Transit Cooperative Research Program
Sponsored by the Federal Transit Administration

RESEARCH RESULTS DIGEST

December 2000—Number 39

Subject Areas: IA Planning and Administration, IB Energy and Environment, VI Public Transit

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Alternative-Fuel Transit Bus Hazard Assessment Model

This TCRP digest summarizes the findings from TCRP Project C-11, "Hazard Assessment of Alternative-Fuel-Related Systems in Transit Bus Operations." The work was performed by a team led by Science Applications International Corporation (SAIC).

INTRODUCTION

A new tool is available for assessing fuel-related hazards on transit buses. It is built on quantitative analysis (summarized in this digest) that shows where the key risks for fuel-related hazards in compressed natural gas (CNG) and liquefied natural gas (LNG) are expected. *The Alternative-Fuel Transit Bus Hazard Assessment Model* (the model) is designed as an Excel spreadsheet tool that can be tailored to the characteristics of a particular fleet and facility after reading the "One-Page User's Guide." Download the model and its accompanying final report/user's guide from the TCRP website at http://www4.nationalacademies.org/trb/crp.nsf/All+Projects/TCRP+C-11. The model and the final report are also available on CD-ROM as *CRP-CD-4* through the American Public Transportation Association's TCRP Dissemination website at http://www.apta.com/tcrp.

EXECUTIVE SUMMARY

The *Alternative-Fuel Transit Bus Hazard Assessment Model* estimates the consequences (injuries and property damage) and losses (in dollars) from fuel-related hazards (fire and non-fire) on transit buses. The model compares hazards, expected losses, consequences, and mitigation measures within and across fuel types. *CRP-CD-4* contains the **Reference Case** model, which uses survey data, estimates based on statistical data, and engineering estimates and judgments developed by the project team. The **Reference Case** becomes the **Base Case** once it is tailored to the characteristics of a particular fleet and facility. The model can then be used to evaluate consequences, expected losses, and the effects of certain mitigation measures on the Base Case. The Reference Case values were developed for a generalized bus and a fleet of 200 buses using CNG and a fleet using LNG. The findings do not represent any single fleet but rather a composite from across the country. Because of limitations on the availability, quality, and applicability of the data in the model, the results should not be interpreted as exact measures of risk, losses, and so on.

A summary of the findings for the Reference Case is presented in Tables ES-1 through ES-4, following the text. Note that the bottom or lower left of each output table identifies the case as the Base Case or the Incremental Case. The Base Case represents the user's fleet and facility as they exist. It is developed from the Reference Case. The Incremental Case represents the user's analysis of measures that could mitigate the losses from releases, fires, injuries, or property damage.

SUMMARY FINDINGS

The Base Case (using the Reference Case in the model) estimates fuel-related losses associated with diesel, CNG, and LNG. Table ES-1, Summary Valuation of Losses, shows the values in more detail.

- Diesel—$48 per bus-year (PBY) or $9,600 per year for a fleet of 200 diesel buses
- CNG—$324 PBY or $64,875 per year for a fleet of 200 CNG buses
- LNG—$480 PBY or $96,015 per year for a fleet of 200 LNG buses.

Summary fuel-related losses from diesel buses are based on survey data developed by the research team. Detailed fuel-related losses for CNG and LNG buses are based on data, estimates, and engineering judgment developed by the research team.

COMPRESSED NATURAL GAS

Losses in the CNG Base Case are estimated at $324 per bus per year. Table ES-1 shows that, overall, more than one-half the losses are from public injuries and fatalities. Most of the remaining loss is from property damage from releases and fires. In terms of the number of events and injuries (rather than dollars), the Base Case estimates 0.14 worker injuries per fleet-year, 0.44 public injuries per fleet-year, and 12 release events causing property damage per fleet-year. Most of the injuries and property damage take place in operation or in parking. Parking contributes significantly to losses, because the bus is fully fueled. Table ES-2 shows that roughly 90 percent of the losses are attributable to fast releases from pressure relief devices (PRDs) ($228 PBY) and fast releases from cylinders ($64 PBY). The remaining 10 percent of the base losses ($32) are attributable to all other components. This observation suggests that the first place to look for cost-effective point mitigation measures would be PRDs and cylinders, rather than other components or broadly defined non-point mitigation measures. This is a significant observation, because it confirms the importance of the industry's current focus on PRDs and cylinders and the relative unimportance of additional effort addressing all other components and systems. The PRD issues are particularly significant in climates where freezing takes place. Table ES-3 shows that a majority of the losses occur in operation and that most of the remaining loss occurs in parking. Parking generates relatively large losses, because the bus is fully fueled before it is parked and parking represents about one-third of the daily cycle. The operating stage, while longer than the parking stage and with a lower probability of release, accounts for more losses, because many more people are exposed during operations than during parking.

The estimated loss of $324 PBY is highly sensitive to the release frequencies used in the analysis. Switching from the 1998-99 release frequencies to the 1996-97 frequencies increases the base loss to $601 PBY. Most of the losses are still attributable to fast PRD releases and fast cylinder releases. This observation also confirms the importance of continuing to address PRD and cylinder issues.

Using the Base Case and 1998-99 release frequencies as a basis, the only cost-effective mitigation measure is the replacement of PRDs. The observation that only one mitigation measure appears cost-effective on average, across the industry, is important. It suggests that there are no systemic deficiencies in components (except PRDs) or industry practices. Rather, there are individual deficiencies in components, systems, practices, and so forth that must be addressed. Point mitigation measures directed at components other than fast releases from PRDs are not cost-effective in the model. Non-point and post-event mitigation measures are also not cost-effective. As with LNG, however, this inference is sensitive to the release probabilities used in the model and the event database behind it. Relatively modest changes in release probabilities in key areas or in the consequences of key release categories would significantly change the relationships. The user should verify that the release frequencies are appropriate for his or her situation.

LIQUEFIED NATURAL GAS

Losses in the LNG Base Case are estimated at $480 per bus per year. Most of the losses are attributable to the following five release points: refueling receptacle ($112); fuel tank rupture ($90); fuel tank vacuum loss ($73); PRD slow release ($71); and fuel line fittings ($61). The remaining $75 in losses is attributable to eight other release points. This observation suggests that point mitigation measures aimed at the five major release points are the most likely ones to be cost-beneficial. The PRD issues are particularly significant in climates where freezing takes place. Table ES-1 shows that about one-half of the losses are from property damage from releases and almost one-fifth are from property damage from fires. Most of the remaining loss is attributed to public injuries and fatalities. In terms of events and injuries (rather than dollars), the Base Case estimates 0.06 worker injuries per fleet-year, 0.83 public injuries per fleet-year, and 173 release events causing property damage per fleet-year. Most of the injuries and property damage take place in operation or in parking. Parking contributes significantly to losses, because the bus is fully fueled. Table ES-3 shows that most of the losses occur in parking and operation (in that order) versus operation and parking (the reverse order) for CNG. Table ES-4 shows the losses in the Base Case.

Using the Base Case in the model and the 1998-99 release frequencies as a basis, the only cost-effective point mitigation measures are replacing all the PRDs and tightening the fuel line fittings. Installation of spark arresters is a cost-effective non-point mitigation measure, costing $2,000 per fleet-year but reducing losses in the Base Case by about $2,800 per fleet-year. Increasing inspections reduces losses by about $10,000 per fleet-year but costs about $20,000 per fleet-year, making it cost-ineffective. The observation that only a small number of mitigation measures appear cost-effective on average is important. It suggests that there are few systemic deficiencies in components (except PRDs) or industry practices. Rather, there are individual deficiencies in components, systems, practices, and so forth that must be addressed. This observation is tied directly to the estimated frequency of releases, however. Fleets with characteristics like those forming the 1996-97 release estimates have much larger estimated losses and many more cost-effective mitigation options. For example, switching from the 1998-99 release frequencies to the 1996-97 frequencies increases the base loss to $9,810 PBY. Moreover, it changes the highest risk release points to fast PRD ($4,124); fuel line ($2,394); regulator ($2,003); couplings ($734); and fuel tank vacuum loss ($457). This radical change in both the overall total and the individual components driving the total suggests that the LNG systems and operational practices are exceedingly variable from fleet-to-fleet and over time. This variability is also an indicator of technical and operational immaturity. Note, for example, that fuel lines and regulators are major sources of loss using the 1996-97 data but that the refueling receptacle is not. In the 1998-99 data, the reverse is true. The 1998-99 release frequencies are based on recent experiences at a medium-sized transit agency in the southwestern United States. The earlier frequencies are based on earlier experiences at a large transit agency in the southwestern United States. LNG operators should also be aware that the variations over time and across components and fleets are based on a relatively small database of buses and events. This observation suggests caution in directly translating the values in the model to individual fleets.

OTHER OBSERVATIONS

The model is capable of depicting significant structural, operational, and safety-related mitigation characteristics and practices. However, the precision of the model far exceeds the statistical validity and accuracy of the data. For example, the failure rate values for CNG and LNG rely on statistical, survey, and observational data, but the data suffer from reporting deficiencies, variation in the buses and components, vintage issues, and definition-related issues. These deficiencies are particularly pronounced for LNG. Moreover, the sparseness of the data when divided across multiple dimensions (e.g., releases from a particular bus component in a particular stage of the daily operating cycle) often makes it impossible to isolate the most likely contributors to hazardous events and the consequences of those events. Real-time or near-real-time data collection would improve the quality of the data but would impose a burden on the transit systems. The available failure rate data do, however, confirm significant improvements in the fuel-related systems for CNG and LNG transit fleets over the past few years.

Data on factors such as the probability of ignition, the probability and severity of injuries from each release or fire, and the effects of mitigation measures were estimated by the project team. There are little or no empirical data on these variables for transit buses. The development of national data for these variables may be difficult but would add significant accuracy to the model. The model is designed to permit the use of fleet-specific data and estimates to increase the accuracy of the analysis. Space is provided in the model for including fuel cell and hybrid bus data when they become available.

Finally, it is worth stressing that the overall cost-effective level of systems, operations, and safety practices depends on a relatively high degree of compliance with established safety practices. The research team has observed substantial occurrences of off-specification safety activities, equipment, facilities, and so on. This degraded adherence to safety standards figures into the losses estimated in the Base Case in the model. Strict adherence to safety standards would lower the base losses and make fewer itemized mitigation measures cost-effective.

POTENTIAL USERS OF THE HAZARD ASSESSMENT MODEL

The model is a practical and credible tool for transit managers to use as they assess, and design mitigation measures for, the hazards associated with the use of alternative fuels. Managers responsible for specification, procurement, maintenance, operations, training, safety, risk management, and facilities design for alternate fuel vehicles (new or used) will find this model useful. It will also be of interest to bus manufacturers and fuel purveyors.

HOW TO OBTAIN COPIES OF THE HAZARD ASSESSMENT MODEL

The *Alternative-Fuel Transit Bus Hazard Assessment Model* and final report may be downloaded from the TCRP website at http://www4.nationalacademies.org/trb/crp.nsf/All+Projects/TCRP+C-11. The model and the final report are also available on CD-ROM as *CRP-CD-4* through the American Public Transportation Association's TCRP Dissemination website at http://www.apta.com/tcrp.

TECHNICAL SUPPORT

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Table ES-1. Summary Valuation of Losses

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VALUATION OF LOSSES

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Valuation of Losses per Bus-Year By Fuel Type

	Diesel	CNG	LNG	Fuel Cell	Hybrid
Worker Injuries		$21	$3		
Worker Fatalities		$5	$6		
Public Injuries		$134	$60		
Public Fatalities		$49	$84		
Property Damage (Release)		$37	$246		
Property Damage (Fire)		$77	$82		
TOTAL	$48	$324	$480		

Frequency of Losses

Valuation of Losses by Stage of Operation

Valuation of Losses per Fleet-Year By Fuel Type

	Diesel	CNG	LNG	Fuel Cell	Hybrid
	200	200	200		
Worker Injuries		$4,271	$620		
Worker Fatalities		$1,054	$1,102		
Public Injuries		$26,870	$11,989		
Public Fatalities		$9,875	$16,762		
Property Damage (Release)		$7,361	$49,199		
Property Damage (Fire)		$15,445	$16,343		
TOTAL	$9,600	$64,875	$96,015		

Case (BASE/INCREMENTAL)		BASE	BASE		

SUMMARY / DIESEL / CNG / LNG / FUEL CELL / HYBRID / GLOSSARY / GO HOME

Table ES-2. Benefits & Costs (CNG, Base Case Losses)

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BENEFITS & COSTS ($/bus-yr.) ? Home

RELEASE POINT	Base Loss	Mit'd Loss	Benefit	Cost	Benefit-Cost
	Rank by:	Rank by:	Rank by:	Rank by:	Rank by:
1. Cylinder - slow	$6	$6	$0	$0	0.00
2. Cylinder - fast	$64	$64	$0	$0	0.00
3. PRD - fast	$228	$228	$0	$0	0.00
4. PRD - slow	$4	$4	$0	$0	0.00
5. Refueling device	$1	$1	$0	$0	0.00
6. Fuel line fittings	$1	$1	$0	$0	0.00
7. Fuel line	$7	$7	$0	$0	0.00
8. LP regulator	$3	$3	$0	$0	0.00
9. HP regulator	$5	$5	$0	$0	0.00
10. Solenoid valve	$4	$4	$0	$0	0.00
11. 1/4 turn valve	$3	$3	$0	$0	0.00
12. Other valve	$1	$1	$0	$0	0.00
13. Other	$0	$0	$0	$0	0.00
14. Open	$0	$0	$0	$0	0.00
15. Open	$0	$0	$0	$0	0.00
TOTAL	$324	$324	$0	$0	0.00

BASE

SUMMARY / DIESEL / CNG / LNG / FUEL CELL / HYBRID / GLOSSARY / GO HOME

Table ES-3. Summary Valuation of Losses by Stage of Operation

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VALUATION OF LOSSES BY STAGE OF OPERATION

? | Home | Frequency of Losses | Valuation of Losses

Valuation of Losses per Bus-Year by Stage of Operation

	Operation	Fueling	Prev. Maint.	Corr. Maint.	Parking	TOTAL
Diesel						$48
CNG	$194	$3	$2	$7	$118	$324
LNG	$186	$8	$3	$10	$273	$480
Fuel Cell						
Hybrid						

Valuation of Losses per Fleet-Year by Stage of Operation

	Fleet	Operation	Fueling	Prev. Maint.	Corr. Maint.	Parking	TOTAL
Diesel	200						$9,600
CNG	200	$38,848	$662	$482	$1,382	$23,500	$64,875
LNG	200	$37,239	$1,611	$692	$1,901	$54,571	$96,015
Fuel Cell							
Hybrid							

Case (BASE/INCREMENTAL)

Diesel	
CNG	BASE
LNG	BASE
Fuel Cell	
Hybrid	

SUMMARY / DIESEL / CNG / LNG / FUEL CELL / HYBRID / GLOSSARY / GO HOME

Table ES-4. Benefits and Costs (LNG, Base Case Losses)

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BENEFITS & COSTS ($/bus-yr.)

RELEASE POINT	Base Loss	Mit'd Loss	Benefit	Cost	Benefit-Cost
1. Fuel tank (Vac. Loss)	$73	$73	$0	$0	0.00
2. Fuel Tank Rupture	$90	$90	$0	$0	0.00
3. PRD - fast (2/tank)	$10	$10	$0	$0	0.00
4. PRD - slow (2/tank)	$71	$71	$0	$0	0.00
5. Refueling receptacle	$112	$112	$0	$0	0.00
6. Fuel line fittings	$61	$61	$0	$0	0.00
7. Fuel line	$19	$19	$0	$0	0.00
8. Regulator	$10	$10	$0	$0	0.00
9. Vaporizer	$25	$25	$0	$0	0.00
10. Solenoid valve	$3	$3	$0	$0	0.00
11. 1/4 turn valve	$0	$0	$0	$0	0.00
12. Injector (Fuel Valve)	$0	$0	$0	$0	0.00
13. Cryo Pump	$0	$0	$0	$0	0.00
14. Gauges	$6	$6	$0	$0	0.00
15. Couplings	$1	$1	$0	$0	0.00
TOTAL	$480	$480	$0	$0	0.00

BASE

SUMMARY / DIESEL / CNG / LNG / FUEL CELL / HYBRID / GLOSSARY / GO HOME