REPORT NO. UMTA-RD-CA-06-0088-76-2

(NASA-CR-154251) COSTS AND ENERGY EFFICIENCY OF A DUAL-MODE SYSTEM (Jet Propulsion Lab.) 76 p HC A05/MF A01 N77-29003
CSCL 05C Unclas
G3/85 39266

COSTS AND ENERGY EFFICIENCY OF A DUAL-MODE SYSTEM

APRIL 30, 1977

AUTOMATED GUIDEWAY TRANSIT TECHNOLOGY PROGRAM

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Office of Research and Development
Washington, D.C. 20590

This document is available to the public
through the National Technical Information
Service, Springfield, Virginia 22151

This document was prepared for
United States Department of Transportation
by Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Technical Report Documentation Page

1. Report No. UMTA-RD-CA-06-0088-76-2	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Costs and Energy Efficiency
of a Dual-Mode System

5. Report Date
April 1977

6. Performing Organization Code

7. Author(s)
R. C. Heft and C. S. Borden

8. Performing Organization Report No.
77-34

9. Performing Organization Name and Address

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-AT-60008
UMTA-RD-CA-06-0088

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Urban Mass Transportation Administration
400 7th Street, S.W.
Washington, D.C. 20590

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report represents a more detailed examination of two areas of a previous analysis on a Dual-Mode System as documented in "Technical and Cost Considerations for Urban Applications of Dual-Mode Transportation" (JPL, May 1972). The present study is divided into two parts: 1) An Economic Analysis and 2) An Energy Consumption Analysis.

The Economic Analysis examines the present value Life Cycle Costs of the System for both public and semi-private system ownership and presents the costs in terms of levelized required revenue per passenger mile.

The Energy Consumption Analysis considers the energy use of the various Duel Mode Vehicle by means of a detailed vehicle simulation program for the control policy and guideway system as described in the previous study. Several different propulsion systems are considered.

17. Key Words Economic Analysis, Life Cycle Cost, Vehicle Simulation, Energy Efficiency	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 76	22. Price

REPORT NO. UMTA-RD-CA-06-0088-76-2

COSTS AND ENERGY EFFICIENCY OF A DUAL-MODE SYSTEM

Ronald C. Heft and Chester S. Borden

APRIL 30, 1977

AUTOMATED GUIDEWAY TRANSIT TECHNOLOGY PROGRAM

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Office of Research and Development
Washington, D.C. 20590

This document was prepared for
United States Department of Transportation
by Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ACKNOWLEDGEMENT

This project was sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA) under contract UMTA-RD-CA-06-0088. The research was conducted with the cognizance of Mr. George Izumi of the UMTA Office of Research and Development, Automated Guideway Transit Technology Program.

The work was performed at the Jet Propulsion Laboratory, California Institute of Technology, by agreement with the National Aeronautics and Space Administration, to which Caltech/JPL is a prime contractor.

PREFACE

The following study represents an extension and reanalysis of certain portions of the previous JPL Dual-Mode Study.[1] Two areas of the previous study, the cost analysis and the energy consumption analysis, were identified for reexamination for the following reasons:

(1) The growing consensus within the professional community on the proper evaluation framework for the analysis of transportation system costs.

(2) The development of significantly more sophisticated analysis tools permitting detailed evaluation of vehicle energy consumption.

The reevaluation of the cost analysis did not attempt to rework or challenge any of the many and detailed cost items in the previous study but rather to cast them into a rigorous present-value/life cycle cost framework under two ownership scenarios: (1) full public ownership and operation; (2) semiprivate ownership with the ways and right-of-way public and rolling stock and operations private.

The reevaluation of the energy consumption analysis assumed the basic vehicle system configuration of the previous study including the headway control and operations policy. The energy consumption of the various vehicle configuration and possible candidate propulsion options were examined in a dual-mode guideway environment using a detailed vehicle simulation system.

---

[1] "Technical and Cost Considerations for Urban Applications of Dual-Mode Transportation," JPL Internal Report 1200-33, May 1972.

DEFINITION OF ABBREVIATIONS

AMTV	Automated Mix Traffic Vehicle
APCD	Air Pollution Control District
BART	Bay Area Rapid Transit
BSFC	Brake Specific Fuel Consumption
Caltech	California Institute of Technology
CAPS	Command Actuated Passenger Service
CBD	Central Business District
CI	Capital Investment
CRF	Capital Recovery Factor
DOT	Department of Transportation
EQL	Environmental Quality Laboratory (Caltech)
FCR	Fixed Charge Rate
FRA	Federal Railroad Administration
FWHA	Federal Highway Administration
GM	General Motors
HUD	Department of Housing and Urban Development
IC	Internal Combustion
IW	Inertial Weight
JPL	Jet Propulsion Laboratory
LADCP	Los Angeles Department of City Planning
LARTS	Los Angeles Regional Transportation Studies
LAX	Los Angeles International Airport
LCC	Life Cycle Costs

MIT	Massachusetts Institute of Technology
NVTC	Northern Virginia Transit Commission
OHSGT	Office of High Speed Ground Transportation
OP	Operating Expenses
OST	Office of Secretary of Transportation
PAAC	Port of Authority Allegheny County
PATH	Pallet Augmented Transit Hybrid
PM	Passenger Miles
PO	Post Office
PRT	Personal Rapid Transit
RCA	Radio Corporation of America
R&D	Research and Development
SCRTD	Southern California Rapid Transit District
SLG	Synchronous Longitudinal Guidance
STEP	Social, Technical, Economic, Political
TRW	Thompson-Ramo-Wooldridge
UMTA	Urban Mass Transportation Administration
UPS	United Parcel Service
VEEP	Vehicle Energy and Emissions Program

CONTENTS

APPENDIXES

Figures

Tables

Tables

SECTION 1

ECONOMIC ANALYSIS

This is a preliminary economic analysis of a dual-mode transportation system (PATH). It uses the technical and cost data presented in "Technical and Cost Considerations for Urban Applications of Dual-Mode Transportation" (JPL, May 1972), which is then evaluated using the life-cycle cost[2] approach. Two transit modes associated with a high-speed guideway system are included, i.e. pallets and command actuated passenger service (CAPS) vehicles. The cost of the entire system including capital outlays and operating expenditures is evaluated on a life-cycle basis, then a parametric description of demand is used to determine required revenues per passenger-mile. This required revenue per passenger-mile will be used as a standard to be compared with similar required revenues for alternate transportation systems. An alternative system design where busses are added to the baseline configuration is analyzed in Appendix D.

1.1 SYSTEM DESCRIPTION AND ASSUMPTIONS

The system evaluated is a 280-mi single lane (140-mi double-lane) high-speed guideway. Guideways would be able to service personal autos on pallets and CAPS vehicles. Table 1-1 summarizes the system characteristics and financial inputs.

Portions of this analysis differ from the original document on dual-mode transportation. These differences include:

(1) Parking is available at all stations including those in and out of the Central Business District (CBD). A total of 1000 spaces at all 34 non-CBD stations was added. It is assumed that parking is situated directly above the station structure since the stations are large and land costs are expensive.

(2) Land costs are considered a real cost for the system, not merely an economic impact. This cost is thus included in capital costs.

---

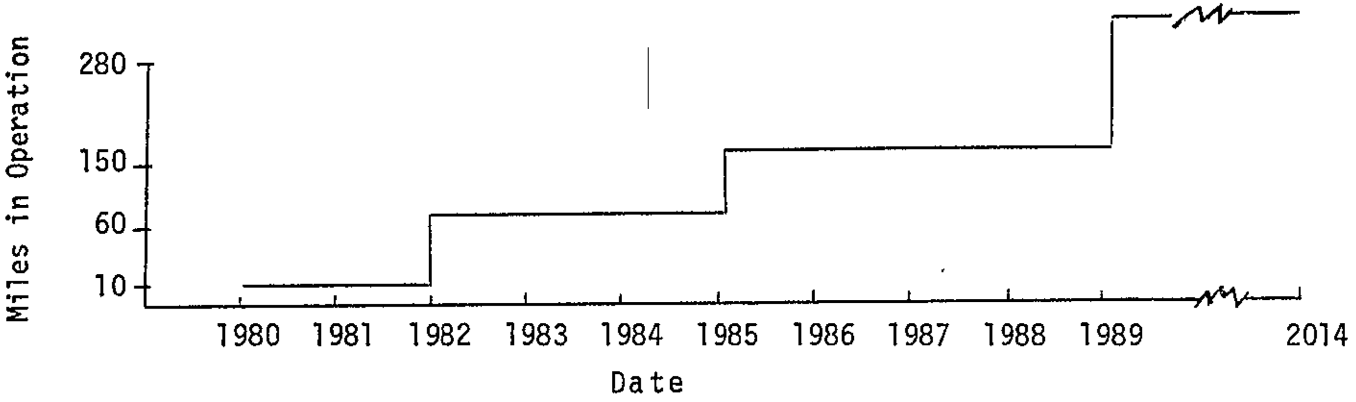
[2] The life-cycle cost methodology is the subject of Appendix B.

Table 1-1. System Description of High-Speed Guideway

Length of Guideway	280 Single-lane miles
Numbers of Vehicles	14,000 Pallets 11,300 10-Passenger CAPS Vehicles
Number of Stations	38 Stations
Station Land Requirements	280 ft x 500 ft
Parking	15,400 Spaces in CBD 1,000 Spaces in each of 34 non-CBD Stations
Guideway Capacity	6000 vehicle/hour
CAPS Vehicles	Occupancy ≤ 10 passengers per vehicle
Autos	Assumed = 1.28 persons/vehicle including dead-head
CAPS Load Factor	Parametric for computing Passenger-Miles
Dead-Head	0.2
Capital Equipment Lifetime	All guideway associated capital items are assumed to have a 35 year lifetime. CAPS vehicles have a 15 year
Discount Rate	10%
Escalation Rate	5%
Ownership Scenarios	Private operating property and public operating property

Table 1-1. System Description of High-Speed Guideway (Continuation 1)

Implementation Schedule :	It is assumed that the guideway will become operational according to the following schedule.



The system initially becomes operational in 1980 with 10 lane-miles of guideway; In 1982, 50 more miles are opened; In 1985, 90 additional miles; In 1989, the final 130 miles completes the 280 lane-mile guidway system.

Capital is allocated according to the same schedule, except that funds are committed three years prior to implementation (eg. funding is in 1977 at 3.6% of total capital requirements for the 10 miles of the 280 mile total which are opened in 1980). Operational costs exactly follow the implementation schedule with proportional percentages of yearly funding in 1980 when the system is complete.

1.2 PRESENT VALUE CALCULATIONS

This section evaluates the present values of capital costs and operating costs for the dual-mode system described in Table 1-1.

Capital costs for this system were derived from the referenced document.[1] The costs are allocated according to the schedule defined in Table 1-2 which follows the criteria from the prior table. Note that CAPS vehicles are purchased in the year operations begin, on a proportional basis with capital costs. Vehicle replacements occur every 15 yr. In years 2010 and 2012 a charge in made consistent with the 35-yr system lifetime.

To calculate the present value of these nominal costs, it was decided that the year of first commercial operation, 1980, would be the year to which present values were evaluated. Using the techniques outlined in Appendix B, the present value of capital expenditures equals $\$2.7474 \times 10^9$ in 1980 dollars.[3]

Operations costs are also from the referenced document.[1] The nominal yearly charges in 1970 dollars are presented in Table 1-3. The present value of all operations costs is $\$6.3245 \times 10^9$ in 1980 dollars. Present values of all operations costs are listed in Appendix C.

Given the present values for capital investment (CI_{pv}) and operating expenditures (OP_{pv}), a life-cycle cost can be evaluated. The life-cycle cost (LCC) is calculated as follows:

$$LCC = FCR \cdot \frac{CI_{pv}}{CRF_k^N} + OP_{pv} \tag{1-1}$$

where

FCR = Fixed charge rate

CRF_k^N = Capital recovery factor at a discount rate of k percent for N years

The fixed charge rate (FCR) is that factor by which the present value of capital investment (CI_{pv}) must be multiplied to obtain the capital outlay contribution to the annualized cost. Dividing then by the capital recovery factor yields the contribution of capital expenditures over the system lifetime to the life-cycle cost. This fixed charge rate (FCR) includes a number of financial parameters and is calculated as follows:

$$FCR = \frac{1}{1 - \tau}\left(CRF_k^N - \tau/N\right) + \beta \tag{1-2}$$

---

[3] This calculation is presented in Appendix C.

Table 1-2. PATH System Capital Expenditures Nominal 1970 Dollars × 10^6

ITEM	1977	1979	1980	1982	1985	1986	1989	1995	1997	2000	2004	2010	2012	TOTAL
Guideway	35.5	176.5		316.5		457.5								$ 986.0
Maint Yard	.6	3.0		5.5		7.9								$ 17.0
Pallets	(504) 7.6	(2506) 37.6		(4494) 67.4		(6496) 97.4								(14000) $ 210.0
CAPS			(407)* 6.1	(2023) 30.3	(3627) 54.4		(5243) 78.6	(407) 6.1	(2023) 30.3	(3627) 54.4	(5243) 78.6	(407/3) 2.0	(2023/5) 6.1	(11300) $ 346.9
LAND	10.8	53.7		96.3		139.2								$ 300.0
PARKING	7.1	35.3		63.5		91.7								$ 197.6
YEARLY TOTALS	61.6	306.1	6.1	579.5	54.4	793.7	78.6	6.1	30.3	54.4	78.6	2.0	6.1	$2057.5

Number in parentheses represent number of vehicles. For years following 1989, numbers represent replacement vehicles.

Table 1-3. PATH System Operations Costs Nominal 1970 Dollars × 10^6

OPERATING COSTS	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990-2014
CONSOLE MAINTENANCE	.258	.258	1.541	1.541	1.541	3.842	3.842	3.842	3.842	7.168	Σ 7.168
CONSOLE OPERATIONS	.246	.246	1.469	1.469	1.469	3.662	3.662	3.662	3.662	6.832	Σ 6.832
STATION OPERATIONS	.195	.195	1.165	1.165	1.165	2.905	2.905	2.905	2.905	5.42	Σ 5.42
PALLET OPERATIONS	.195	.195	1.165	1.165	1.165	2.905	2.905	2.905	2.905	5.42	Σ 5.42
GEN & ADMIN (PALLETS)	.264	.264	1.576	1.576	1.576	3.929	3.929	3.929	3.929	7.33	Σ 7.33
GEN & ADMIN (CAPS)	.306	.306	1.828	1.828	1.828	4.556	4.556	4.556	4.556	8.50	Σ 8.50
VEHICLE MAINT (PALLETS)	4.122	4.122	24.618	24.618	24.618	61.372	61.372	61.372	61.372	114.50	Σ 114.50
VEHICLE MAINT (CAPS)	.598	.598	3.569	3.569	3.569	8.898	8.898	8.898	8.898	16.60	Σ 16.60
CAPS OPERATORS	2.585	2.585	15.437	15.437	15.437	38.485	38.485	38.485	38.485	71.80	Σ 71.80
VEHICLE POWER (CAPS)	.091	.091	.544	.544	.544	1.356	1.356	1.356	1.356	2.53	Σ 2.53
VEHICLE POWER (PALLETS)	1.256	1.256	7.504	7.504	7.504	18.706	18.706	18.706	18.706	34.90	Σ 34.90
GUIDEWAY ROADBED MAINT	.093	.093	.557	.557	.557	1.388	1.388	1.388	1.388	2.59	Σ 2.59
GUIDEWAY POWER	.176	.176	1.049	1.049	1.049	2.616	2.616	2.616	2.616	4.88	Σ 4.88
YARDS OPS (PALLETS)	.504	.504	3.010	3.010	7.504	7.504	7.504	7.504	7.504	14.00	Σ 14.00
YARDS OPERATIONS(CAPS)	.407	.407	2.430	2.430	2.430	6.057	6.057	6.057	6.057	11.30	Σ 11.30
TOTAL	11.295	11.295	67.460	67.460	67.460	168.181	168.181	168.181	168.181	313.77	Σ 313.77

where

τ = income tax rate

CRF_k^N = Capital Recovery Factor at a discount rate of k% for N years.

N = System lifetime

β = Other (nonincome) taxes, insurance premiums and licensing fees.

The fixed charge rate includes those items of major concern to a private firm, such as taxes and depreciation. If a public property were to be considered, taxes (τ) would equal zero, and the new fixed charge rate would be:

$$FCR = CRF_{k'}^N + \beta' \tag{1-3}$$

where

k' = New discount rate, as this is a public institution and may have a lower discount rate since capital financing is generally by tax exempt securities which sell at lower yields than private issues.

β' = Insurance premiums and licensing fees. Property taxes and other nonincome taxes are not included.

For the dual-mode system under consideration, the cost to both a private operating property, and a public operating property will be evaluated.

The cost to a private concern is found by combining Equations (1-1) and (1-2). The inputs to this formula are:

$$CI_{pv} = \$2.7474 \times 10^9$$

$$OP_{pv} = \$6.3245 \times 10^9$$

$$CRF_{.10}^{35} = 0.10369$$

$$\tau = 0.50$$

$$N = 35$$

$$\beta = 0.009$$

where β reflects 0.007 in insurance payments[4] plus a percentage of property and other taxes equal to 0.002. The 0.002 amount was derived by assuming public ownership of all but the pallets and CAPS vehicles and 30% of the maintenance yard; this implies 28.5% of all capital items are privately owned, on a present value basis, with an assumed property tax rate of 0.007, or 0.002.

$$\text{LCC} = \left[\frac{1}{1 - (0.5)} \left(0.10369 - \frac{0.5}{35} \right) + 0.009 \right] \frac{\$2.7474 \times 10^9}{0.10369} + \$6.3245 \times 10^9$$

$$= 0.18781\ (\$2.6496 \times 10^{10}) + \$6.3245 \times 10^9$$

$$= \$11.301 \times 10^9$$

The cost of this system to a public institution is found by inserting Equation (1-3) into Equation (1-1). The parameters is this case equal:

$$\text{CI}_{\text{pv}} = \$2.7474 \times 10^9$$

$$\text{OP}_{\text{pv}} = \$6.3245 \times 10^9$$

$$\text{CRF}^{35}_{.10} = 0.10369$$

$$\beta' = 0.007$$

The capital recovery factor for the public concern case was chosen equal to the private firm case for simplicity of calculation. A 10% discount rate is reasonable for government investments. The life-cycle cost calculation is:

$$\text{LCC} = (0.10369 + 0.007)\ \frac{\$2.7474 \times 10^9}{0.10369} + \$6.3245 \times 10^9$$

$$= \$9.257 \times 10^9$$

Of course, this amount is less then in the private ownership case since taxes are not included under public ownership.

---

[4] Inclusion of insurance in the fixed charge rate is discussed in Appendix B.

A useful method for describing dual-mode transportation costs is required revenues per passenger mile ($\bar{C}$). To evaluate the present value of required revenues, the following condition is assumed: For a project to be able to cover all of its costs on a life-cycle basis, the minimum condition which must be satisfied is that the present value of revenues (REV_{pv}) must equal the life-cycle cost (LCC). This is calculated as follows:

$$LCC = REV_{pv} \tag{1-4}$$

or

$$LCC = \sum_{t=1}^{N} REV_t \; (1 + k)^{-t+1} \tag{1-5}$$

REV_t can be broken down further into its component parts

$$REV_t = \bar{C} \cdot PM_t \tag{1-6}$$

where

$\bar{C}$ = constant revenue required per passenger-mile over the system lifetime required to cover the present value of all system-costs.

PM_t = passenger-miles traveled in year t.

Combining Equation (1-6) into Equation (1-5),

$$LCC = \sum_{t=1}^{N} \bar{C} \cdot PM_t \; (1 + k)^{-t+1}$$

Since $\bar{C}$ is constant for all t, it can be brought outside the summation as

$$LCC = \bar{C} \sum_{t=1}^{N} PM_t \; (1 + k)^{-t+1}$$

To solve for the required revenue per passenger mile in year of first commercial operation is:

$$\bar{C} = \frac{LCC}{\sum_{t=1}^{N} PM_t \ (1 + k)^{-t+1}} \qquad (1-7)$$

Equation (1-7) represents the general case for the calculation $\bar{C}$. In the special case where passenger-miles per year are constant the formula simplifies as follows:

$$\bar{C} = \frac{LCC}{PM \sum_{t=1}^{N} (t + k)^{-t+1}}$$

where

$\overline{PM}$ = constant passenger-miles per year.

The summation in the denominator equals[5] $(CRF)^{-1}$. When this is put in the numerator, the final form for the required revenue per passenger-mile ($\bar{C}$) in year of first commercial operation current dollars becomes:

$$\bar{C} = \frac{LCC \times CRF}{\overline{PM}} \qquad (1-8)$$

---

[5] The CRF is actually equal to

$$\sum_{t=1}^{N} (1 + k)^{-t}$$

reflecting the end of the year cash flows. In the above case, a beginning of the year CRF is calculated. To remedy this inconsistency, divide the life-cycle cost by (1 + k).

Passenger-miles per year have been calculated for the pallet and CAPS vehicle systems in the referenced document. These figures are computed as the product of:

vehicle speed × yearly time system in operation ×

number of vehicles × baseline vehicle occupancy ×

load factor ratio.

The PATH document projects vehicle occupancy to be 5 passengers/CAPS vehicle and 1.28 passengers/auto on pallet, including deadhead. This translates to:

$$\text{Pallets} = 7.326 \times 10^9 \text{ passenger-mi/yr}$$

$$\text{CAPS} = 1.765 \times 10^9 \text{ passenger-mi/yr}$$

which totals 9.091×10^9 passenger-mi/yr. This figure represents the baseline value for annual demand when the system is in full operation and the load factor ratio associated with each vehicle type equals "1". In this analysis it is assumed that the guideway demand will follow the same schedule as the implementation scheme outlined in Table 1-1. This means that for those years prior to system completion in 1986, only a percentage of the demand will actually be realized, and this percentage mimics the capital allocation schedule.

Required revenues per passenger-mile can now be evaluated using Equation (1-7). Summing the yearly demand in passenger-miles $\times 10^9$ the PATH baseline system gives the following results:

Vehicle Type	$\sum_{t=1}^{N} PM_t (1 + k)^{-t+1}$
Pallet	43.861
CAPS	10.568
Total PATH System	54.429

The load factor ratio for the total PATH system will be varied parametrically to produce a range of required revenues per passenger-mile. This ratio will vary from 0.8 to 2.0 and Table 1-4 presents the results of the different demand assumptions. Figure 1-1 graphically illustrates the results presented in Table 1-4.

1.3 SYSTEM COMPARISONS

This section presents two types of comparisons of the PATH system:

(1) the component parts of the PATH system CAPS vehicles and autos on pallets with each other and

(2) the baseline PATH configuration to a modified version assuming CAPS vehicles are driverless [similar to Automated Mix Traffic Vehicle (AMTV)].

The comparison of the parts of the PATH system with each other proceeds in the following manner. Capital costs of the entire system are divided into vehicle and nonvehicle expenditures. The nonvehicle capital costs are evaluated below.

$$\begin{array}{c}\text{nonvehicle}\\ \text{capital cost}\end{array} = \text{present value}\left\{\begin{array}{l}\text{guideway + maintenance yard}\\ \text{+ land + parking}\end{array}\right\}$$

Year	Nonvehicle Expenditures In Nominal 1970 Dollars × 10^6	Nonvehicle Present Value[6] In 1980 Dollars × 10^6
1977	54.0	101.2
1979	268.5	458.2
1982	481.8	715.1
1986	696.3	858.0
Total		$2132.5 × 10^6

Nonvehicle capital expenditures are associated to each vehicle type as a percentage of vehicle-miles. Table 1-5 shows the cost allocation in 1980 present value terms.

---

[6] See Appendix B for calculation technique.

Table 1-4. PATH System Required Revenue per Passenger-Mile in 1980 Dollars Assuming Private and Public Operating Property Ownership. Baseline Demand is 9.091×10^9 Passenger-mi/yr When Fully Operational

LOAD FACTOR RATIO	ANNUAL 1989 DEMAND PASS-MI x 10^9	PRIVATE OWNERSHIP LIFE-CYCLE COST \$ x 10^9	PRIVATE OWNERSHIP REV/PASS-MI	PUBLIC OWNERSHIP LIFE-CYCLE COST \$ x 10^9	PUBLIC OWNERSHIP REV/PASS-MI
0.8	7.273	11.301	0.260	9.257	0.213
1.0	9.091	11.301	0.208	9.257	0.170
1.2	10.909	11.301	0.173	9.257	0.142
1.4	12.727	11.301	0.149	9.257	0.121
1.6	14.546	11.301	0.130	9.257	0.106
1.8	16.364	11.301	0.116	9.257	0.094
2.0	18.182	11.301	0.104	9.257	0.085

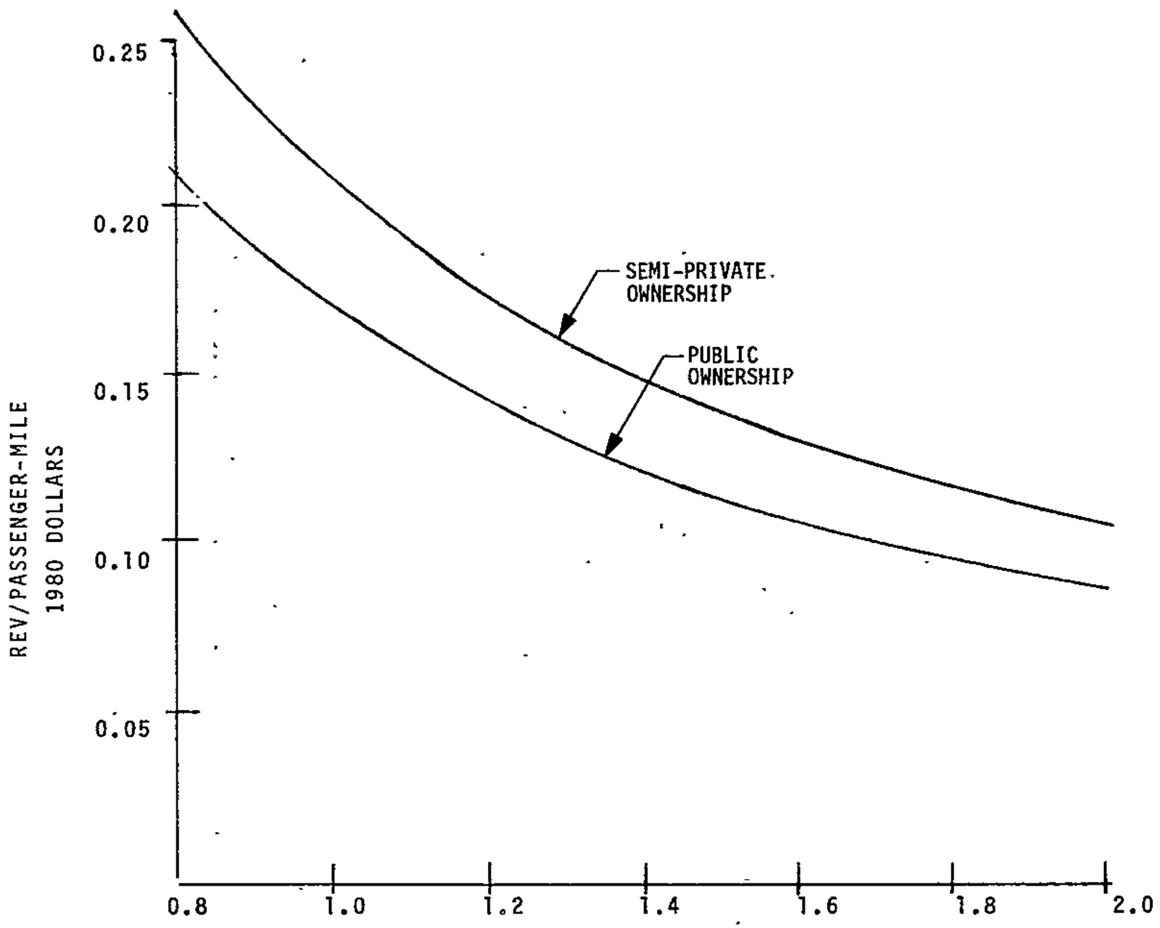


Figure 1-1. Plot of PATH System Rev/Passenger-Mile for a Range of Load Factors and Two Ownership Scenarios

Table 1-5. Nonvehicle Capital Expenditures (in 1980 Dollars × 10^6)

Vehicle	Vehicle-miles	Proportion of Total Vehicle Miles	Associated Amount Of Nonvehicle Capital Cost
Pallets	14000 x 280	55.3%	1179.3
CAPS	11300 x 280	44.7%	953.2
TOTAL	25300 x 280		

The costs related to each vehicle in the PATH system can now be easily evaluated. Each vehicle's capital cost is the sum of the associated nonvehicle costs plus the cost of the vehicle. Operations costs are allocated along the same proportions as capital costs for those operations common to both vehicles. These costs are outlined in Table 1-6 for the entire PATH system.[7]

The figures from Table 1-6 are now evaluated within the framework of the life-cycle cost approach. Associated costs for each vehicle on a life-cycle basis (LCC') are calculated as in Equation (1-1).

$$LCC' = FCR \cdot \frac{CI_{pv}}{CRF_k^N} + OP_{pv} \tag{1-9}$$

These costs are outlined in Table 1-7 below for the PATH system under the two ownership scenarios. Note that the sum of the associated vehicle costs exactly totals the life-cycle costs of the system for both private and public ownership.

As in Section 1.3 for a project to be able to cover all of its costs on a life-cycle basis, the minimum condition which must be satisfied is that the present value of revenues must equal the life-cycle cost ($REV_{pv} = LCC$). Required revenues/passenger-miles are presented in Table 1-8 using Equation (1-7), the cost data from Table 1-7 and the passenger-mile estimates from Section 1.3.

From the data in Table 1-8, it is clear that the REV/passenger/mile in the CAPS case is more sensitive to passenger miles travelled.

As in Section 1.3 of this analysis, passenger-miles can be considered parametric in the load factor. Load factors for each vehicle type, or the entire system, may be varied to determine a range of passenger miles and thus required revenues/passenger-mile.

The second comparison to be considered includes the follow following:

(1) The baseline PATH system described in Table 1-1.

(2) PATH system with driverless CAPS vehicles (similar to AMTVs).

The life-cycle cost for the PATH system has already been calculated. In evaluating the driverless CAPS vehicles scenario, all that need be considered is the additional capital cost of guidance equipment ($1000 each) and lowered operating costs for the removal of CAPS

---

[7] See Appendix C for detailed explanation of vehicle capital costs and operations costs by account.

Table 1-6. Cost Allocation by Vehicle Type 1980 Dollars × 10^6

ASSOCIATED COSTS FOR PALLET SYSTEM		
Capital Costs		
Nonvehicle Cost	1179.3	
Pallet Cost	298.4	
		1477.7
Operations Costs		
Console Maintenance	79.9	
Console Operations	76.2	
Station Operations	60.4	
Pallet Operations	109.2	
General/Administration (Pallet)	147.7	
Vehicle Maintenance (Pallet)	2307.9	
Vehicle Power (Pallet)	703.5	
Guideway Roadbed Maintenance	28.9	
Guideway Power	54.4	
Yard Operations (Pallet)	282.2	
		3850.3
TOTAL COST		5328.0
ASSOCIATED COSTS FOR CAPS SYSTEM		
Capital Costs		
Nonvehicle Cost	953.2	
CAPS Cost	316.6	
		1269.8
Operations Costs		
Console Maintenance	64.6	
Console Operations	61.6	
Station Operations	48.8	
General/Administrative (CAPS)	171.3	
Vehicle Maintenance (CAPS)	334.6	
CAPS Operator Cost	1447.2	
Vehicle Power (CAPS)	51.0	
Guideway Roadbed Maintenance	23.3	
Guideway Power	44.0	
Yard Operations (CAPS)	227.8	
		2474.2
TOTAL COST		3744.0

Table 1-7. Associated Costs on a Life-Cycle Basis by Vehicle Type for the PATH System in 1980 Dollars × 10^9

Vehicle Type	Private Ownership Scenario	Public Ownership Scenario
Pallets	6.526	5.428
CAPS	4.774	3.830
TOTAL SYSTEM	11.300	9.258

Table 1-8. Required Revenues per Passenger-Mile for PATH System Components (1980 Dollars)[8]

Vehicle Type	Passenger-Miles/Year x 10^9	Private Ownership REV/Passenger-Mile	Public Ownership REV/Passenger-Mile
Pallets	7.326	0.149	0.124
CAPS	1.765	0.452	0.362
TOTAL SYSTEM	9.091	0.208	0.170

drivers. Capital costs are increased by \$21.1 × 10^6 and operating costs decreased by \$1447.2 × 10^6 in present value terms. The private ownership cost is:

$$\text{LCC} = 0.18781 \left(\frac{\$2768.5 \times 10^6}{0.10369}\right) + \$4877.3 \times 10^6 = \$9.892 \times 10^9$$

---

[8] See Appendix C for a more detailed breakdown.

[9] The allocation of CAPS driver costs to the guideway portion of the system for the baseline case results from the assumption that ∿30% of the CAPS vehicles on the guideway would be carrying drivers. This 30% was assumed to be composed as follows: 10% from origins/destinations which require only a short guideway travel such that it would be more practical for the driver to remain with the vehicle, 10% from absense of drivers at the CAPS guideway exit, and 10% from the transporting of drivers to locations of need.

Public ownership cost for the PATH system with driverless CAPS vehicles would be:

$$LCC = 0.11069\left(\frac{\$2768.5 \times 10^6}{0.10369}\right) + \$4877.3 \times 10^6 = \$7.833 \times 10^9 .$$

The following table presents the costs per passenger-mile consistent with the above assumptions.

1.4 CONCLUSIONS

Two outputs have been generated by this report. The first is a life-cycle methodology which can be used as a standard to evaluate and compare various transportation system designs. Second, this methodology was exercised to compute costs for the PATH dual-mode transportation system. Modifications to the baseline were those imposed on the system design, and the resultant costs were determined. Additional modifications, including busses on the guideway, are presented in Appendix D.

Additional work is now necessary to improve the input data and reevaluate system costs under the life-cycle cost technique.

Table 1-9. Costs per Passenger-Mile Two-Path System Designs (1980 Dollars) Assuming Constant Ridership

	Private Ownership	Public Ownership
PATH Baseline System	0.208	0.170
Pallets	0.149	0.124
CAPS	0.452	0.362
PATH -- Driverless CAPS	0.182	0.144
Pallets	0.149	0.124
CAPS	0.318	0.318

SECTION 2

ENERGY ANALYSIS

The energy consumption reanalysis was structured as follows: (1) identification and quantification of the vehicles to be included, (2) identification and parameterization of the candidate propulsion options relevant to each vehicle type, (3) sizing of the propulsion system to each of the vehicle types with regard to the performance requirements, (4) development and quantification of a "driving cycle" appropriate to the dual-mode system, (5) simulation of various vehicle-propulsion system configurations in the dual-mode guideway environment to determine the respective energy consumption.

2.1 VEHICLES

Five vehicles were included in the energy analysis:

- Car/Pallet
- Bus (CAPS)
- Bus (CAPS)/Pallet
- Bus (Transit)

A CAPS Bus (the acronym taken from the previous JPL Study) refers to a large van-type small bus of about 7000 lb inertial weight, the transit bus is a standard intracity 52-passenger 25,000 lb inertial weight bus. The first two vehicles are the baseline vehicles of the previous study. The palleted CAPS bus is included to permit the option of palleting a fleet of existing van-sized or dial-a-ride sized buses on a dual-mode system. The large transit buses, while probably not suitable for operation on a lightweight, inexpensive guideway, were examined for the same basic reason as the palleted CAPS buses, and to evaluate what penalties in terms of energy and propulsion system size would be incurred for possible limited use of transit buses on the dual-mode system. The specifications for these vehicles are presented in Table 2-1, where IW is the inertial weight in pounds, C_D is the coefficient of aerodynamic drag (dimensionless), AF is the frontal area in square feet. In all cases the rolling resistance was that of radial-ply rubber tires.

2.2 PROPULSION SYSTEMS

Three candidate propulsion systems were considered:

- Electric traction (DC series)
- Diesel (4 stroke)
- Otto (4 cycle)

Table 2-1. Vehicle Configuration Specifications

Car + Pallet	IW=10250 lb C_D=0.50 A_F=50 ft^2
Car Pallet Alone	IW=5250 lb C_D=0.55 A_F=25 ft^2
CAPS Bus	IW=6940 lb C_D=0.55 A_F=40 ft^2
CAPS Bus + Pallet	IW=17340 lb C_D=0.57 A_F=80 ft^2
CAPS Bus Pallet Alone	IW=10400 lb C_D=0.55 A_F=40 ft^2
Transit Bus	IW=25000 lb C_D=0.55 A_F=75 ft^2
Transit Bus + Pallet	IW=55000 lb C_D=0.57 A_F=150 ft^2
Transit Bus Pallet Alone	IW=30000 lb C_D=0.55 A_F=75 ft^2

These were selected because: (1) they are currently in use in vehicles similar to the dual-mode vehicles considered, and therefore permit energy consumption comparisons to be made readily; (2) being based upon real data, simulation results are more certain than those based upon hypothetical propulsion systems.

The only departure from standard engine configuration is the diesel option, taken to be the Ricardo Diesel mated to a three-speed automatic transmission as opposed to the Detroit Diesel mated to a two-speed transmission. This departure was made because the Ricardo's flater brake specific fuel consumption (BSFC) map and broader power profile makes it considerably more suitable for the dual-mode application.

The specifications for these propulsion systems are presented in Table 2-2. The power profiles and BSFC maps will be found in Appendix F.

Table 2-2. Propulsion System Specification

Electric Traction	D.C. Series
	Chopper Control
	"Generic" Westinghouse Power Profile
	Contact Rail Power
	No Transmission
Diesel	Naturally Aspirated
	Compression ignition
	8 cylinder
	Swirl Chamber 4 Stroke
	Ricardo Power Profile, BSFC Map
	3 SPD Auto Transmission
Otto	Naturally Aspirated
	Spark ignition
	8 Cylinger
	Carburetor
	G-M Power Profile, BSFC Map
	3 SPD Auto Transmission

2.3 PROPULSION SYSTEM SIZING

The size (in horse power) of a propulsion system is determined by the performance requirements the vehicle must satisfy in a specific application. For example, subway train traction motors are sized to meet a total system RMS speed requirement over a given service network; transit buses must meet both starting acceleration, top speed, and grade-hauling requirements. The most stringent performance requirement of the dual-mode system specified in the previous JPL study is an acceleration capability of 2.2 mph/sec at a guideway cruise speed of 60 mph. The requirement results from the attempt to maintain the total system capacity when there exists frequent merge or demerge operations. Without such a capability, space for a merging vehicle could only be created by slowing the vehicle flow, and spaces created by a demerging vehicle could be filled by slowing the leading stream or by a fortuitously merging vehicle.

It should be noted that there exist many other possible headway and control policies which would not require the above acceleration capability. For example, one could choose to merge only into a space previously created by a demerge or resulting from vehicle "bunching" in a low demand situation. For such a control policy the only acceleration requirement would be to reach cruise velocity within the merge ramp length.

The procedure used to "size" the propulsion system was as follows: (1) for each of the vehicle configurations a horsepower and rear axle ratio which seemed likely to satisfy the given performance requirement was chosen; (2) after specifying all the horsepower-dependent motor parameters (moment of inertial, idle fuel flow, etc.), perform a simulation of the vehicle under maximum acceleration at the guideway cruise-velocity; (3) reestimate the horsepower (and rear axle ratio if required) in accordance with the delivered versus the required acceleration; (4) iterate on step 2 and 3 until the performance requirement of 2.2 mph/sec at guideway cruise speed of 60 mph is satisfied.

The results of this analysis are presented in Table 2-3. For the electric traction motors, the stated horsepower represents the "top" of the power profile (i.e. a very short-term rating) so as to be commensurate with the heat engines. To transform it into the RMS system horsepower (i.e. long-term rating) customarily used in describing transit system traction motors, take about 60% of the specified number.

The horsepowers required to meet the specified performance requirement as presented in Table 2-3 are considerably in excess of what is customarily installed in both private and transit vehicles of similar type and size. In particular, for the vehicles which would be directly operated both on and off the guideway (the nonpalleted buses), the engine size is such that they would incur a significant fuel-use penalty in normal off guideway operation.

Table 2-3. Power Requirements for Dual-Mode Vehicles

Vehicle Configuration	Brake Horsepower	Power System Weights in lb		
		Electric	Otto	Diesel
Car/Pallet	300	1800	1400	1600
CAPS Bus	230	NA	1030	NA
CAPS Bus/Pallet	490	2525	NA	2270
Transit Bus	720	3400	3400	3070
Transit Bus/Pallet	1300	6200	NA	4600

2.4 DUAL-MODE DRIVING CYCLE

The energy utilization of a vehicle is dependent upon the velocity versus time profile (driving cycle) over which it is operated. The automated guidance and control, and the dedicated guideway result in a "driving cycle" for a vehicle on the dual-mode system substansively different from what the vehicle would experience on the surface streets or freeway environment. The energy consumption of a vehicle on the dual-mode guideway cannot therefore be accurately or readily inferred from its know energy consumption over, for example, the federal driving cycle.

A driving cycle consistent with the operational policies and the guidance and control systems described in the previous JPL study is defined as follows:

- Dynamic pallet loading at 7 mph
- Smooth acceleration to 60 mph (average - 3.1 mph/sec)
- Five-mile cruise
- Five velocity pertubations induced by other near vehicles executing merge or demerge
- Smooth de-acceleration to 7 mph

This driving cycle represented graphically in Figure 2-1 was coded into the vehicle simulation system and used to analyze the energy consumption of the various dual-mode vehicle and propulsion system configurations.

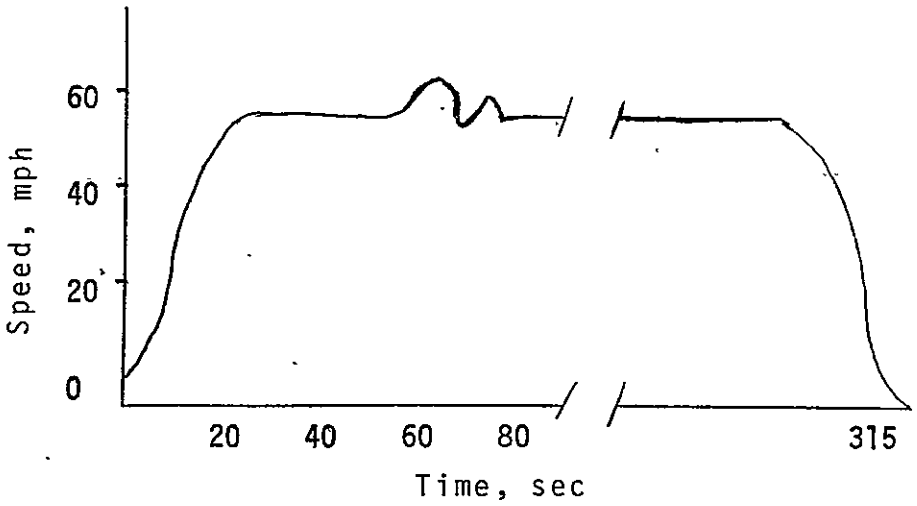


Figure 2-1. Dual-Mode Driving Cycle

2.5 ENERGY CONSUMPTION RESULTS

The following represents the results of the simulations of the operation of the various vehicle and propulsion systems over the dual-mode driving cycle.

The car/pallet system was examined for all three propulsion system options to present a comparison of all the options on one system. All other pallet configurations were simulated for the electric traction option only. The transit bus and the CAPS bus were simulated with their customary propulsion source, diesel and Otto respectively, and also for the electric traction option.

The weighted average for the pallets assumes 80% full load operation and 20% dead heading. The percent split of energy-use does not sum to 100% because of auxiliaries (power steering, brakes) and internal losses (fan, generator, etc.). The mpg equivalent for the electric traction was defined as (mi/kW-hr)/0.0775 = mi/gal. The results do not reflect second-order effects of the increased propulsion system weight or the effect of the resulting weight propagation.

Table 2-4. Energy Consumption Results

CAR/PALLET 2.4.1

Otto Option (300 hp)

	Mile/Gal	Energy Split in % Inertial	Energy Split in % Rolling	Aero	Total Energy (hp-hr)
Fully Loaded	5.48	24.6	23.9	37.1	8.1
Dead Heading	6.26	23.3	23.3	32.9	5.5
Wghted Aver.	5.64				

Diesel Option (320 hp)

	Mile/Gal	Energy Split in % Inertial	Energy Split in % Rolling	Aero	Total Energy (hp-hr)
Fully Loaded	6.57	24.3	23.8	36.9	8.2
Dead Heading	7.89	23.0	23.2	32.0	5.6
Wghted Aver.	6.83				

Electric Traction Option (300 hp)

	Mile/kWhr		Energy Split in % Inertial	Energy Split in % Rolling	Aero	Total Energy (hp-hr)
Fully Loaded	0.81	10.45	28.8	26.7	41.8	6.3
Dead Heading	1.34	17.29	30.3	27.3	37.9	3.7
Wghted Aver.	0.92	11.82				

Table 2-4. Energy Consumption Results (Continuation 1)

CAPS BUS 2.4.2

Otto Option (230 hp)

Mile/Gal	Energy Split in % Inertial	Rolling	Aero	Total Energy (hp-hr)
7.53	19.8	19.2	35.3	7.00

Electric Traction Option (230 hp)

Mile/KwHr	Mile/Gal	Energy Split in % Inertial	Rolling	Aero	Total Energy (hp-hr)
1.06	13.68	22.3	20.8	42.4	5.34

CAPS BUS/PALLET 2.4.3

Electric Traction Option (490 hp)

	Mile/kWhr	Mile/Gal	Energy Split in % Inertial	Rolling	Aero	Total Energy (hp-hr)
Fully Loaded	0.48	6.19	27.5	25.6	44.7	10.7
Dead Heading	0.85	10.97	30.1	27.4	38.7	6.1
Wghted Aver.	0.55	7.15				

TRANSIT BUS 2.4.4

Diesel Option (730 hp)

Mile/Gal	Energy Split in % Inertial	Rolling	Aero	Total Energy (hp-hr)
3.09	28.4	28.8	29.3	16.7

Table 2-4. Energy Consumption Results (Continuation 2)

Electric Traction Option (730 hp)

Mile/kWhr	Mile/Gal	Energy Split in %			Total Energy (hp-hr)
		Inertial	Rolling	Aero	
0.40	5.16	32.8	31.7	32.3	12.6

TRANSIT BUS/PALLET 2.4.5

Electric Traction Option (1300 hp)

	Mile/kWhr	Mile/Gal	Energy Split in %			Total Energy (hp-hr)
			Inertial	Rolling	Aero	
Fully Loaded	0.19	2.45	33.7	31.4	32.5	27.7
Dead Heading	0.34	4.39	35.0	31.9	29.1	15.0
Wghted Aver.	0.22	2.84				

2.6 CONCLUSIONS

- The dual-mode control policy is a primary determinate of the size of the propulsion system. Policies such as considered in this study result in a relatively high energy consumption per vehicle mile directly for heat-engines because of the nonuniform efficiency across the BSFC maps and indirectly for all engines because of the increased weight of the propulsion systems.
- Nonpallet dual-mode vehicles which meet the performance requirements used in this study would not be competitive in the sense of energy efficiency with equivalent standard vehicles in off-guideway operation.
- Electric traction is more energy efficient than Otto or diesel for the dual-mode pallets.
- Large (52 passenger) transit buses do not appear to be viable candidate for dual-mode operation either with or without pallets because of both propulsion system size and energy efficiency.

APPENDIX A

THE VEHICLE SIMULATION PROGRAM

The Energy utilization of the various dual-mode vehicle and propulsion system configuration was analyzed by the use of the vehicle simulation program called VEEP (for Vehicle Energy and Emissions Program) previously developed by JPL for the analysis of alternate automotive engines[1]. Being a general purpose vehicle simulator it was possible to adapt it for the analysis of the dual-mode vehicles, both for sizing of the propulsion systems and for the evaluation of energy consumption in guideway operations. The adaptation was done at the input data level with no changes required in the program structure or code.

As implied in the name, VEEP was originally intended to calculate emissions as well as fuel economy. Engine transients are a major contributor to emissions, and our calculations confirmed that, especially for intermittent-combustion engines, emission indices based on steady-state measurements are not adequate for simulating total emissions over a driving cycle. For continuous-combustion engines, an indication of the trend of emissions with vehicle weight can be obtained.

Program Description

Briefly, VEEP breaks up each driving cycle into 1-sec increments, calculates the power required and numerous other quantities for each second, and then sums these over the cycle or any designated segments thereof. The EPA Urban and Highway cycles are stored as part of the program, but any desired driving cycle may be input as a velocity-time profile. When the velocity-time profile is not given every second, the program interpolates linearly between the given points. Constant-speed and 0=60 mph acceleration capability is also incorporated.

For clarity of organization and ease of "debugging" and modification, VEEP consists of 14 subroutines. The primary one (Drive) calls the others, such as TRANS, which determines the appropriate gear ratio, transmission efficiency, and engine speed, VEEMAX, which calculates the vehicle maximum speed as well as a reference velocity for gear-shifting in TRANS: POWACC, for accessory power consumption; and FDCDATA, which contains the federal driving cycle information. The program is written in FORTRAN V.

Program Logic

For an illustration of the computation process, let us follow through the major steps for a typical second in a driving cycle. Engine and vehicle characteristics are evaluated at conditions corresponding to the midpoint of each second; since the maximum

---

[1] This section was adapted directly from Volume II, Chapter 10 of the JPL Report: "Should We Have A New Engine?", An Automobile Power Systems Evaluation, Aug. 1975.

acceleration during the EPA driving cycles is only 3.3 mph/sec, this is a negligible cause of error.

The acceleration is the difference of the next and previous car velocity; let us assume now that it is positive. The power required for rolling friction, aerodynamic drag and vehicle acceleration are added and, allowing for rear axle efficiency give the required power out of the transmission. From this and vehicle speed, the proper gear ratio, engine speed and transmission efficiency are computed. From the latter, the required transmission input power is found and added to the engine acceleration (inertial) power and accessory power to give the total power the engine must produce.

This total is compared to the maximum power the engine can produce at that engine speed by interpolating on the engine boundary map. If the total is less than this maximum, this second of the driving cycle is satisfied and, after calculating all the quantities of interest such as brake specific fuel consumption (BSFC), emissions, energies, etc., the program can go on to the next second.

If the total power exceeds the available maximum, the acceleration is adjusted until the power match and the insufficient acceleration are noted. The number of times this happens during the driving cycle is divided by the total driving cycle duration and printed on the output page as Percent Slow. The next second then uses the actual velocity reached at the end of the previous second as its initial point and proceeds as before.

This latter feature underlines the 0-60 mph acceleration mode: The vehicle is commanded to reach 75 mph in 1 sec. Each second it accelerates at its maximum rate from the previous second's terminal velocity. After the vehicle surpasses 60 mph, the acceleration is terminated and the last second's results ratioed to the mph point. The distance reached at the 10-sec point is also retained and printed out.

The program can simulate either normal road operation (road load) or operation on the EPA-prescribed dynamometer (dyno load). On the road, rolling friction and aerodynamic drag determine the total steady-speed propulsion power, which is given (in hp) by

$$P_T = 2.667 \times 10^{-3} C_R (W_C + 300) V + 6.676 \times 10^{-6} C_D A_F V^3$$

where

C_R = rolling resistance coefficient

W_C = curb weight, lb

V = velocity, mph

C_D = aerodynamic drag coefficient

A_F = frontal area, ft^2

The second-by-second simulation employed in the VEEP program is inherently more accurate than the practice of approximating a driving cycle by groups of steady-velocity and constant-acceleration segments, as sometimes done in an attempt to keep computer programs simple. The EPA driving cycles have many small, sharp speed variations which require deliberate driver action to follow on a dynamometer test and must not be averaged away. In fact, it may be argued that a second-by-second simulation is almost too severe in that it requires complete and exact velocity matching at each second, whereas the actual driver of the dynamometer car typically varies fractions of both mph and seconds from the prescribed trace, which may result in a slight smoothing effect. Experience with VEEP indicates the present second-by-second simulation yields consistent and numerically reliable results.

Program Inputs

Perhaps the most critical area of a simulation program is the quality of the input data. The results can at best be only as good as the accuracy of the underlying parameters, and a considerable effort was made in gathering the information required for the vehicle characterization. Multiple sources were sought in all cases to minimize aberrations in the data. While not intended to be comprehensive, a description of the important input quantities is given in this section.

The major sources of power dissipation are rolling friction, aerodynamic drag, transmission losses and engine-powered accessories. Tire rolling resistance is described by a fourth-order polynomial plus expotential term best-fit to the average of three tire manufacturer's rolling resistance coefficient curves as a function of velocity for bias-ply, belted-bias and radial-ply tires.

Tire sizes suitable to each vehicle size were established; they provide the values for wheel-tire moment of inertia, which affects the acceleration power of the vehicle, and rolling diameter, which enters into the rpm vs mph relationship, or over all "gearing." Radial construction tires were presumed in all cases.

The three-speed automatic transmission with torque converter is used in most of our simulations. The torque ratio, speed ratio, and efficiency of the torque converter as a function of output rpm and power, and gearbox efficiencies in each gear are incorporated in the VEEP program. Data were similarly developed for the four-speed manual transmission with clutch. Gear ratios are typical values derived from the nearly identical ratios employed by the three major U.S. manufacturers in the first case and from averaging eight small and subcompact car sets of ratios for the manual gearbox.

Rear axle ratio is generally changed from the baseline vehicle value only when the engine peak rpm differs from that of the original engine, and then by their ratio. Thus the alternate engines are operating in the same portion of their speed range as the Otto engine. As mentioned earlier, with current Otto-engined cars, changing the rear axle ratio (within 10-20% of the usual value) and adjusting the engine horsepower for equal performance gives little fuel economy change. Some spot checks indicated that this is also true for the alternate-engined cars; so the exact choice of final-drive ratio is not critical to the results of the simulation. Rear axle efficiency was taken as a constant 96%.

Auxiliaries and accessories can represent a sizable power absorption. For use in the VEEP program, representative data were used to establish horsepower variation with engine rpm for current cars with V-8 engines. Auxiliaries, defined as components essential to engine functioning, are usually included in the basic engine operating map except for the radiator cooling fan in some cases. The fan is then applied as a separate load with the proper multiplier for that engine (relative to the Otto engine). The power steering pump losses assume straight-ahead driving, and alternator power demand is based on a partial charging rate. Some of the continuous-combustion alternate engines require air supply blowers for their burners, which would increase the load on the electrical system. The effect should not be large, and no explicit allowance was made in the alternator power absorption.

The curve for the air conditioning compressor is based on high-load operation. Under EPA dyno load simulation, the air conditioner is turned off and is represented by a rather small (10%) increase in the dynamometer dissipation setting. For road load, the compressor power has been multiplied by a factor of 0.2 to arrive at a roughly average power, considering the unit is not always working at high load and is not turned on at all much of the time.

The fan loss is assumed to vary linearly with engine power for both the baseline and alternate engines. The other auxiliary and accessory loads are taken to vary as the 3/4-power of engine horsepower, since they are correlated more nearly with vehicle size and weight than engine size.

The engine brake specific fuel consumption (BSFC) matrix was generated for each engine type from available engine maps. Such maps are typically very poorly defined in the low-power region which, however, is extremely important to the accuracy of the simulation, since much of the engine operation during the federal driving cycle is in this region. Contours in this area were established by fairing the zero-net-power ("idle") fuel flow at all engine speeds smoothly into the given data in the upper protion of the map.

The abscissa and ordinate of the BSFC map were nondimensionalized so that the resulting percent speed vs percent power matrix is applicable to all engine sizes. To include the efficiency improvements of the mature and advanced engines, the fuel consumption modification factor multiplies all values in the VSFC matrix by that constant. This factor also permits inclusion of the efficiency penalty for small gas turbines without using a different BSFC map.

APPENDIX B

LIFE-CYCLE COST METHOD

This appendix describes the capital budgeting technique of life-cycle costing[1]. The life-cycle cost is defined as the present value, as of a specified time, of all the costs included in purchasing, installing and operating a particular system. The present value operation thus "collapses" a distribution of cash flows over the project lifetime into a single number. System resultant life-cycle costs are then combined with demand assumptions and the revenue required per passenger-mile can be calculated. The revenue required reflects the charge necessary to recover all system costs and financial obligations, including taxes, interest, and a specified return to equity holders for a private operating property. Figure A-1 illustrates this procedure. Adjusted annual system ridership refers to all non-LCC components in Equations (1-7) and (1-8). Revenue required per passenger-mile is the value used for comparisons of alternate or component systems in the main text.

This section describes the financial considerations involved in life-cycle costing.

- Reference Periods

Costs are input in 1970 current dollars as per the Pallet Augmented Transit Hybrid (PATH) document figures. Costs in present value terms are expressed in year of commercial operation (1980) current dollars.

- Discount Rate (k)

Cost of capital is used as a proxy for the discount rate, which reflects the opportunity cost of investment. For the PATH system, a 10% discount rate was assumed for both the private and public ownership scenarios.

- Capital Recovery Factor (CRF)

This represents the uniform annual payment, as a fraction of the original principal, necessary to fully amortize a loan over a specified period. The discount rate (k) is used as the interest rate and the system lifetime (N) is used as the amortization period. The standard formula for the capital recovery factor (CRF) is:

---

[1] Much of the description of the life-cycle cost methodology is from "The Cost of Energy From Utility-Owned Solar Electric Systems," J. W. Doane, et al, JPL Document 5040-29 Jet Propulsion Laboratory, June 1976.

$$\mathrm{CRF}_k^N = \frac{k}{1 - (1 + k) - N}$$

The CRF is used to compute the annualized fixed charge rate and to annualize the present values of recurrent costs.

- Fixed Charge Rate (FCR)

This is an annualized ratio which describes an operating property's economic characteristics as related to capital investment. When the fixed charge rate (FCR) is multiplied by the present value of capital investment ($\mathrm{CI}_{\mathrm{pv}}$), the result is the entire contribution of capital costs, income taxes, insurance, property taxes, depreciation, etc., to the annualized system cost. It is computed as

$$\mathrm{FCR} = \frac{1}{1-\tau}\left(\mathrm{CRF}_k^N - \frac{\tau}{N}\right) + \beta$$

where

τ = income tax rate

N = system lifetime

β = nonincome taxes, insurance premiums and licensing fees.

In the case of public ownership, $\tau = 0$ and

$$\mathrm{FCR} = \mathrm{CRF}_{k'}^N + \beta'$$

as described in Section 1.2 of text.

- Present Value of Capital Investment ($\mathrm{CI}_{\mathrm{pv}}$)

The present value of capital investment expenditures ($\mathrm{CI}_{\mathrm{pv}}$) summarizes the total investment in the transportation system. All investment outlays are normalized to express their significance as of the end of the year of first commercial operation, 1980. This normalization adjusts for escalation of costs between the year of expenditure and the 1970 cost input year, and an adjustment for compound interest and discounting. This cost can be evaluated as

$$CI_{pv} = (1 + g)^p \sum_t \left[CI_t \left(\frac{1 + g}{1 + k} \right)^j \right]$$

where

g = escalation rate

k = discount rate

p = year of first commercial operation (1980) minus cost input year (1970)

j = year of capital outlay (year t) minus year of first commercial operation

t = year of capital outlay subscript

Since expenditures have an uneven distribution, the summation operation adds each year's expenditures separately to compute CI_{pv} in 1980 current dollars.

- Present Values of Recurrent Operating Costs (OP_{pv})

When a system has varying annual costs, such as when it is only partially completed and requires incremental expenditures each year, annual costs must be computed separately as in the capital investment case. However, when a system's recurrent operating costs are a constant stream in nominal base year dollars, the following equation sums the cost stream.

$$X_{pv} = \begin{cases} (1 + g)^P \; X_o \left(\frac{1 + k}{k - g} \right) \left(1 - \frac{1 + g}{1 + k} N \right) & \text{if } k \neq g \\ (1 + g)^P \; X_o \cdot N & \text{if } k = g \end{cases}$$

where

X_{pv} = present value of cost in year of first commercial operation dollars

X_o = annual cost in cost input year dollars

P = year cf first commercial operation minus year of cost input

The constant (uniform) stream of costs over the system life can be interpreted in two senses:

(i) Outlays constant in real terms, growing in dollar amount at the constant rate of escalation.

(ii) Outlays growing at a constant rate in real terms, and thus growing in dollar amount at a larger rate which equals the sum of the constant escalation rate and the rate of real growth.

In the methodology outlined in the text, the first of these interpretations has been employed. Escalation as defined here is the sum of escalation rate and real growth.

- Life-Cycle Cost (LCC)

This is the sum of all system costs on a present value basis and is found as follows

$$LCC = FCR \cdot \frac{CI_{pv}}{CRF} + OP_{pv}$$

If it is desired to convert this to cost input year dollars, or any year t dollars, the life-cycle cost is

$$LCC = (1 + g)^{-d} \left[FCR \cdot \frac{CI_{pv}}{CRF} + OP_{pv} \right] .$$

where

d = year of commercial operation minus year t

- Required Revenue per Passenger-Mile (REV)

This is the value which will be used to compare alternative transportation systems. The value is in year of commercial operation dollars as presented in the text. It represents the constant amount of revenues required to cover the present value of system costs. If annual demand varies, Equation (1-7) applies such that

$$\text{REV/passenger-mile} = \frac{\text{LCC}}{\sum_{t=1}^{N} \text{PM}_t \, (1 + k)^{-t + 1}} .$$

If annual demand is constant,

$$\text{REV/passenger-mile} = \frac{\text{LCC} \times \text{CRF}}{\overline{\text{PM}}} .$$

- Timeframes

When comparing alternative systems with this methodology, it is important to have the same year of commercial operation for cost comparisons and the same operating lifetimes. In the text, an adjustment had to be made for varying vehicle lifetimes by using replacement vehicles.

- Insurance

Insurance for PATH can be thought of in two ways. There is a system insurance for capital items which should be based upon capital cost. In addition, there is liability insurance which is properly determined as a function of passenger-miles. In this analysis only the insurance for capital items will be considered; liability insurance is assumed to be a part of a general liability policy. Therefore, insurance is included as a part of the fixed charge rate.

APPENDIX C

DETAILED COST CALCULATIONS

This appendix details many of the results outlined in the text.

Table C-1, lists the present value calculation for the baseline PATH system expenditures. Table C-2 presents the vehicle capital costs for the system. The PATH system operating costs are evaluated in present value terms in Table C-3.

In Section 1-2, some assumptions about demand for the PATH system were made. Pallets and CAPS vehicles figures were taken from the referenced document.

The driverless CAPS vehicles require \$1000 in guidance equipment per vehicle (same as auto). The present value of CAPS vehicles costing \$15,000 without guidance is $\$316.61 \times 10^6$. An additional \$1000 per vehicle capital cost would translate to

$$1/15\ (\$316.61 \times 10^6) = \$21.1 \times 10^6$$

in present value terms. Total capital cost is then $\$2768.5 \times 10^6$ for this system. The savings for operation would be $\$1447.2 \times 10^6$ since CAPS operators are replaced by guidance systems. Operating costs now become $\$4877.3 \times 10^6$.

Table C-1. Present Value of Baseline PATH System Capital Expenditures[a]

YEAR	CAPITAL INVESTMENT (CI_t) (nominal 1970 dollars x 10^6)	PRESENT VALUE (1980 dollars x 10^6)
1977	61.6	115.37
1979	306.1	522.35
1980	6.1	9.94
1982	579.5	860.08
1985	54.4	70.22
1986	793.7	977.98
1989	78.6	84.23
1995	6.1	4.94
1997	30.3	22.38
2000	54.4	34.95
2004	78.6	41.92
2010	2.0	0.81
2012	6.1	2.24
TOTAL	$\$2.0575 \times 10^9$	$\$2.7474\ 1 \times 10^9$

---

[a] As in Appendix A, capital investment (CI_{pv}) is calculated as follows:

$$CI_{pv} = (1+g)^{1980-1970} \sum_{t=1}^{N} CI_t \left(\frac{1+g}{1+k}\right)^{y_t - 1980}$$

$$= (1.05)^{10} \sum_{t=1}^{N} CI_t \left(\frac{1.05}{1.10}\right)^{y_t - 1980}$$

$$= (1.6289) \sum_{t=1}^{N} CI_t \, (0.954545)^{y_t - 1980}$$

Table C-2. Vehicle Capital Costs for Baseline PATH System
Present Value 1980 Dollars × 10^6

PALLETS		CAPS	
1977	$ 14.23	1980	$ 9.94
1979	64.16	1982	44.97
1982	100.04	1985	70.22
1986	120.01	1989	84.23
	$298.44	1995	4.95
		1997	22.38
		2000	34.95
		2004	41.92
		2010	0.81
		2012	2.24
			$316.61

Table C-3. PATH System Operations Costs Present Value 1980 Dollars × 10^6

Operation	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990-2014	TOTAL
Console Maintenance	0.420	0.401	2.287	2.183	2.084	4.959	4.734	4.519	4.313	7.682	110.899	144.481
Console Operations	0.401	0.383	2.180	2.081	1.986	4.727	4.512	4.307	4.111	7.322	105.699	137.709
Station Operations	0.318	0.304	1.729	1.650	1.575	3.750	3.579	3.417	3.261	5.808	83.854	109.245
Pallet Operations	0.318	0.304	1.729	1.650	1.575	3.750	3.579	3.417	3.261	5.808	83.854	109.245
Gen. & Admin. (Pallets)	0.430	0.410	2.339	2.233	2.131	5.072	4.841	4.621	4.411	7.855	113.404	147.747
Gen. & Admin. (CAPS)	0.498	0.475	2.713	2.590	2.472	5.881	5.614	5.359	5.115	9.109	131.506	171.332
Vehicle Maint. (Pallets)	6.714	6.409	36.538	34.877	33.292	79.222	75.621	72.184	68.903	122.707	1771.463	2307.930
Vehicle Maint. (CAPS)	0.974	0.930	5.297	5.056	4.826	11.486	10.964	10.466	9.990	17.790	256.824	334.603
CAPS Operators	4.211	4.020	22.911	21.870	20.875	49.678	47.420	45.265	43.207	76.946	1110.838	1447.241
Vehicle Power (CAPS)	0.148	0.141	0.807	0.770	0.735	1.750	1.671	1.595	1.522	2.711	39.142	50.992
Vehicle Power (Pallets)	2.046	1.953	11.137	10.631	10.148	24.147	23.049	22.001	21.001	37.401	529.948	703.462
Guideway Roadbed Maint.	0.151	0.144	0.827	0.789	0.754	1.792	1.710	1.633	1.558	2.776	40.071	52.205
Guideway Power	0.287	0.274	1.557	1.486	1.419	3.377	3.223	3.077	2.937	5.230	75.500	98.367
Yard Operations (Pallets)	0.821	0.784	4.467	4.264	4.070	9.687	9.246	8.826	8.425	15.003	216.598	282.191
Yard Operations (CAPS)	0.663	0.633	3.607	3.443	3.287	7.819	7.463	7.124	6.800	12.110	174.825	227.774
Totals	18.398	17.561	100.123	95.573	91.228	217.093	207.229	197.809	188.826	336.260	4854.425	6324.524

APPENDIX D

COST EFFECTS OF DUAL-MODE TRANSIT BUSSES

This appendix evaluates a modified PATH system where standard 52-passenger busses are allowed on the guideways. Two variations are considered: busses with guidance equipment and busses on pallets are added to the configuration while the remainder of the PATH system remains unchanged. There are 700 busses at full operation with a baseline occupancy of 26 passengers/bus. A 15-yr vehicle life-time is assumed before replacement must occur.

In nominal 1970 dollars, busses with guidance equipment are allocated according to the implementation schedule in Table 1-1. Replacements are bought every 15 yr as required and illustrated below in Table D-1.

Operations costs for the busses with the guidance equipment using the same implementation schedule, have the following annual costs in 1970 dollars.

1980 - 1981	\$ 3.0 × 10^3
1982 - 1984	\$15.0 × 10^3
1985 - 1988	\$38.0 × 10^3
1989 - 2014	\$70.0 × 10^3

The present value of these expenditures in 1980 dollars is \$69.09 × 10^6 for the busses and replacements, and \$1.415 × 10^6 for

Table D-1. Bus Acquisition Schedule Nominal 1970 Dollars × 10^6

YEAR	1980	1982	1985	1989	1995	1997	2000	2004	2010	2012	Total
NUMBER OF BUSSES	25	125	225	325	25*	125*	225*	325*	25*/3	125*/5	700
CAPITAL EXPENDITURES	1.3	6.6	11.9	17.2	1.3	6.6	11.9	17.2	0.4	1.3	75.7

*Replacement Vehicles

operations and maintenance on the busses. Using these figures and the data from Section 1.2, the modified PATH system costs are:

$$CI_{pv} = \$2.8165 \times 10^9$$

$$OP_{pv} = \$6.3259 \times 10^9$$

The life-cycle cost (LCC) for the private operating property is evaluated by combining Equations (1-1) and (1-2). System inputs are:

$$CRF^{35}_{0.10} = 0.10369$$

$$\tau = 0.50$$

$$N = 35$$

$$\beta = 0.009$$

where reflects 0.007 in insurance payments and 0.002 in property and other taxes. Life-cycle cost thus equals:

$$LCC = \left[\frac{1}{1 - (0.5)}\left(0.10369 - \frac{0.5}{35}\right) + 0.009\right]\frac{\$2.8165 \times 10^9}{0.10369}$$

$$+ \$6.3259 \times 10^9$$

$$= 0.18781\ (\$2.71627 \times 10^{10}) + \$6.3259 \times 10^9$$

$$LCC = \$11.427 \times 10^9$$

The cost of this system to a public institution is found by inserting Equation (1-3) into Equation (1-1) such that

$$LCC = (CRF + \beta')\frac{CI_{pv}}{CRF} + OP_{pv}$$

where

$$CI_{pv} = \$2.8165 \times 10^9$$

$$OP_{pv} = \$6.3259 \times 10^9$$

$$CRF_{0.10}^{35} = 0.10369$$

$$\beta' = 0.007 .$$

The life-cycle cost calculation is:

$$LCC = (0.10369 + 0.007)\ \frac{\$2.8165 \times 10^9}{0.10369} + \$6.3259 \times 10^9$$

$$LCC = \$9.333 \times 10^9$$

To evaluate required-revenues per passenger-mile ($\overline{C}$) the additional passenger-miles attributable to the bus system must be calculated. Demand for busses was computed in the same manner as in the referenced document, using the product of average vehicle speed; yearly time system is in operation, number of vehicles, vehicle baseline occupancy, and load factor ratio. The baseline bus demand when the system is completely operational is thus computed to be

$$\frac{53\ \text{mi}}{\text{hr}} \times \frac{12\ \text{hr}}{\text{day}} \times \frac{250\ \text{days}}{\text{yr}} \times 700\ \text{busses} \times \frac{26\ \text{passengers}}{\text{bus}} \times 1$$

$$= 2.894 \times 10^9\ \text{passenger-miles/year}$$

When this is added to the fully operational demand for pallets and CAPS vehicles, the total is 11.985×10^9 passenger-miles/year. This analysis has assumed an incremental demand paralleling the capital allocation schedule.

Therefore, Equation (1-7) of the text must be used to evaluate ($\overline{C}$) where

$$\overline{C} = \frac{LCC}{\sum_{t=1}^{N} PM_t\ (1 + k)^{-t+1}}$$

The demoninator of the right-hand side in passenger-miles × 10^9 is computed for the bus-included system yielding

Vehicle Type	$\sum_{t=1}^{N} PM_t \; (1+k)^{-t+1}$
Pallet	43.861
CAPS	10.568
Bus	17.324
Total PATH System	71.752

for the baseline demand of 11.985 × 10^9 passenger-miles per year and assuming a load factor ratio equal to "1". Required revenues per passenger-mile can now be evaluated for both ownership scenarios. The load factor ratio for the modified PATH system is varied parametrically from 0.8 to 2.0. The implied charges are presented in Table D-2 and illustrated in Figure D-1.

The PATH system just described is now disaggregated into its component parts, pallets, CAPS vehicles and busses. Costs associated with each vehicle type are compared on a required-revenue basis.

Capital costs for the PATH system with busses are divided into vehicle and nonvehicle expenditures as in Section 1.3. Nonvehicle capital costs are assumed constant at \$2.1325 × 10^9 in 1980 present value terms. This cost is allocated as a percentage of vehicle-miles as in Table D-3 below.

Each vehicle's associated costs are now compiled. Respective vehicle costs are added to the capital expenditures outlined in Table D-2. Operations costs are assumed equivalent to the operations costs in the main text. For those operations activities shared by all vehicles, costs are distributed according to the same schedule as capital costs. Table D-4 contains a complete presentation of costs associated to each vehicle.

Life-cycle costs associated with each vehicle (LCC') are evaluated as in Equation (1-1). These costs, assuming two ownership scenarios, are shown in Table D-5. As in Section 1.3, the sum of the associated vehicle costs exactly totals the life-cycle costs of the system for both private and public ownership.

Required-revenues per passenger-mile can now be computed using Equation (1-7), the baseline demand data in the text table in this appendix and associated costs from Table D-5. The results are presented in Table D-6. If a range of load factor ratios were desired, an analysis similar to that in Table 1-8 could be evaluated.

Table D-2. PATH System Required Revenue (REV) per Passenger-Mile in 1980 Dollars Assuming Private and Public Operating Property Ownership. Baseline Demand is 11.985 × 10^9 Passenger-Miles/Year When Fully Operational

LOAD FACTOR	ANNUAL 1989 DEMAND PASS-MI x 10^9	PRIVATE OWNERSHIP LIFE-CYCLE COST $ x 10^9	PRIVATE OWNERSHIP REV/PASS-MI	PUBLIC OWNERSHIP LIFE-CYCLE COST $ x 10^9	PUBLIC OWNERSHIP REV/PASS-MI
0.8	9.588	11.563	$0.201	9.333	$0.162
1.0	11.985	11.563	$0.161	9.333	$0.130
1.2	14.382	11.563	$0.134	9.333	$0.108
1.4	16.779	11.563	$0.115	9.333	$0.093
1.6	19.76	11.563	$0.101	9.333	$0.081
1.8	21.573	11.563	$0.089	9.333	$0.072
2.0	23.970	11.563	$0.081	9.333	$0.065

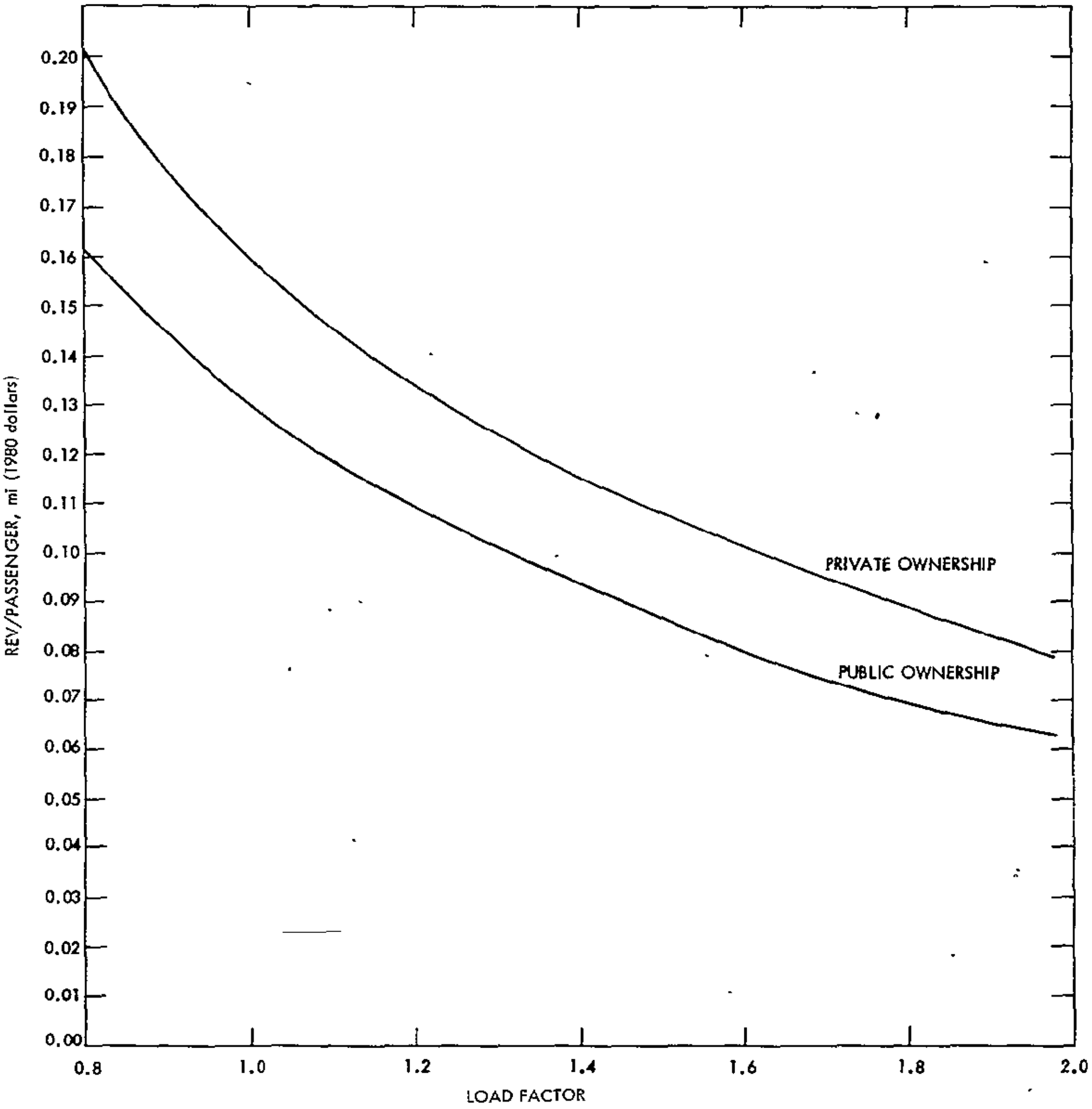


Figure D-1. Plot of PATH System REV/Passenger-Mile for a Range of Load Factors and Two Ownership Scenarios

Table D-3. Nonvehicle Capital Expenditures Present Value 1980 Dollars × 10^6

Vehicle	Vehicle-Miles	Proportion of Total Vehicle Miles	Associated Amount of Nonvehicle Capital Cost
Pallets	14000 x 280	54%	\$1151.5
CAPS	11300 x 280	43%	\$ 917.0
Busses	700 x 280	3%	\$ 64.0
TOTAL	26000 x 280		

The next comparison includes the following:

(1) The baseline PATH system described in Table 1-1

(2) PATH System with busses having guidance systems

(3) PATH System with busses on pallets

(4) Baseline system with driverless CAPS vehicles

The life-cycle cost for items (1), (2) and (4) has already been calculated. Cost for the PATH system with busses on pallets is evaluated starting with the cost of the baseline system. Added to that is the cost of 700 bus pallets at \$75,000 each. These become a part of the system according to the implementation schedule in Table 1-1. Table D-7 computes the present value of additional bus pallets.

The busses travelling on pallets differ from those considered at the beginning of this appendix in that no guidance system is required. This saves \$3000 per vehicle yielding the following net capital cost increase.

Bus guidance savings = \$3000/bus

Bus costs \$53,000 - \$3,000 = \$50,000

Total bus vehicle cost with guidance equipment - \$69.09 × 10^6

Table D-4. Cost Allocation by Vehicle Type
1980 Dollars x 10^6

ASSOCIATED COSTS FOR PALLET SYSTEM		
Capital Costs		
Nonvehicle Cost	1151.5	
Pallet Cost	298.4	$1449.9
Operations Costs		
Console Maintenance	78.0	
Console Operations	74.4	
Station Operations	59.0	
Pallet Operations	109.2	
General/Administrative (Pallet)	147.7	
Vehicle Maintenance (Pallet)	2307.9	
Vehicle Power (Pallet)	703.5	
Guideway Roadbed Maintenance	28.2	
Guideway Power	53.1	
Yard Operations (Pallet)	282.2	$3843.2
TOTAL COST		$5293.1
ASSOCIATED COSTS FOR CAPS SYSTEM		
Capital Costs		
Nonvehicle Cost	917.0	
CAPS Cost	316.6	$1233.6
Operations Costs		
Console Maintenance	62.1	
Console Operations	59.2	
Station Operations	47.0	
General Administrative (CAPS)	171.3	
Vehicle Maintenance (CAPS)	334.6	
CAPS Operator Cost	1447.2	
Vehicle Power (CAPS)	51.0	
Guideway Roadbed Maintenance	22.4	
Guideway Power	42.3	
Yard Operations	227.8	$2464.9
TOTAL COST		$3698.5
ASSOCIATED COSTS FOR BUSSES WITH GUIDANCE SYSTEMS		
Capital Costs		
Nonvehicle Cost	64.0	
Bus Cost	69.1	$ 133.1
Operations Cost		
Console Maintenance	4.3	
Console Operations	4.1	
Station Operations	3.3	
Guideway Roadbed Maintenance	1.6	
Guideway Power	3.0	
Bus Guidance Maintenance	1.4	$ 17.7
TOTAL COST		$ 150.8

Table D-5. Associated Costs on a Life-Cycle Basis by Vehicle Type for the PATH System in 1980 Dollars × 10^9

Vehicle Type	Private Ownership Scenario	Public Ownership Scenario
Pallets	6.539	5.391
CAPS	4.759	3.782
Busses	0.265	0.160
TOTAL SYSTEM	11.563	9.333

Table D-6. Required Revenues per Passenger-Mile for PATH System Components (1980 Dollars)

Vehicle Type	Passenger-Miles/Year x 10^9	Private Ownership REV/Passenger-Mile	Public Ownership REV/Passenger-Mile
Pallets	7.326	0.149	0.123
CAPS	1.765	0.450	0.358
Busses	2.894	0.015	0.009
TOTAL SYSTEM	11.985	0.161	0.130

Guidance equipment savings is

$$\left(\frac{3000}{53{,}000}\right) (\$69.09 \times 10^6) = \$3.91 \times 10^6$$

Net additional capital cost is

$$\$74.59 \times 10^6 - \$3.91 \times 10^6 = \$70.68 \times 10^6$$

In addition, operating cost savings are $\$1.42 \times 10^6$ from guidance equipment not maintained.

Table D-7. Additional Capital Cost for PATH System with Busses on Pallets

Bus Pallets Cost $75,000 Each (1970 Dollars)

YEAR	QUANTITY	NOMINAL 1970 COST x 10^6	PRESENT VALUE 1980 DOLLARS x 10^6
1977	25	$ 1.875	$ 3.512
1979	125	9.275	15.998
1982	225	16.875	25.046
1986	325	24.375	30.034
			$ 74.59

Capital cost for this system totals

$\$2816.5 \times 10^6$	(Baseline PATH system with busses)
$+\ 70.7 \times 10^6$	(Bus pallets and no guidance equipment)
$\$2887.2 \times 10^6$	

Operating costs are

$\$6325.9 \times 10^6$	(Baseline PATH system with busses)
$-\ 1.4 \times 10^6$	(Guidance equipment not maintained)
$\$6324.5 \times 10^6$	

under private operating property ownership, the life-cycle cost (LCC) for PATH with busses on pallets is:

$$\text{LCC} = 0.18781 \left(\frac{\$2887.2 \times 10^6}{0.10369} \right) + \$6324.5 \times 10^6 = \$11.554$$

For public operating property ownership, the life-cycle cost for busses on pallets is:

$$\text{LCC} = 0.11069 \left(\frac{\$2887.2 \times 10^6}{0.10369} \right) + \$6324.5 \times 10^6 = \$9.407 \times 10^9$$

When dividing this cost into its component costs, busses assume 5% of all pallet operating costs. The required-revenues per passenger-mile are compared for the four system designs in Table D-8.

Table D-8. Costs per Passenger-Mile for Three PATH System Designs (1980 Dollars) Assuming Constant Ridership

	PRIVATE OWNERSHIP	PUBLIC OWNERSHIP
PATH -- Baseline System	0.208	0.170
Pallets	0.149	0.124
CAPS	0.452	0.362
PATH -- with busses added	0.161	0.130
Pallets	0.149	0.123
CAPS	0.450	0.358
Busses	0.015	0.009
PATH -- Busses on Pallets*	0.163	0.131
Pallets	0.145	0.119
CAPS	0.450	0.358
Busses	0.033	0.024
PATH -- Driverless CAPS	0.182	0.144
Pallets	0.149	0.124
CAPS	0.318	0.228

*Busses include 5% $\left(\frac{700 \times 280 \text{ vehicle-miles}}{14700 \times 280 \text{ pallet-miles}} \approx 5\% \right)$ of pallet operating costs.

APPENDIX E

AERODYNAMICS OF DUAL-MODE VEHICLES

For a typical dual-mode system the aerodynamic drag coefficient of the vehicle[1] has been estimated under the following conditions.

(1) Pallet alone (dead-heading condition); low capacity operation (spacing >5 lengths),

(2) same as (1); high capacity operation (spacing = 2 lengths),

(3) pallet with car mounted; low capacity operation,

(4) same as (3); high capacity operation.

For the purposes of this analysis, the pallet is assumed to be aerodynamically similar to a box on wheels. The drag coefficient has been experimentally determined by many authors. Perhaps the most recent effort is that Ed Saltzman at FRC (Reference E1) which confirms the drags coefficient to be of order unity based on the projected frontal areas. In a subsequent effort (Reference E2), he verifies the benefits to be derived by rounding the vertical corners ($C_D = 0.68$). Clearly, practical corner rounding should be done on the pallet to take advantage of this effect.

The drag coefficient for a typical car is quite well documented and verified by myself (Reference E3) to fall near 0.5. Relatively few modifications are necessary to bring the coefficient down to 0.45 or less but the current "classic" or "Gatsby" styling will probably remain for some time. Also, as the trend to smaller and smaller cars continues, they become more box-like in order to retain seating comfort. Generally, the aerodynamics suffer (Honda civic has a drag coefficient of 0.6). For this exercise, $C_D = 0.5$ for the basic car drag coefficient will be used.

When the car is mounted on the pallet, the combined drag coefficient is not simply an area weighted average of the two. Some interference drag exists due to the proximity of each other. Horner (Reference E4), has some experimental data on selected shapes but it is nearly hopeless to estimate the effect for a situation such as this. Suffice to say, my intuition tells me that here it's a small effect (>5%). For this reason, the complexity required to fit a nose fairing to the pallet is not warranted. Also, it may not even be beneficial since the fairing would presumably have to adapt to a variety of cars and positionings and would, therefore, not be an optimum design for any.

For this analysis, the interference drag increment will be assumed to be 3%.

---

[1] This section was prepared by Don Kurtz of the JPL Technical Staff.

The combined drag coefficient of the car on pallet becomes:

$$C_D^1 = \left[\frac{(C_D A)_{car} + (C_D A)_{pallet}}{A_{car} + A_{pallet}}\right] \times 1.03$$

Since the absolute shapes of the car and pallet are unknown it will be assumed that the car and pallet frontal areas are the same so,

$$C_D^1 = 1/2\left[(0.5) + 0.68\right] \times 1.03 = 0.61$$

This, then, is representative of the drag coefficient if it were rolling down the street with nothing else influencing the flow field. In this case, the vehicle operates within a guideway with sidewalls and in some cases with extremely short headways.

Without knowing the geometry, quantifying the wall effects are difficult. Bill Bettes at Caltech has done extensive work on streamline curvature effects near solid boundaries and his Reference E5 can be used for a first cut look at the order of influence. If we assume that the sidewalls extend up to about window level of the car and allow about 3 ft of clearance on either side of the vehicle, the drag coefficient increment, ΔC_D, is of order 0.04 for the car-pallet combination and 0.02 for the wall pallet alone.

During high capacity operation, a beneficial drafting effect can be achieved. Gerry Romberg at Chrysler Corp. has done some excellent experimental work relating to stock car drafting (Reference E6). Slightly modifying the results for this case, we find that for a separation distance of 2 lengths, the system drag coefficient may be reduced by about 22% (1/2 a length is 27% and 3 lengths is still 20%). This 22% factor, then, is applied to both the car on pallet and pallet alone drag coefficients during high capacity operations.

In Summary: the aerodynamic drag experienced by a dual-mode vehicle is a function of a reasonably complex flow situation which cannot be closely predicted without fixing geometry and running sub-scale tests.

The following summary of drag coefficients should be treated with some caution but their relative magnitudes cannot be grossly inappropriate for a first cut analysis of dual-mode energy requirements.

(1) pallet alone (low capacity), $C_D = 0.70$

(2) pallet alone (high capacity), $C_D = 0.55$

(3) car on pallet (low capacity), $C_D = 0.64$

(4) car on pallet (high capacity), $C_D = 0.50$

NOTE: All coefficients are based on frontal area. The car on pal-coefficients is based on the sum of the car and pallet frontal areas.

REFERENCES

E-1 Saltzman, E.J., et. al., "Drag Reductions Obtained by Modifying a Box-Shaped Ground Vehicle," NASA TM x-56027, Oct. 1974.

E-2 Saltzman, E.J., et. al., "Drag Reductions Obtained by Rounding Vertical Corners on a Box-Shaped Ground Vehicle," NASA TM x-56023, March 1974.

E-3 Marte, Weaver, Kurtz, Dayman, "A Study of Automotive Aerodynamic Drag," DOT-TSC-OST-75-28, Sept. 1975.

E-4 Horner, S.F., "Fluid Dynamic Drag," Published by Author, 1965.

E-5 Bettes, W.H. and Kelley, K.B., "The Influence of Wind Tunnel Solid Boundaries on Automotive Test Data," Advances in Road Vehicle Aerodynamics, BHRA Fluid Engineering, 1973.

E-6 Romberg, G.F., et. al, "Aerodynamics of Race Cars in Drafting and Passing Situations," SAE 710213, Jan. 1971.

APPENDIX F

BSFC MAPS AND ENGINE POWER BOUNDARIES

F.1 OTTO Engine

BSFC MAP (lb Fuel/Brake hp - hr)

PERCENT MAXIMUM ENGINE SPEED							
100.0	17.50	8.80	3.75	1.92	1.08	0.61	0.46
84.4	14.50	7.50	3.17	1.68	0.97	0.58	0.46
73.3	11.00	6.00	2.65	1.47	0.87	0.53	0.48
62.2	10.80	6.00	2.72	1.50	0.84	0.52	0.45
48.9	6.30	3.75	1.87	1.10	0.65	0.46	0.45
42.2	7.10	3.80	1.67	0.95	0.60	0.47	0.47
33.3	5.40	2.80	1.28	0.78	0.57	0.47	0.47
28.9	4.50	2.38	1.12	0.70	0.50	0.50	0.50
22.2	3.15	1.72	0.88	0.63	0.54	0.54	0.54
17.8	3.15	1.72	0.85	0.66	0.55	0.57	0.57
14.4	2.87	1.35	0.75	0.70	0.59	0.61	0.61
	1.0	2.0	5.0	10.0	20.0	50.0	100.0

Percent of Maximum Engine Horsepower

Engine Boundary

PERCENT OF MAXIMUM SPEED	PERCENT MAXIMUM POWER AVAILABLE AT GIVEN SPEED
5.0	0.0
22.2	28.8
28.9	39.7
33.3	48.6
44.4	64.4
48.9	74.0
62.2	88.4
73.3	95.2
89.4	97.9
88.9	98.6
100.0	100.0

F.2 Ricardo Diesel

BSFC MAP

Special Fuel Consumption
(Lb Fuel/Brake - hp - hr)

Percent of Maximum-Power	1.0	4.0	10.0	20.0	40.0	60.0	100.0
100.0	11.27	3.87	1.67	0.98	0.61	0.51	0.50
90.0	9.61	2.94	1.37	0.81	0.56	0.48	0.47
80.0	8.14	2.35	1.13	0.71	0.51	0.45	0.45
75.0	7.45	2.13	1.03	0.67	0.49	0.44	0.48
70.0	6.86	1.96	0.97	0.63	0.47	0.43	0.51
65.0	6.27	1.80	0.91	0.60	0.46	0.426	0.59
60.0	5.64	1.67	0.85	0.57	0.44	0.43	0.665
55.0	5.10	1.55	0.80	0.55	0.43	0.45	0.715
50.0	4.61	1.42	0.75	0.56	0.42	0.48	0.755
47.5	4.31	1.37	0.72	0.51	0.42	0.50	0.805
40.0	3.63	1.18	0.65	0.49	0.44	0.58	0.95
30.0	2.75	0.95	0.58	0.46	0.53	0.73	1.14
20.0	1.86	0.75	0.51	0.43	0.69	0.92	1.35
12.5	1.23	0.61	0.47	0.41	0.84	1.13	1.56

PERCENT OF MAXIMUM SPEED

Engine Boundary

PERCENT OF MAXIMUM SPEED	PERCENT OF MAXIMUM POWER AVAILABLE AT GIVEN SPEED
6.0	3.0
25.0	28.0
41.0	50.0
56.0	70.0
70.0	84.0
80.0	92.0
91.0	98.0
100.0	100.0

F.3 Electric Traction

BSFC MAP

Percent Efficiency

PERCENT OF MAXIMUM SPEED	1.0	33.3	66.7	100.0
100.0	75.0	75.0	75.0	75.0
66.7	75.0	75.0	75.0	75.0
33.3	75.0	75.0	75.0	75.0
1.0	75.0	75.0	75.0	75.0

Percent of Maximum Horsepower

Engine Boundary

PERCENT OF MAXIMUM SPEED	MAXIMUM POWER AVAILABLE AT GIVEN SPEED
11.1	42.8
22.2	85.7
27.8	100.0
33.3	100.0
55.5	93.3
77.8	86.5
83.3	75.9
88.9	65.3
100.0	57.1