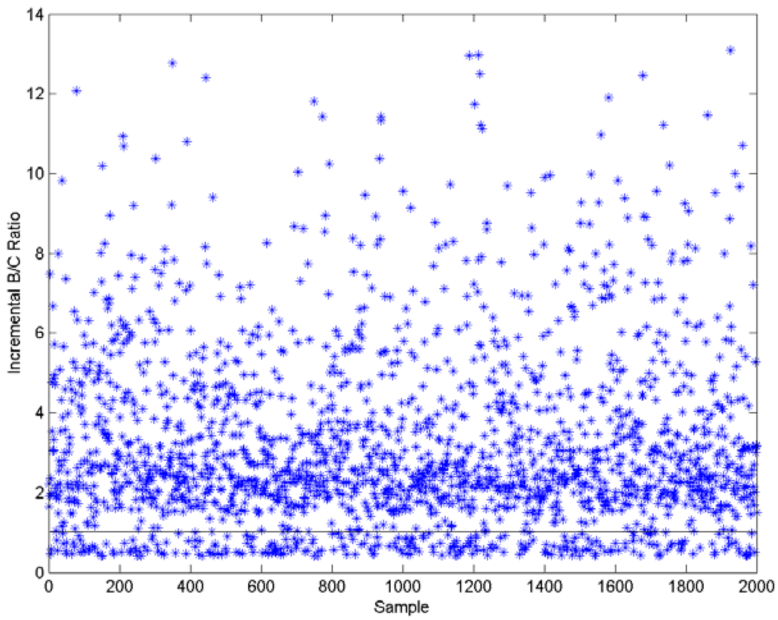

FIGURE 7 B/C ratios of Alternative 5 Compared to Alternative 2 (Conventional Truck Only Facility) in the Monte-Carlo Analysis

It can be found that there were 289 cases over 2000 samples that the incremental B/C ratio of Alternative 5 is less than one. After reviewing these 289 cases, we found that all of them are associated with the assumption that the actual traffic volume would not require the additional lane in Alternative 2. Note that not all the cases that the additional lane would not be needed will result in the B/C ratio less than one. However, if coupled with the occurrence of other adverse effects, Alternative 5 will be likely to be marginally economical. Therefore, the key risk factor here is the variability in the growth of truck traffic that might or might not require the additional lane in Alternative 2. Although this is an uncontrollable uncertainty, the desirability of Alternative 5 can still be maintained by adjusting the year of upgrading from Alternative 2 to be an automated truck-way, based on the realization of truck traffic growth.

We conducted a *t*-test to test the null hypothesis that "the incremental B/C ratio of Alternative 5 is less or equal to one". The resultant *t*-statistic was 43.9. Even at the 0.1% significance level, with 1999 degrees of freedom, we rejected the null hypothesis. Therefore, the *t*-test implies that application of CVHAS technologies does improve the performance of a conventional truck-only facility, and this conclusion is also reliable and robust.

CONCLUSIONS AND RECOMMENDATIONS

This paper investigated the opportunity to implement CVHAS technologies to improve the performance of the freight movement system in the metropolitan Chicago area. Based on the current intermodal freight flow pattern in this area, we proposed a truck-only roadway facility whose alignment was selected by mainly making use of available rail rights-of-way. Besides the baseline, four alternative operational concepts were suggested after a systematic investigation of the maximum possible set of alternatives. We performed comparative analyses across alternatives, calculating both benefits and costs associated with the alternatives against the baseline. Our evaluation showed that all of the alternatives are economically viable and CVHAS technologies are able to help improve the performance of the intermodal freight system. However, the times and ways of deploying CVHAS technologies play important roles for their efficiency and success. We have recommended Alternative 5 for further investigation, which was a conventional truck-only facility open to all trucks before 2015 and then upgraded to an automated highway open only to automated trucks.

Further study could be conducted in the following directions:

- Creating a time-staged model of market penetration of CVHAS, considering that the growth of adoption of CVHAS is determined by the benefits gained from the technologies and the costs;
- Investigating the impacts of the new intermodal terminals at Rochelle and Joliet on overall regional goods movement and evaluating the long-term alignment and the corresponding operational concepts;
- Examining the concept of automated truck platoons with no drivers in the following vehicles for the long-term alignment case, with fewer network access nodes at larger separations.
- Testing some other networks. For example, consider a network addressing the full range of regional truck accessibility needs from the start, and considering the opportunities for developing truck lanes, both with and without CVHAS technologies, in other parts of the Chicago region, unconstrained by the locations of intermodal terminals and railroad rights of way.

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