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Ann Arbor, MI

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## Document Description

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## **Introduction**

In the United States, the predominant mode of personal transportation is the automobile with over 90% of all passenger miles traveled in 1997 (Davis and Diegel 2002). Similarly, total passenger miles traveled annually in the U.S. have been growing at nearly three times the rate of population over past two decades. With transportation contributing more than 25% of global carbon dioxide emissions (WBCSD 2001) and personal vehicles accounting for 14% of U.S. energy use (Davis and Diegel 2002), the critical role of the automobile in sustainability challenges is clear.

The development of meaningful sustainable mobility solutions requires detailed understanding of the relationships between vehicle economics, vehicle performance, individual behavior, emissions, and more general societal and community factors. This study provides a framework for understanding overall vehicle economics and key economic variables in relation to individual ownership costs, operating decisions and replacement intervals. In combination with a parallel study of vehicle emissions and the implications for retirement (Kim et al. 2003), a more comprehensive view of the complex economic, environmental, and social system surrounding automobile use in the US is possible.

This study of automobile ownership economics and replacement intervals was carried out in two phases. Phase I considered the specific example of a single vehicle operated over a long period of time by a single owner while Phase II applied learning from Phase I to the study of a generic North American sedan operated under various sets of conditions grouped into scenarios. Phase I examined actual operator records and owner experience for a 1991 Model Year (MY) Ford Escort wagon. The framework developed to support the Escort analysis was then applied to the more general case of a generic sedan operated under typical or national average conditions.

For both studies, results were considered in terms of annual ownership costs, total life cycle ownership costs and optimum replacement intervals for ownership over the period 1985-2020. In addition, the generic vehicle results were considered in terms of used vehicle ownership costs and premiums associated with non optimal replacement intervals. Standard economic calculations and simple spreadsheet models were used for cost analysis, and a dynamic replacement model was developed to analyze the economic implications of vehicle replacement.

A note on costs: Unless otherwise specified all values reported in tables, figures and in the text of this document are in current (nominal) U.S. dollars. Results were calculated using constant 1985 dollar values, however, much of the original research information was collected in actual dollars and where possible original source data are repeated here. Where constant 1985 dollar values are reported they are calculated using a 4% inflation rate. When necessary, nominal dollar values were adjusted between years according to the Consumer Price Index (as published by the U.S. Bureau of Labor Statistics).

## Phase I – Ford Escort Case Study

### 1.1. Vehicle Studied

As a starting point for investigating vehicle economics a single case study of an anecdotal example vehicle was conducted. The example vehicle for this study was the 1991 MY Ford Escort wagon, driven by a single owner, in a consistent location over a 12 year period. This specific vehicle and owner were selected based on the overall quality of information available. The high quality of owner records available enabled the verification of data models and an understanding of the potential significance of results.

The 1991 Ford Escort studied is a LX 4-door wagon with a 1.9-liter sequential electronic fuel injection 4-cylinder engine connected to a 5-speed transaxle. The optional equipment included: a preferred equipment package (including power steering, light convenience group, lt. group/ cupholder tray, dual electric remote mirrors, removable decklid/fuel door release, and rear window defroster), wagon group, and clearcoat paint. Data were available through May of 2003 when the car had approximately 145,000 miles on the odometer driven primarily in Ann Arbor, Michigan. Available records included receipts and written records in the car manual; several conversations with the vehicle owner supplemented written records when needed. In the case of written records, the date and nature of the bill was recorded and then compiled by year of ownership (see Table 1 below)<sup>1</sup>.

**Table 1. Owner Reported Operating Expenses Related to a 1991 MY Ford Escort Wagon (nominal \$)**

Year of Ownership	Oil, Lube, & Filter <sup>(a)</sup>	Tires	Scheduled Maintenance	Unscheduled Repairs	Insurance <sup>(b)</sup>	Total Expense
1	0.00	0.00	8.68	4.66	565.64	578.98
2	42.14	0.00	18.70	0.00	580.53	641.37
3	65.92	0.00	4.23	138.80	595.43	804.38
4	94.94	0.00	183.50	0.00	610.32	888.76
5	81.50	369.60	0.00	1,654.41	625.25	2,730.76
6	33.23	68.59	116.57	476.43	640.14	1,334.96
7	80.16	95.24	205.38	765.56	655.03	1,801.37
8	108.53	47.59	499.38	531.63	669.93	1,857.06
9	62.83	0.00	903.17	103.50	684.86	1,754.36
10	64.60	273.56	464.54	160.87	699.75	1,663.32
11	64.17	0.00	235.00	0.00	714.64	1,013.81
12	42.50	0.00	540.23	78.86	729.54	1,391.13

(a) An average oil change cost of \$21.67 (2003 \$) was added where needed to fill gaps in actual owner records

(b) Premiums paid in increments ranging from 6-12 months were averaged to determine annual costs

### 1.2. Methodology

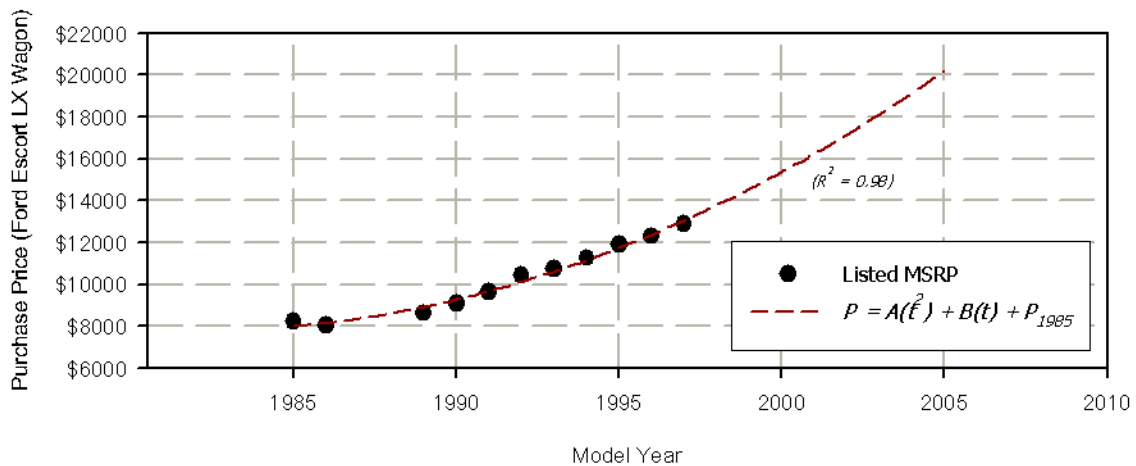
Costs to own and operate a Ford Escort wagon were estimated from available data sources. These data sources included:

<sup>1</sup> The data in table 1 includes only actual owner records, no records of gasoline purchase were available.

1. Actual owner records of vehicle insurance premiums, operating records (e.g. maintenance and repair), insight into general vehicle condition and expected future repair costs.
2. Region specific data sources, i.e. when possible data were taken to reflect the costs or conditions of vehicle operation in the Midwest or Ann Arbor, MI specifically.
3. In some cases national average data from sources such as the *Transportation Energy Data Book* (TEDB) (Davis and Diegel 2002), were used to establish overall trends.

### 1.2.1. PURCHASE PRICE AND DEPRECIATION

The retail purchase price (manufacturer's suggested retail price, MSRP) for the Ford Escort LX Wagon was taken from Ward's Automotive Yearbook (Ward's Communication 1985-2001). These data, beginning with the 1985 Model Year (MY) vehicle are shown in Figure 1.



**Figure 1. Purchase Price (MSRP) for Ford Escort Wagons (LX trim line) by Model Year (Source: (Ward's Communication 1985-2001), Note: LX wagon data not available for years 1987 and 1988 or beyond 1998)**

The data in Figure 1 were used to determine the retail price for the Ford Escort wagon in all model years studied. Initial purchase price for the vehicles studied was determined according to Equation 1.

$$(1) P = A(t^2) + B(t) + P_{1985MY}$$

Where,

- $P$  = Retail Price
- $t$  = vehicle model year relative to 1985 (1985  $t = 0$ )
- $P_{1985MY}$  = Retail Price of the 1985MY Escort wagon LX = \$7994.90
- $A$  = Empirical constant = 23.54
- $B$  = Empirical constant = 139.08

This approach to determining the initial purchase price for the vehicles studied includes delivery (or destination) charges, but excludes taxes, title, license, and other fees typically paid by the buyer at the time of purchase. These fees added \$223 (1%), on average, to the retail price of a new car in 2000 (Davis and Diegel 2002) and \$450.70 (5%) to the cost of the subject 1991 MY Escort wagon. Owner fees, including those paid at the time of purchase and annual fees (e.g. license, registration, etc.) were not included in this analysis.

Changes in vehicle value over time were based on observed vehicle depreciation for historical Ford Escort wagon models. Current average retail values for Ford Escort wagons were provided by the National Automobile Dealers Association via the website NADAguides.com (NADA 2003). Vehicle values and corresponding depreciation rates are shown in Table 2.

**Table 2. Average 2003 Retail Value and Depreciation Rate for Ford Escort Wagons (LX trim line)**

Model Year	Age (years)	Purchase Price <sup>(a)</sup>	Retail Value <sup>(b)</sup>	Depreciation Rate (nominal)	Depreciation Rate (real)
1985	18	\$7,995	\$1,225	11%	15%
1986	17	\$8,158	\$1,400	11%	15%
1989	14	\$8,483	\$1,475	13%	18%
1990	13	\$8,808	\$1,725	13%	18%
1991	12	\$8,971	\$1,875	14%	18%
1992	11	\$9,133	\$2,050	15%	19%
1993	10	\$9,286	\$2,375	15%	19%
1994	9	\$9,458	\$2,550	16%	20%
1995	8	\$9,621	\$2,825	17%	21%
1996	7	\$9,784	\$3,600	15%	20%
1997	6	\$9,946	\$4,150	16%	20%

<sup>(a)</sup> Source: (Ward's Communication 1985-2001)

<sup>(b)</sup> Source: (NADA 2003)

The data in Table 2 were used to determine the relationship between vehicle age and depreciation rate. The empirically derived relationship is described in Equation 2.

$$(2) D = P_r (1 + A \ln(n) + B)^n$$

Where,

- $D$  = depreciated value for a given model year vehicle
- $n$  = vehicle age in years
- $A$  = constant = -0.0706
- $B$  = constant = 0.3032

### **1.2.2 INSURANCE COST**

Insurance costs for the Ford Escort wagon were determined based on owner experience with the 1991 MY vehicle. Owner experience provided the basis for initial (new vehicle) insurance cost and for the expected impact of time on insurance premiums.

According to the *Transportation Energy Data Book*, new vehicle insurance rates<sup>2</sup> have been increasing \$32.31 (in constant 2000\$), or approximately 2%, per year since 1985 (Davis and Diegel 2002). This information was combined with owner data on the reported initial cost to insure a 1991MY Ford Escort wagon in Ann Arbor, MI to estimate the initial (year 1) insurance cost of other model year vehicles. Owner data were used to determine the expected changes in insurance rates over time with vehicle age. Limited experience suggests insurance rates exhibit slow growth according to Equation 3.

$$(3) I = A(n - 1) + B$$

Where,

$I$	= annual insurance premium for a given model year vehicle
$n$	= vehicle age in years
$A$	= constant = 14.806
$B$	= initial annual insurance premium = \$544.82

While this approach provided useful insight into the economics of ownership under the specific conditions described, this relationship is not expected to provide useful information under alternative conditions. Previous studies (see for example (Butler 1996), and significant anecdotal evidence, have shown that insurance rates are highly variable and exhibit a strong dependence on individual operator characteristics (such as age, driving history, gender, etc.) and region of operation<sup>3</sup>. Vehicle age, per se, is not expected to have a direct correlation with insurance rates. In addition, potential changes in coverage with vehicle age have not been taken into account<sup>4</sup>.

### **1.2.2 DRIVING PATTERNS (MILEAGE)**

Annual vehicle miles traveled were considered using two scenarios, the first approximates the known operator driving patterns, and the second uses a constant annual mileage value. Both scenarios consider the Escort wagon as a primary household vehicle.

The operator profile scenario attempted to account for the fact that actual vehicle usage is highly dependent on owner activity and is potentially independent of vehicle age. This scenario considers vehicle use over three periods:

- 1985-1990** Constant annual mileage of 14,828 miles per year. This value was selected based on operator driving patterns between 1991 and 1992 and is intended to represent a period of consistent activity for the owner.
- 1991** One year of increased activity at 15,596 miles based on owner records.
- 1992-2025** Slow decline in activity levels according to the Equation:  
 $M = A \ln(j) + M_{1991}$  where,  $M$  is the annual vehicle mileage,  $A$  is a constant equal to  $-1801.1$  (based on owner records),  $j$  is an integer that

<sup>2</sup> Insurance categories covered include fire & theft, collision, and property damage & liability.

<sup>3</sup> Specifically Butler (1996) notes six classes used to determine insurance prices: territory, type of car, use of car, type of driver (i.e. age and gender), annual mileage, and driver record.

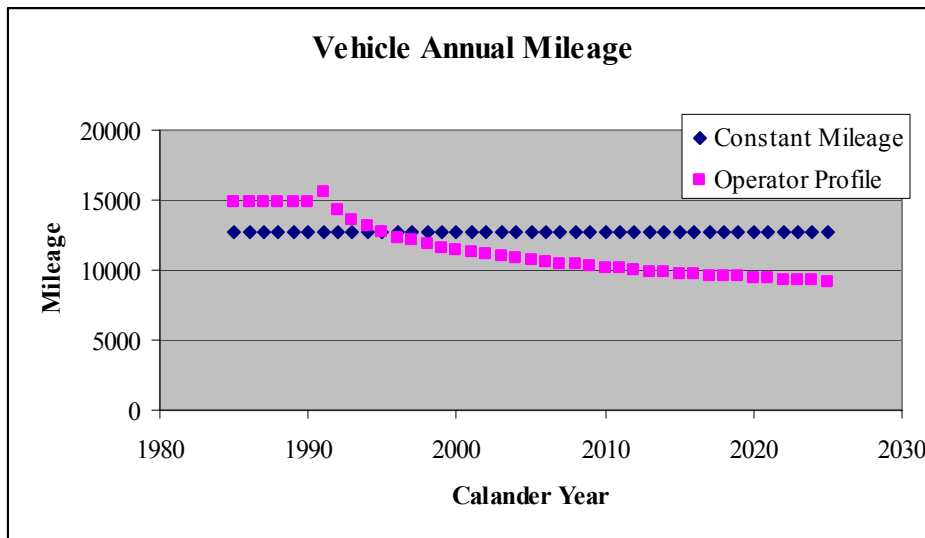
<sup>4</sup> For example, vehicle owners may decline collision coverage on older vehicles as the cost of premiums approaches the vehicle value.



represents the number of calendar years from 1990 (e.g. 1991  $j=1$ ), and  $M_{199j}$  is the mileage in 1991 (15,596 as stated earlier).

In the constant mileage scenario, Escort owner records were used to determine the average annual vehicle miles traveled and this value (12,766 miles/year) was used throughout the analysis. The use of constant mileage is based on the assumption that actual driving will fluctuate consistently around a constant average. This assumption eliminates the possibility of secondary vehicle ownership, career (e.g. work location), lifestyle or similar changes from influencing vehicle annual mileage and related economics.

Figure 2 shows the resulting annual mileage under both the constant mileage and operator profile scenarios.



**Figure 2. Annual Vehicle Miles Traveled Under Two Conditions**

#### **1.2.4 GAS PRICES**

The cost of regular unleaded gasoline was determined based on values reported by the U.S. Bureau of Labor Statistics (BLS) and the Energy Information Administration (EIA). When available, the 12-month average retail price in Ann Arbor, MI was taken as reported on the BLS website (BLS 2003). Location specific data were available for 1985-2003; beyond this time period EIA forecasts for national average unleaded regular were taken from the Annual Energy Outlook (DOE 2003).

#### **1.2.5 FUEL ECONOMY**

A linear annual improvement in new vehicle fuel economy can be described by Equation 4.

$$(4) FE = A(i) + FE_B$$

Where,

$FE$  = fuel economy for a given model year vehicle

- $A$  = constant = 0.297 based on data reported for U.S. average passenger vehicles between 1985 and 2000 (Davis and Diegel 2002).  
 $i$  = years from 1991 (base model year for this analysis)  
 $FE_B$  = baseline fuel economy = 32.15 mpg for 1991 MY Ford Escort wagon

Equation 4 was used to determine the fuel economy for all of the model years studied. Fuel economy was held constant with age for a given model year vehicle. Previous research suggests that changes in fuel economy with age are unpredictable at best (Kim et al. 2003).

### **1.2.6 SCHEDULED MAINTENANCE**

Operator records for 12 years of actual maintenance on a 1991 Ford Escort wagon were used as the basis for determining a regular maintenance schedule for the vehicles considered here. The maintenance schedule derived from owner experience is shown in Table 3.

**Table 3. Maintenance Schedule and Costs Derived from Owner Records for a 1991 Model Year Ford Escort Wagon**

Maintenance Item	Frequency (miles)	Cost <sup>(a)</sup>
Tires	60,000	\$324.56
Oil Change	3,000	\$21.67
Misc. Maintenance <sup>(b)</sup>	5,800	\$147.39

(a) 2003 \$

(b) Examples of miscellaneous maintenance items include inspections, cleanings, spark plugs, air filters, belts, etc.

This schedule was used to calculate the total annual maintenance under the mileage scenarios described above. As a verification of initial results, the schedule shown in Table 3 was applied to 12 years of vehicle life (at constant annual mileage) to determine total maintenance costs. The results indicated a 12 year cost of \$4,086.75 while actual owner records indicate a 12 year scheduled maintenance cost of \$4,191.74.

### **1.2.7 UNSCHEDULED MAINTENANCE**

Unscheduled maintenance and repair costs were evaluated using a two-step process. The first step covers the first 12 years of vehicle life and is based on actual owner experience; while, the second step covers the final 8 years of vehicle life and remaining expected repair problems.

For the first 12 years of vehicle operation, unscheduled maintenance costs were taken as reported by the owner for the 1991 Escort wagon. All model year vehicles were assumed to experience repair problems at the same mileage as the 1991 vehicle. Repair costs were scaled according to the rate of inflation<sup>5</sup>. In years 13 to 20, additional information was required to assess the potential for unscheduled repairs.

<sup>5</sup> As measured by the Consumer Price Index

Two scenarios were considered for the final eight years of vehicle operation. In the “better” case only those systems rated as highly unreliable by the owner and those rated as *much* worse than average for a 1991 MY vehicle by *Consumer Reports* (Consumer Reports 1987-2003) are repaired<sup>6</sup>. These systems included the radiator, water pump, clutch, brakes, and alternator. In the “worse” case, these parts were repaired plus any components rated as worse than average for a 1991 MY vehicle in *Consumer Reports* (Consumer Reports 1987-2003). This resulted in the addition of the ignition coil, shocks and struts to the repair list.

Repairs were randomly ordered with no more than one repair in any given year. Repair costs were provided in a telephone interview with a service shop that had frequently repaired the subject vehicle (Soules 2003). Repair costs for unscheduled systems are shown in Table 4.

**Table 4. Unscheduled Repairs for Ford Escort Vehicles Older than 12 Years**

System/Component	Consumer Reports Rating <sup>(a)</sup>	Repair Cost (2003)
Radiator	Worse than Average <sup>(b)</sup>	\$400.00 <sup>(c)</sup>
Water Pump	Worse than Average <sup>(b)</sup>	\$525.00 <sup>(c)</sup>
Ignition Coil	Worse than Average	\$150.00 <sup>(d)</sup>
Clutch	Average <sup>(b)</sup>	\$850.00 <sup>(c)</sup>
Shocks & Struts	Worse than Average	\$650.00 <sup>(c)</sup>
Brakes	Much Worse than Average	\$132.35 <sup>(e)</sup>
Alternator	Much Worse than Average	\$367.71 <sup>(e)</sup>

<sup>(a)</sup> source: (Consumer Reports 1987-2003)

<sup>(b)</sup> Replaced in all scenarios due to owner concern

<sup>(c)</sup> source: (Soules 2003)

<sup>(d)</sup> source: (CarParts.com 2003), part cost = \$75, labor cost = \$75

<sup>(e)</sup> source: Owner receipt for repair, adjusted for inflation

### 1.3 Results

#### 1.3.1 VEHICLE OWNERSHIP COSTS

Ownership costs for 20 years of operating a Ford Escort wagon were calculated using the equations, assumptions, data sources and methods described earlier. These calculations resulted in both annual fixed cost estimates (costs that tend not to vary with mileage, e.g. insurance and depreciation) and annual variable cost estimates (costs that depend on mileage traveled, e.g. fuel costs, maintenance and repair). Fixed and variable costs for the 1991 MY Ford Escort wagon are shown for the scenario with worst-case repair and constant annual mileage in Figure 3 and for the scenario with base-case repair and simulated operator mileage in Figure 4. Overall total ownership costs for all scenarios considered are shown in Figure 5.

These results highlight the relatively small variation between scenario conditions. In fact, the scenarios considered here are intended to provide boundaries for relatively well-understood operating conditions and accordingly show variability mainly beyond year 11 – the last full year of available owner records.

<sup>6</sup> Cosmetic repairs, such as body rust, trim, or hardware are not considered.

### *Life Cycle Costs*

In addition to considering the costs to an owner who sells a vehicle for fair market value at the end of the ownership period (albeit at a depreciated price), costs were evaluated assuming the vehicle would have to be scrapped at the end of the ownership period. Under these conditions the owner receives payment for the vehicle from a dismantling operation totaling \$80<sup>7</sup> (1997 \$) (Keoleian et al. 1997). Table 5 provides the total life cycle cost to vehicle owners for various lifetimes subject to the scenarios examined in this study.

**Table 5. Total Life Cycle Per Mile Ownership Costs (\$/mile) for a Ford Escort Wagon (constant 2003 \$)<sup>8</sup>**

Scenario Conditions	Vehicle Lifetime (years)			
	5	10	15	20
Operator Mileage	\$0.38	\$0.30	\$0.26	\$0.24
Constant Mileage	\$0.43	\$0.30	\$0.26	\$0.22

The data in Table 5 represent the total lifetime per mile cost to purchase a vehicle (with a cash payment), operate it for  $n$  years ( $n= 5,10,15$  or  $20$  in Table 5) and then deliver it to a dismantler for disposal with minimal compensation. Since these assumptions require that vehicle is depreciated to near zero value<sup>9</sup> at the end of life, the strong dependence of the results on lifetime mileage is not surprising. For example the total lifetime mileages at five years are 69,323 and 63,830 for the operator simulation case and constant mileage case respectively. After 20 years the mileages are 235,371 for the operator simulation case and 255,319 for the constant mileage case.

Although alternative scenarios for unscheduled maintenance were considered, the change in repair costs did not have a significant effect on the overall life cycle ownership costs and these scenarios are not included in the results shown in Table 5.

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<sup>7</sup> Maximum payment for a vehicle delivered to the dismantler.

<sup>8</sup> Values calculated in constant 1985\$ and converted to 2003\$ for ease of reference.

<sup>9</sup> Less than 1% of initial purchase price

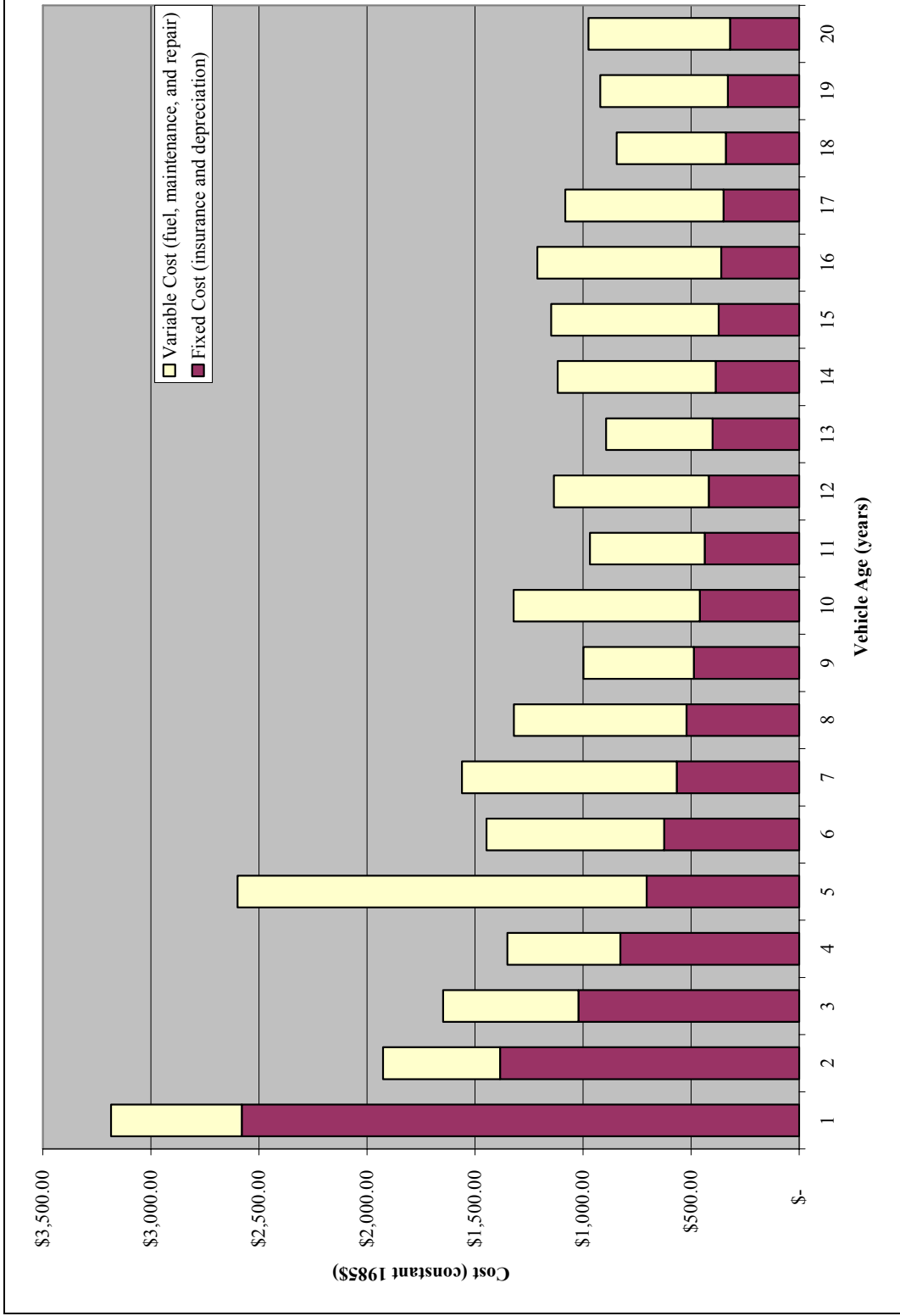


Figure 3. Fixed and Variable Ownership Costs for a 1991 MY Ford Escort wagon (with constant annual mileage and “worse” case unscheduled repair costs)

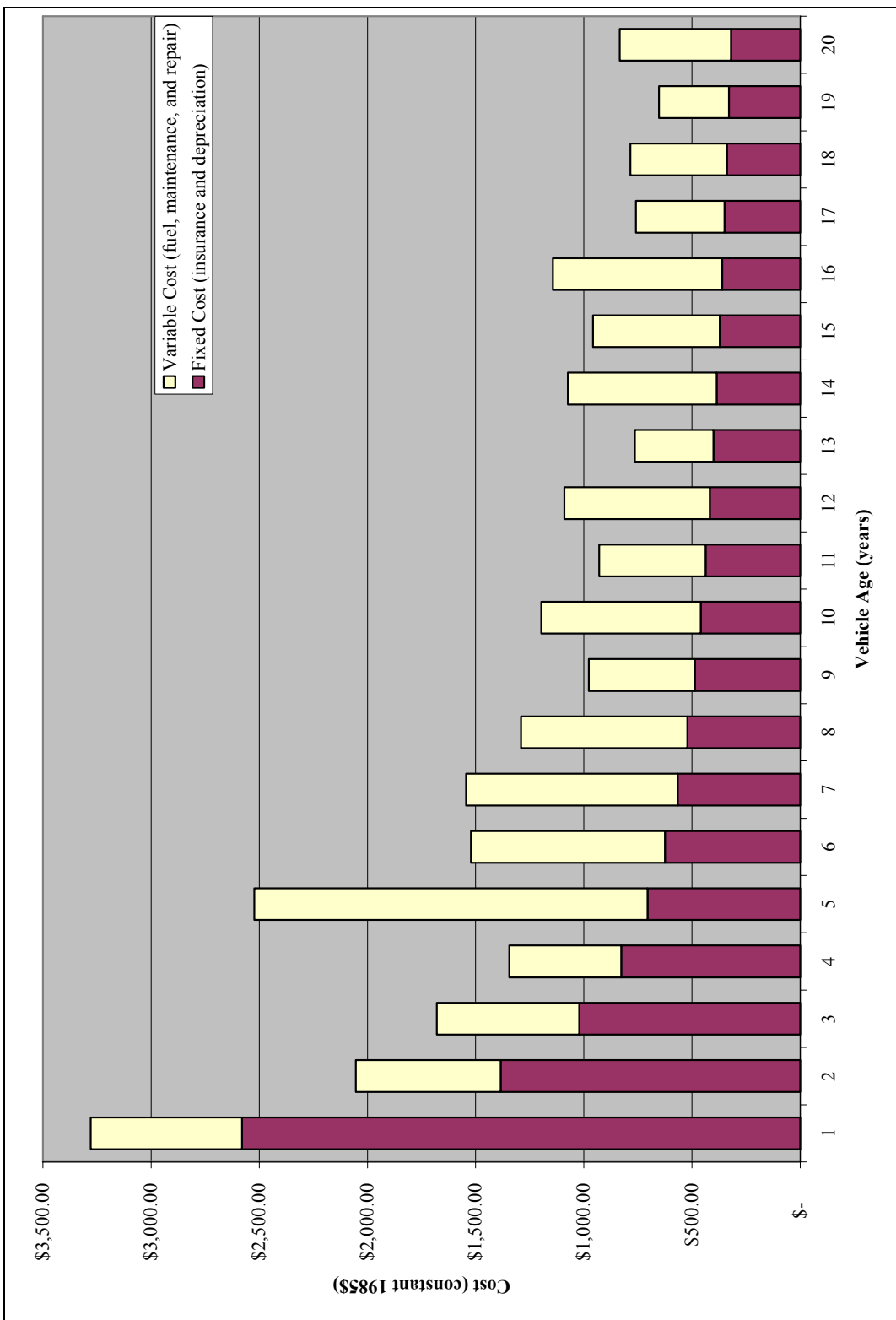


Figure 4. Fixed and Variable Ownership Costs for a 1991 MY Ford Escort Wagon (with declining annual mileage and “better” case unscheduled repair costs)

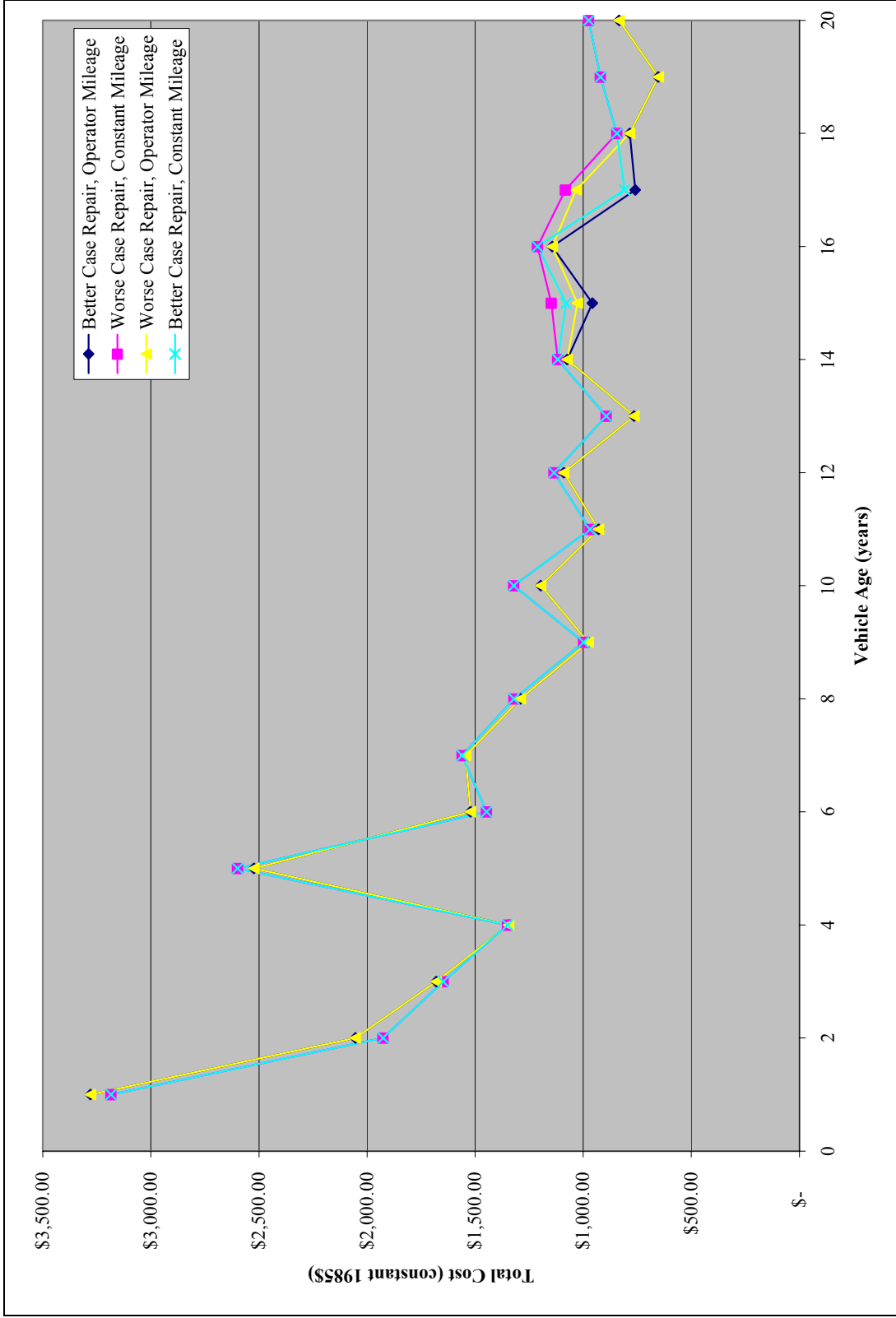


Figure 5. Total Annual Operating Costs for a 1991 MY Ford Escort Wagon Under Various Conditions

### **1.3.2 OPTIMAL REPLACEMENT INTERVALS**

Optimal replacement intervals for the Ford Escort wagon were calculated using dynamic replacement modeling. Dynamic programming is a mathematical tool which enables the decision-maker to analyze a system for which a sequence of decisions must be made. The decision-maker is then able to choose the particular sequence of decisions which best satisfies his/her criteria. The present study considers an annual decision for a vehicle owner: “keep the existing vehicle, or replace it with a new vehicle?”

To perform the desired analysis, the characteristics of the problem must be completely specified. In this study, the *time horizon* of the problem, the period over which the decisions are being made, is 1985 – 2020. Throughout the study, it is assumed that a vehicle has just been purchased at the beginning of 1985, and the decision to buy or keep is made at the start of every successive year through 2020.

In each year, a decision is made, and this changes the *state* of the system. The state is the particular set of characteristics of the system that one wishes to analyze over the time horizon. For the present study, the state is the age and model year of the present vehicle. With this information, the costs to be incurred by the owner in the present year are calculated, and actions available for the next decision are understood. For example, the limit on vehicle ownership is 20 years<sup>10</sup>. Therefore, an owner with a 20-year-old vehicle does not have the option to keep the vehicle; he or she must replace.

At every decision epoch, the decision-maker chooses an action based on the current state of his system, the system moves to a new state, and the decision-maker incurs the corresponding cost for the year. This process is then repeated for the remainder of the time horizon<sup>11</sup>.

In the present study, the decision-maker is interested in choosing the sequence of decisions which will cause him/her the least possible cumulative cost over time. The dynamic programming recursive equations developed for the problem evaluate each of these sequences to determine the one which best satisfies the decision-maker’s objective. This best sequence, the *optimal path*, identifies the sequence of best decisions to be made at each decision epoch over the entire time horizon. A C Program was constructed to solve the recursive equations for the various data scenarios described above for the Escort wagon.

This dynamic program was used to determine the optimal replacement schedule for each vehicle scenario over the 1985-2020 time horizon. In each year the options are either keep the existing vehicle or replace it with a new vehicle, so the output is a series of vehicle service lives. For example, “10 years, 12 years” would indicate that the first vehicle is kept for 10 years and then replaced by a vehicle which is kept for 12 years. The optimal replacement policies for the four Escort scenarios are shown in Table 6.

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<sup>10</sup> 20 years (230,000 – 260,000 miles) is assumed to be the maximum period over which a typical vehicle will maintain structural integrity and effective function.

<sup>11</sup> For further information on dynamic programming methodology, please see (Denardo 1982).



**Table 6. Optimal Replacement Intervals for a Ford Escort Wagon**

	<b>Best-case Unscheduled Maintenance</b>	<b>Worst-case Unscheduled Maintenance</b>
<b>Constant Mileage</b>	17 years; 19 years Total Cost <sup>(a)</sup> : \$47,167	17 years; 19 years Total Cost <sup>(a)</sup> : \$47,803
<b>Operator Profile Mileage</b>	17 years; 19 years Total Cost <sup>(a)</sup> : \$47,273	17 years; 19 years Total Cost <sup>(a)</sup> : \$47,909

<sup>(a)</sup>1985 dollars

Although the total cost to the owner varies, the optimal replacement schedule in each case is identical. In addition, a scenario in which the vehicle is purchased by personal loan (20% down payment with 9% interest for payments over 4 years) was considered; for this case, the optimal policies remain the same though they incur slightly higher total costs.

## Phase II – Generic Vehicle Case Study

Phase II of the study considered the life cycle economic and replacement optimization of a generic North American sedan. This effort builds on two notable previous studies; the United States Automotive Materials Partnership (USAMP) *Life Cycle Inventory Analysis of a Generic Vehicle* (Ecobalance and National Pollution Prevention Center 1999) and doctoral research conducted by Darby Grande as published in (Kim et al. 2003).

The USAMP generic vehicle life cycle inventory (referred to hereafter as the USAMP study) established a life cycle profile for a generic sedan produced in North America. The vehicle studied represented a combination of 1995 MY vehicles from the sponsor organizations, including the Ford Taurus, Chevrolet Lumina (GM) and Dodge Intrepid (Chrysler<sup>12</sup>). The inventory study included the material acquisition, manufacturing, assembly, use<sup>13</sup>, and retirement of a single complete vehicle. This single generic sedan represented an aggregation of the material requirements, manufacturing impacts, and operating conditions of the three production vehicles.

Where possible, the present study maintained the original USAMP definition of a generic North American sedan. Accordingly the generic vehicle studied here is a combination of the Ford Taurus, Chevrolet Lumina, and Dodge Intrepid. However, much of the data collection utilized U.S. average data for all passenger vehicles, or where possible mid-sized sedans. In at least one case, data were available only for the Taurus and these data were used as representative of the generic vehicle. Additionally, this study required data collection over a much larger time horizon than the original USAMP study with requirements for both historical data and future projections. None of the subject vehicles were produced over the complete time horizon of the study (1985-2020). In several cases, equivalent or nearly equivalent alternatives had to be identified to fill data gaps. Table 7 identifies the model year vehicles covered in this study and the alternative vehicles considered.

**Table 7. Vehicles Contributing to the Definition of a Generic North American Sedan**

Vehicle Model	Base Vehicle			Alternatives Considered <sup>(a)</sup>
	Trim Line	Engine Type	MY Available	
Ford Taurus	GL	V-6	1986, 1992-1997	Taurus LX (1987-1991, 1998-2000) LTD (1985)
Chevrolet Lumina	na	V-6	1994-2000	Lumina L-4 engine (1990-1993) Celebrity (1985-1989)
Dodge Intrepid	na	V-6	1993-2000	Monaco (1990-1992) Dynasty (1988-1989) 600 (1985-1987)

(a) Equivalent models were required mainly for the acquisition of historical price and depreciation data  
na = trim line not specified in original USAMP project

<sup>12</sup> Currently DaimlerChrysler

<sup>13</sup> In the USAMP study the use phase was considered 10 years and 120,000 miles, here the maximum useful life of a vehicle is 20 years 240,000 miles.

## 2.1 Methodology

### ***2.1.1 USE OF SCENARIOS***

A series of scenarios were used to examine the potential impact of alternative conditions on life cycle economics and corresponding optimal replacement intervals. Typical operating circumstances were often difficult to identify for the diverse range of regions, owners, and operating conditions found in the U.S. For example, the USAMP study found that auto industry (manufacturer and service center) recommendations for routine activities such as engine oil change can vary as much as 56% (8,000 km – 12,500 km) between sources (Ecobalance and National Pollution Prevention Center 1999).

A total of twelve possible sets of alternative conditions were considered relative to a single baseline case. The scenarios considered are summarized in Table 8 and described in the paragraphs that follow. Additional detailed discussion of specific scenario conditions is provided in sections 2.1.2 – 2.1.10.

**Table 8. Generic Vehicle Life Cycle Cost Scenarios (*gray* indicates no change from baseline)**

Scenario Name	Purchase Method	Unscheduled Repair	Gasoline Price	Powertrain	External Costs	Depreciation Rate
“Baseline”	Personal Loan	Baseline Case	Baseline Case	Conventional ICE	Not Included	Baseline
“Durable”	<i>Personal Loan</i>	High Durability Case	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	<i>Baseline</i>
“Unreliable”	<i>Personal Loan</i>	Low Durability Case	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	<i>Baseline</i>
“Increasing Durability”	<i>Personal Loan</i>	Increasing Durability Case	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	<i>Baseline</i>
“Cash Payment”	Cash	<i>Baseline Case</i>	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	<i>Baseline</i>
“Gas Tax”	<i>Personal Loan</i>	<i>Baseline Case</i>	Gasoline Tax	<i>Conventional ICE</i>	<i>Not Included</i>	<i>Baseline</i>
“Advanced ICE”	<i>Personal Loan</i>	<i>Baseline Case</i>	<i>Baseline Case</i>	Advanced ICE <sup>(a)</sup>	<i>Not Included</i>	<i>Baseline</i>
“Accelerated Advanced ICE”	<i>Personal Loan</i>	<i>Baseline Case</i>	<i>Baseline Case</i>	Advanced ICE (2005) <sup>(a)</sup>	<i>Not Included</i>	<i>Baseline</i>
“Accel. Advanced ICE w/Gas Tax”	<i>Personal Loan</i>	<i>Baseline Case</i>	Gasoline Tax	Advanced ICE (2005) <sup>(a)</sup>	<i>Not Included</i>	<i>Baseline</i>
“External Cost”	<i>Personal Loan</i>	<i>Baseline Case</i>	<i>Baseline Case</i>	<i>Conventional ICE</i>	Pollutant Costs & Personal Time	<i>Baseline</i>
“Slow Depreciation”	<i>Personal Loan</i>	<i>Baseline Case</i>	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	Less Rapid
“High Cost”	<i>Personal Loan</i>	Low Durability Case	Gasoline Tax	<i>Conventional ICE</i>	Pollutant Costs & Personal Time	<i>Baseline</i>
“Low Cost”	Cash	High Durability Case	<i>Baseline Case</i>	<i>Conventional ICE</i>	<i>Not Included</i>	Less Rapid

ICE = Internal Combustion Engine

(a) Also incorporates an increase in vehicle retail price

*Baseline Scenario*

The baseline scenario is designed to represent the most typical conditions for vehicle design, purchase, operation, and repair. In the sections (2.1.2 – 2.1.10) that follow baseline conditions are described unless otherwise specified.

*Durable Scenario*

This scenario modifies the baseline assumptions to increase the expected durability of components not scheduled for

routine replacement. Unscheduled repair takes place according to the high durability mileage listed in Table 13.

*Unreliable Scenario*

In this case, the baseline scenario is modified by decreasing the durability of parts and components. Repairs are accounted for using the low durability data in Table 13.

*Increasing Durability Scenario*

In this scenario the potential implications of design changes that improve individual component reliability/durability are considered. This scenario uses the low durability replacement intervals shown in Table 13 for the 1985 MY vehicle, then increases component durability with each model year equivalent to a 40% improvement in durability every ten years. While not reflective of actual expected improvements in component durability, this scenario helps determine the significance of repair costs and the availability of more attractive alternatives in the overall replacement policy.

*Cash Payment*

While national averages suggest most purchased vehicles<sup>14</sup> are financed using a personal loan (69% according to (Richardson et al. 1997), the remaining 31% are paid for in a single lump sum. The impacts of cash payment on total life cycle cost and replacement intervals are considered in this scenario. However, the opportunity costs associated with cash payment are not included in the analysis.

*Gas Tax*

Current retail gasoline taxes in the United States are much lower than those paid by consumers in other developed nations (Davis and Diegel 2002). This scenario examines the impacts for vehicle replacement and ownership costs of a substantial increase in U.S. gas taxes. This scenario does not account for any potential changes in operator behavior (e.g. less driving) and does not introduce the possibility of substantially more fuel efficient vehicles.

*Advanced ICE*

This scenario introduces more fuel efficient vehicles in a series of stages beginning with the 2005 MY vehicle. Step change fuel economy and retail price increases in 2005, 2013, and 2020 are included in the advanced ICE scenario.

*Accelerated Advanced ICE*

While the baseline scenario considers a gradual improvement in fuel economy over time, this scenario introduces a single radical improvement in vehicle fuel

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<sup>14</sup> Excludes leased vehicles

economy in 2005. This improvement is accompanied by a dramatic increase in vehicle purchase price as well.

*Accelerated Advanced ICE with Gas Tax* The potential economic and replacement implications of a substantial tax on gasoline and the availability of more fuel efficient vehicles (with substantially higher sticker prices) were considered in this scenario. This scenario examines the impacts of the vehicle price and fuel economy described for the accelerated advanced ICE scenario in combination with the fuel prices described for the gas tax scenario.

*External Cost* The external costs scenario was designed to examine the economic and replacement impacts of more fully accounting for the externalities related to automobile use. Specific externalities accounted for in this scenario include the cost of lost time for the owner due to vehicle repair and maintenance and the expected cost to society of the damage caused by air pollution.

*Slow Depreciation* The costs associated with loss of vehicle value over time are a substantial portion of total ownership costs, especially in the early years of vehicle life. Additionally, high variability in rate of depreciation between sources<sup>15</sup> suggests the need for a scenario that examines an alternative depreciation profile.

*High Cost* The high cost scenario combines conditions present in other scenarios to maximize the variable cost of vehicle operation. This allows the consideration of additive impacts such as low durability combined with valuation of owner time lost to repair.

*Low Cost* As a counter-point to the high cost scenario, the low cost scenario considers conditions that minimize the fixed and variable ownership costs. In combination with the high costs scenario, this supports a set of boundary assumptions for the study.

### **2.1.2 PURCHASE PRICE AND DEPRECIATION**

The initial purchase price for the generic vehicle was determined from the retail prices listed in the Ward's Automotive Yearbook (Ward's Communication 1985-2001) for the Taurus, Lumina and Intrepid. For model years 1985-2000 the average retail price for

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<sup>15</sup> Sources examined for this report varied between 20% and 46% loss of vehicle value in the first year of ownership for relevant mid-sized 2003 MY North American sedans.

these three vehicles was taken as the initial purchase price for the generic vehicle<sup>16</sup>. For model year 2001 and beyond, the initial purchase price was determined using the relationship shown in Equation 5. This equation was derived from the 1985-2000 model year purchase price data and is designed to continue the gradual increase clearly demonstrated in this data.

$$(5) P = A(i) + P_{2000}$$

Where,

- $P =$  Purchase price for a given model year generic vehicle
- $i =$  Vehicle model year relative to 2000 (2000  $i = 0$ )
- $A =$  Price escalation constant = \$650.23/yr
- $P_{2000} =$  Purchase price for a 2000 MY generic vehicle

In scenarios where the introduction of an advanced engine vehicle is considered, a price increase reflecting the increased cost of new technology is incorporated. For example, the introduction of an modestly advanced engine vehicle with light-weighting in 2005 adds \$1770 (or 8%) to the cost of a 2005 MY vehicle<sup>17</sup>.

Loss of vehicle value due to depreciation in the first few years of a vehicle's life is a critical factor in overall ownership costs. While nearly all vehicles depreciate in value over time, the rate of depreciation for a specific vehicle may depend on several factors, including: brand image, new model pricing, mileage range, trim line, and vehicle class (IntelliChoice 2003). In an effort to capture the potential range of depreciation costs for a generic vehicle, two depreciation scenarios were considered – a base line using *Kelley Blue Book* values and a less rapid depreciation based on *IntelliChoice* data.

#### *Baseline*

Vehicle depreciation data were based on observed vehicle depreciation for the Taurus, Lumina and Intrepid (V6 engine models only) according to the *Kelley Blue Book* expected retail price for a vehicle in good condition (Kelley Blue Book 2003). The current (2003) value of selected model year vehicles is shown in Table 9.

**Table 9. Current (2003) Value<sup>(a)</sup> of Selected Model Year North American Sedans**

Vehicle <sup>(b)</sup>	Model Year			
	1994	1995	1996	1997
Ford Taurus	\$1,955	\$2,305	\$2,890	\$3,600
Chevrolet Lumina	\$2,160	\$2,385	\$2,955	\$3,575
Dodge Intrepid	\$2,480	\$2,855	\$3,600	\$4,475

<sup>(a)</sup> Value as listed in Kelley Blue Book (Kelley Blue Book 2003)

<sup>(b)</sup> The generic vehicle considered here is the linear average of the three component sedans.

Data, such as that shown in Table 9, on the current value of previous model year vehicles were used to determine the estimated depreciation rate for vehicles of different ages. The

<sup>16</sup> For model years during which the subject vehicles were not produced, historical equivalents were identified.

<sup>17</sup> For a complete discussion of advanced vehicle see section 2.1.6

average annual depreciation rate for the generic vehicle studied here is shown in Table 10.

**Table 10. Annual Depreciation Rate for Generic Vehicles**

Vehicle Age	Annual Depreciation Rate (nominal)
1	37%
2	27%
3	23%
4	20%
5	18%
6	17%
7	15%
8	14%
9	13%
10	13%
11	12%
12	11%
13	11%
14	10%
15	9%
16	9%
17	9%
18	8%
19	8%
20	7%

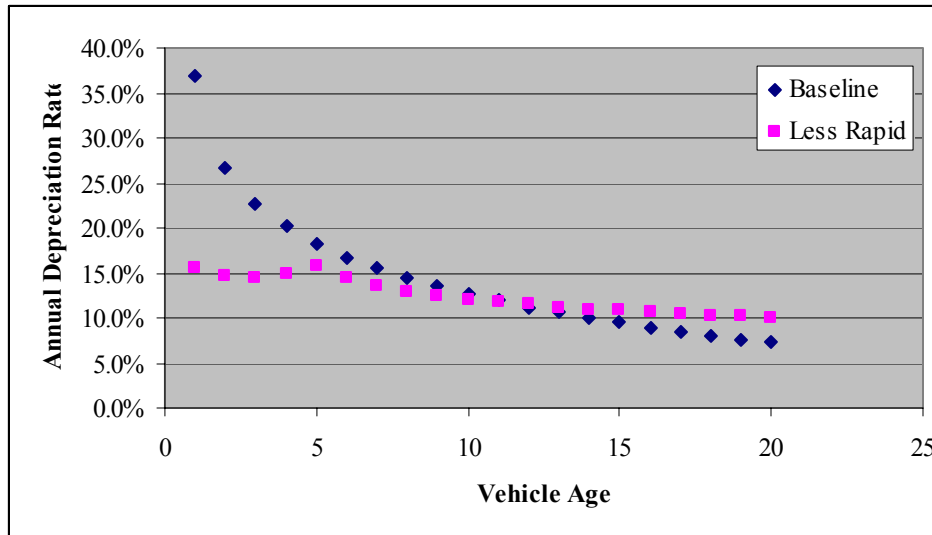
*Less Rapid Depreciation*

While the *Kelley Blue Book* is the most widely cited source of vehicle values, the estimates derived from this source (shown in Table 10) exceeded other published depreciation ranges for vehicles in this study<sup>18</sup>. This observation, combined with the highly variable nature of depreciation data, necessitated the consideration of an alternative depreciation profile.

Depreciation profiles for the generic vehicle derived from *the Complete Car Cost Guide* show a more gradual decline in value over time with a first year loss in value of 16% (IntelliChoice 2003). This less rapid profile is shown in Figure 6 along with the baseline depreciation profile.

<sup>18</sup> For example, the North Carolina State Cooperative Extension has vehicle depreciation in the range of 13-31% in the first year and 13-15% in the second year (NCCES 2003).





**Figure 6. Annual Depreciation Profiles for a Generic Vehicle**

In addition to the less rapid rate of decline, the “less rapid” profile also incorporates the effects of vehicle warranty on depreciation rate. The impact of the end of the standard three-year warranty period for the generic vehicle is evident in the slight increase in depreciation rate for years four and five of the vehicle life in Figure 6. In fact, according to *IntelliChoice*, a generic sedan will depreciate at the same rate in years one and five<sup>19</sup> (IntelliChoice 2003).

### **2.1.3 INSURANCE COST**

Initial (year one of ownership) model year insurance costs for the generic vehicle are based on national average automobile insurance rates provided by the *Transportation Energy Data Book*<sup>20</sup> (Davis and Diegel 2002). The cost to insure the generic vehicle in the first year of operation for model years 1985-2001 are those reported in the TEDB. These values were derived from a series of annual reports by the AAA insurance company (AAA Association Communication 1999). The AAA data reflects the cost to insure a new average vehicle<sup>21</sup> for use in short distance commutes (less than 10 miles) with no young drivers. Beyond 2001 MY vehicles, the average annual increase of 1.7% was used to continue trends evident in the AAA data.

As stated earlier, the age of a vehicle is not expected to have a direct correlation with insurance cost due to the dominance of other driver and operating condition factors. However, insurance rates are expected to increase over time. To estimate the changes in insurance cost over time, data on annual consumer automotive insurance spending were considered. Data from the U.S. Bureau of Labor Statistics Consumer Expenditure Survey suggest that between 1991 and 2001 consumer spending on automobile insurance

<sup>19</sup> 16% depreciation rate for years one and five; however, total monetary losses are much lower in year five than in year one.

<sup>20</sup> Listed as fixed costs for fire & theft, collision, property damage & liability.

<sup>21</sup> In 1999 the average vehicle consisted of equal weighting of the Chevrolet Cavalier, Ford Taurus, and Mercury Grand Marquis.

increased 3% per year on average (BLS 2003). Insurance costs for the generic vehicle are assumed to increase 3% per year over the life of the vehicle. This is slightly higher than the 2.3% average annual increase observed in the Phase I Ford Escort data.

#### **2.1.4 VEHICLE ANNUAL MILEAGE**

In order to ensure comparable service demands on current and future vehicles, we assume a constant 12,000 miles are driven per year, regardless of the age of the vehicle. This value corresponds to the ratio of U.S. vehicle travel (1,601,914 million miles in 2000) and the number of vehicles registered in the U.S. (133,621 thousand in 2000) (Davis and Diegel 2002).

#### **2.1.5 FUEL PRICE**

Fuel prices consistent with the generic vehicle studied were examined under two conditions. First, prices representing the national average retail price of unleaded regular gasoline were examined. Then, a scenario was constructed to investigate the potential impacts of higher gasoline prices on vehicle replacement.

##### *Baseline Fuel Prices*

Baseline gasoline prices were taken from published reports by the Energy Information Administration within the Department of Energy. Historical retail unleaded motor gasoline prices for 1985-2001 are those published by EIA in the 2001 Annual Energy Review (DOE 2002). Beyond 2001, gasoline prices are the sales weighted average price for all gasoline grades (including taxes) as published in the Annual Energy Outlook 2003 (DOE 2003).

##### *Gasoline Tax*

U.S. taxes on retail gasoline are among the lowest in the developed world (see Table 11). Several scholars and environmental groups have suggested that a tax on gasoline in the U.S. more consistent with that in Europe would provide economic incentive for improved fuel economy and reduced environmental impact (Porter 1999), (Parry 2002), (Fullerton and West 2002), (Comeau and Chapman 2002). In order to investigate the potential impact of a gasoline tax on vehicle economics and replacement, a scenario introducing a gasoline tax equivalent to that in the U.K. in 2001 was constructed. As shown in Table 11, the 2001 gasoline tax in the U.K. was equivalent to \$3.43/gal (2000 \$) while U.S. gasoline taxes in 2001 totaled \$0.37/gal (2000 \$). For the gasoline tax scenario, gas prices were increased by \$3.06/gal starting in 2001<sup>22</sup>.

**Table 11. Gasoline Taxes (2001)**

Country	Tax <sup>(a)</sup> (\$/gal)
U.S.	\$0.37
Canada	\$0.84
Japan	\$2.09
Germany	\$2.70
France	\$2.76
U.K.	\$3.43

<sup>(a)</sup> Constant 2000 U.S. \$, source: (Davis and Diegel 2002)

<sup>22</sup> Beyond 2001 the gas tax was scaled according to the consumer price index.

### **2.1.6 VEHICLE FUEL ECONOMY**

The starting point for determining the baseline fuel economy for the generic vehicle was the stated fuel economy of the 1995 MY generic vehicle in the USAMP study, 22.8 mpg<sup>23</sup> (Ecobalance and National Pollution Prevention Center 1999). Other model year vehicle fuel economy is determined using an average annual change of 1% from the 1995 levels. This rate of fuel economy improvement is consistent with values published for national average passenger cars (Davis and Diegel 2002). Fuel economy was held constant with age for a given model year vehicle. Previous research suggests that changes in fuel economy with age are unpredictable at best (Kim et al. 2003).

Issues of national and international interest such as fluctuations in oil prices, regional instability, global warming emissions, and other political/environmental impacts of petroleum products create ongoing interest in near-term improvements in automotive fuel economy. Companies including Honda, Toyota, GM and Ford have or are planning to introduce more fuel efficient gasoline-electric hybrid engines in several vehicles. While hybrid vehicles continue to emerge in the marketplace, other technologies for improving the fuel economy of conventional internal combustion engine (ICE) vehicles have also shown promise. Technologies including compression ignition engines (both diesel and gasoline fueled), automated clutch transmissions, lightweight aluminum and magnesium components, lightweight steel body construction, displacement-on-demand (also known as cylinder shut-off), continuously variable transmissions, and reduced engine displacement (moving to in-line five cylinder or three cylinder engines) have all shown promise for short-term improvements in fuel economy for ICE vehicles. Due to limitations in data availability regarding maintenance, repair, and overall durability of hybrid vehicles, only improvements in ICE powered vehicles were considered in the current study.

Previous studies (see for example (DeCicco, An, and Ross 2001), (Ogden, Williams, and Larson 2004), (Weiss et al. 2000)) have examined the potential fuel economy and retail price implications of ICE vehicles with advanced technologies. For example, Weiss et al. suggest the introduction of overall vehicle weight reduction, gasoline direct injection, automated clutch transmission, variable valve lift timing, and corresponding engine size reduction would improve the fuel economy of their reference vehicle (a 6 cylinder 1996 mid-sized sedan) from 27.8 mpg to 43.2 mpg by 2020. This improvement in fuel economy corresponds to a 2% annual improvement. Weiss et al. further suggest that additional weight reduction through aluminum or magnesium components<sup>24</sup>, improvements in overall vehicle aerodynamics, and additional engine size reduction (equivalent to a three cylinder engine) would improve fuel economy to 49.1 mpg in 2020. These improvements would add \$800 and \$2200 (constant 1997\$) to achieve 43.2 mpg and 49.1 mpg respectively (Weiss et al. 2000). These values form the basis of the alternative powertrain vehicle scenarios examined in the current study.

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<sup>23</sup> Fuel economy values discussed in this document are combined city/highway values calculated assuming 45% highway driving and 55% city driving.

<sup>24</sup> Total mass reduction from reference vehicle equivalent to 20%.

### *Advanced Internal Combustion Engine (ICE)*

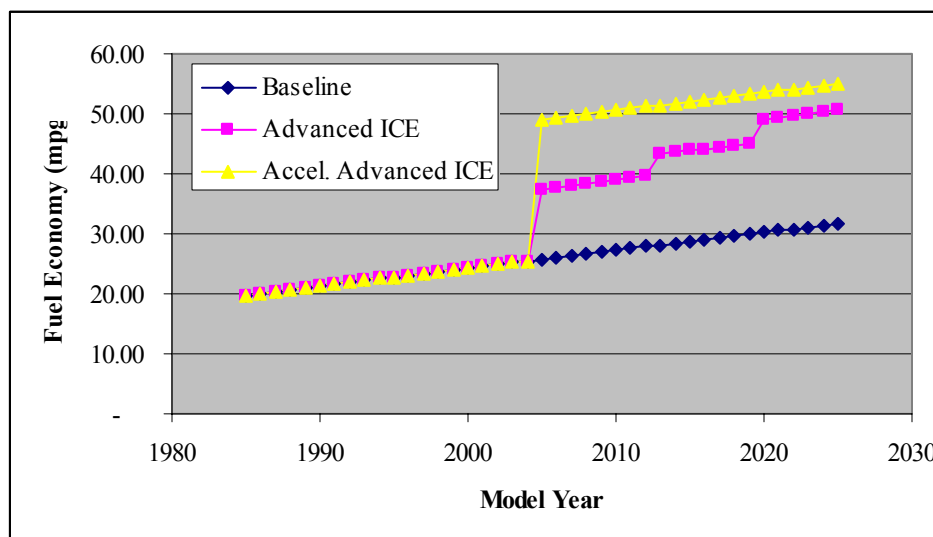
The advanced ICE scenario is derived from the overall vehicle technology improvements discussed in Weiss et al. (Weiss et al. 2000). Conditions studied under this scenario include a series of step-change improvements in vehicle fuel economy accompanied by increases in vehicle retail price. In between step changes in vehicle configurations the baseline 1% annual increase in fuel economy continues based on the assumption that minor tuning and refinement in technology will result in gradual improvement over time. The stages of vehicle improvements considered are as follows:

- 2005** Introduction of technology consistent with an 11.6 mpg improvement in fuel economy (to 37.4 mpg) accompanied by a \$1,770 increase in 2005 vehicle price from the baseline.
- 2013** Introduction of further improvements in fuel economy to achieve 43.3 mpg at a cost of \$2,175 relative to a baseline 2013 vehicle.
- 2020** A final improvement consistent with the advanced 2020 ICE vehicle considered by Weiss et al. with a fuel economy of 49.1 mpg and a \$2,529 price premium above the baseline.

### *Accelerated Advanced ICE*

This scenario considers the potential economic significance of introducing a fully realized advanced ICE engine vehicle on an accelerated timeline. This scenario takes the Weiss et al. 2020 advanced ICE vehicle and introduces corresponding technology in a 2005 generic vehicle. In this case, fuel economy makes a one time jump from 25.8 mpg for a 2005 baseline vehicle to 49.1 mpg for a 2005 advanced ICE generic vehicle. This is accompanied by a retail price increase of \$12,283 for the advanced ICE vehicle. Beyond 2005 fuel economy continues to improve at the national average rate of 1% annually.

Figure 7 shows the annual fuel economy improvement for all of the conditions examined in the current study.



**Figure 7. Generic Vehicle Fuel Economy by Scenario**

### 2.1.7 SCHEDULED MAINTENANCE

Scheduled maintenance activities and intervals were determined from interviews with representative service centers and through consultation with service manuals and research reports. The complete set of scheduled maintenance activities is shown in Appendix A and includes four inspection/cleaning groups and ten individual part replacements (such as spark plugs, wiper blades, mufflers, batteries and tires). In addition to the replacement schedule, Appendix A includes a full listing of the maintenance cost values used in the current study. These values were determined through interviews with dealer service centers in Southeastern Michigan. Calculation of annual scheduled maintenance cost assumes all events take place when scheduled.

### 2.1.8 UNSCHEDULED REPAIRS

Vehicle repairs due to unexpected part and component failure were considered unscheduled repairs in the current study. The annual cost of such repairs is difficult to determine as they are highly dependent on the operating conditions of the vehicle and nature of the specific part. As a starting point, data were taken from the *Reliability History* feature in the April issue of *Consumer Reports* between 1987 and 2003 (Consumer Reports 1987-2003). This annual feature provides the results of a vehicle owner survey of 333,000 to 480,000<sup>25</sup> *Consumer Reports* subscribers in 14 vehicle system categories. Results are provided in terms of percentage of vehicle owners reporting serious<sup>26</sup> repair problems with vehicle systems for specific model year vehicles at ages up to eight years. For the current study, values reported for the vehicles listed in Table 7 were examined when available. The maximum reported problem rate between the three vehicles studied was taken as the generic vehicle rate. Example values for eight systems consistently reported in the survey and of interest here are shown in Table 12.

**Table 12. Reported Problem Rates by Age for 1995 MY Generic Vehicle<sup>(a)</sup>**

Vehicle System	Age							
	1	2	3	4	5	6	7	8
Engine	≤2%	≤2%	2-5%	2-5%	5-9%	9-15%	9-15%	9-15%
Cooling	≤2%	≤2%	2-5%	5-9%	9-15%	>15%	>15%	>15%
Fuel	2-5%	2-5%	2-5%	5-9%	9-15%	9-15%	5-9%	5-9%
Ignition	≤2%	≤2%	2-5%	2-5%	5-9%	9-15%	5-9%	5-9%
Transmission	≤2%	2-5%	9-15%	>15%	>15%	>15%	5-9%	>15%
Electrical	2-5%	5-9%	5-9%	9-15%	9-15%	>15%	9-15%	>15%
Air Conditioning	≤2%	2-5%	9-15%	>15%	>15%	>15%	>15%	>15%
Suspension	2-5%	2-5%	5-9%	9-15%	9-15%	>15%	>15%	>15%

<sup>(a)</sup> Source: (Consumer Reports 1987-2003); Maximum reported range for the vehicles studied

The *Consumer Reports* reliability data were examined to determine the age at which 10%<sup>27</sup> of owners began to report problems with specific vehicle systems. This age combined with the assumed annual mileage of 12,000 miles/year was used to establish the component durability shown in Table 13. In the case of the ignition system, the

<sup>25</sup> Number of responses varies by year

<sup>26</sup> Seriousness of repair as determined by cost, failure, safety or extended downtime.

<sup>27</sup> Problems in the range of 9.3% to 14.8%

reported problem rate did not reach the 10% threshold in the eight years of data available; a 10 year life was assigned to this system. As a baseline assumption, individual components within the system believed to be more prone to replacement were assigned the initial replacement mileage<sup>28</sup>. For example, within the engine system, cost data were available for two components, the valves and gaskets and the short block. Valves and gaskets only were replaced in the first repair (96,000 miles) while the complete engine system was replaced every 192,000 miles. All replaced parts and components are considered to have durability equivalent to the original part.

Unscheduled repair costs are expected to show an extremely high degree of variability between owners. For this reason, two additional repair scenarios were considered. The first represents an improvement in the overall component durability, the second a decrease in overall component reliability. These scenarios were included in the analysis in an attempt to better capture the range of expected repair costs.

**Table 13. Generic Vehicle Unscheduled Repair Costs and Frequency**

Vehicle System	Component Part	Replacement Cost (2000 \$) <sup>(a)</sup>	Baseline	Durable	Unreliable
Engine	Valves and Gaskets	\$810	96,000	144,000	48,000
	Short Block	\$2,430	192,000	216,000	96,000
Cooling	Water Pump	\$200	60,000	96,000	60,000
	Radiator and Hoses	\$360	120,000	144,000	120,000
Fuel	Fuel Pump	\$290	144,000	168,000	96,000
	Fuel Injector	\$610	144,000	168,000	96,000
	Control Module	\$250	72,000	108,000	48,000
	Oxygen Sensor	\$110	72,000	108,000	48,000
Ignition	Starter	\$210	120,000	144,000	60,000
	Alternator	\$220	120,000	144,000	60,000
Transmission	Transmission	\$1,500	72,000	108,000	48,000
Electrical	Window Motor	\$170	48,000	72,000	48,000
	Wiper Motor	\$230	96,000	108,000	96,000
Air Conditioning	Blower and Heater Core	\$570	120,000	144,000	120,000
	Compressor	\$480	60,000	96,000	60,000
Suspension	Tie Rod	\$110	60,000	96,000	60,000
	Ball Joint	\$200	60,000	96,000	60,000
	Struts/Shocks	\$620	120,000	144,000	120,000

<sup>(a)</sup> Costs are for a Ford Taurus, costs for other vehicles not available; source (Consumer Reports 2000)

Overall, the range of resulting repair intervals for individual components compares favorably with other reported average component durability values. For example, *IntelliChoice* reports a typical replacement mileage for an alternator of 125,000 miles (the scenarios used in this study cover a range of 60,000 to 144,000 with a baseline of

<sup>28</sup> Only components for which cost data were available are included

120,000), a shock absorber at 75,000 miles (a range of 120,000 to 144,000 is used here) and a starter at 100,000 miles (60,000 to 144,000 here) (IntelliChoice 2003).

### **2.1.9 FINANCING**

Due to the fact that at least twice as many new vehicles are purchased with a personal loan than are purchased with cash (Richardson et al. 1997), we implement a personal loan for vehicle purchase in the baseline scenario, as described above. The details of the personal loan, taken from “Your Driving Costs,” (AAA Association Communication 1999), require a 20% down payment followed by 4 years of payments at an interest rate of 9%. Annual decisions made within the present model assume a single payment at the end of each of the first four years of ownership. If the vehicle is replaced before all payments are completed, the owner receives the depreciated value less the loan’s remaining principal in the sale.

### **2.1.10 EXTERNAL COSTS**

Model results were determined two ways: (1) using conventional ownership costs, and (2) accounting for ownership costs plus less-tangible costs typically overlooked in traditional economic analysis. Two categories of external costs were considered:

- Value of owner time required to accommodate vehicle repair and maintenance
- Societal costs of pollutant damages

The methodology and calculations supporting these evaluations are discussed in the sections that follow.

#### *Owner Time Investment*

Values in literature for the cost (or value) of personal time invested in driving vary over the range \$5.04 to \$12.85 per person-hour (Locke and Townley 1993), (Carstensen et al. 2001), (Schrank and Lomax 2002), (FHWA 2001). For the purposes of this study, a value of \$12.85 (2002 \$) was selected for use in determining the value of owner time required to accommodate vehicle repair. This value is proposed by Schrank et al. in the *2002 Urban Mobility Study*, a widely cited study of societal impacts of traffic congestion.

Our expanded cost analysis examines the cost associated with round trip travel for one occupant associated with each vehicle maintenance event<sup>29</sup>. Three alternative approaches to determining travel time requirements were considered. In the first approach, travel to and from repair/maintenance facilities was considered equivalent to national average trip length for shopping trips. Trips of this type covered an average distance of 6.1 miles according to the 1995 National Personal Transportation Survey (as reported in (Davis and Diegel 2002)). The same source reports a national average travel speed (for journey-to-work trips) of 29.8 miles per hour<sup>30</sup>. This results in a total travel time (two round trips) for each maintenance event of 0.8 hours. This approach resulted in an increase of between 2.5% and 49% for each scheduled maintenance event, with an average 15% increase, and between 0.3% and 2.5% increase for unscheduled repairs, with an average of 1.3%. Similarly, baseline total life cycle repair costs would increase 5% using this

<sup>29</sup> Maintenance events include scheduled maintenance such as oil change, inspections, and tune-ups, as well as unscheduled repairs.

<sup>30</sup> Value calculated based on reported average distance of 11.6 miles and average time of 23.35 minutes.

approach. However, these results account exclusively for owner time in transit between home and repair location and fail to consider any supplemental lost time such as time at the repair/maintenance facility, time for arrangements/logistics, or travel delays due to vehicle failure.

Therefore, two additional methods for calculating personal time required for repair were considered. The two approaches differ only in the length of time considered for each maintenance event. The first approach used an assumption of two hours of personal time for each scheduled repair and four hours for each unscheduled repair. The second increased these values to four hours for scheduled and six hours for unscheduled. In both cases the intent was to reflect the full range of expected time requirements associated with vehicle repair in addition to actual driving time. The assumption of two hours for scheduled maintenance results in a cost increase of between 6.1% and 120%, while four hours for each unscheduled repair adds 1.5% to 12.3% to repair costs. Overall this set of assumptions adds 15% to the baseline 20 year maintenance and repair costs. The second set of assumptions (four hours for scheduled, six hours for unscheduled) resulted in a per event increase between 12% and 250% for scheduled and 2.3% to 18% for unscheduled. The total baseline cost of 20 year repair and maintenance would increase 28% with this set of assumptions.

Only the approach accounting for two hours of personal time for each scheduled maintenance event and four hours for each unscheduled repair was included in the full scenario analysis. Values reported for the “external cost” scenario are based on a cost of \$25.70 (2002 \$) for owner time associated each scheduled maintenance event and \$51.40 associated with each unscheduled repair.

### *Pollutant Damages*

The societal costs of pollution were determined based on Equation 6.

$$(6) \quad C = \sum u_i e_i$$

Where,

- $C =$  Cost of pollutant damages
- $u_i =$  Unit damage cost of pollutant  $i$ <sup>31</sup> (e.g. \$/g emitted)
- $e_i =$  Life cycle tailpipe emissions (e.g. g)

A wide range of assumptions and valuation systems for determining unit costs associated with pollution exist in literature. Evaluations typically require assumptions with regard to societal willingness to pay for pollution avoidance and/or valuations of human life and well-being. The subjective nature of these variables has led to a wide range of reported unit pollutant costs. For example, ranges of \$5 to \$124 and \$13 to \$462 per ton of CO<sub>2</sub> emissions have been reported in the literature (by (Lewis et al. 1999) and (Ogden, Williams, and Larson 2004) respectively). Table 14 provides selected values for the pollutants studied here.

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<sup>31</sup> According to Spadro (1999)  $u_i$  is a function of the impact of emissions on human health, agriculture, and man-made structures.



**Table 14. Example Pollutant Unit Damage Costs**

Source	(a)	(b)	(c)	(d)
Units	(€/kg)	(€/metric ton)	(\$/ton)	(\$/ton)
Carbon Dioxide (CO <sub>2</sub> )	0.03	18.00	32.73	8.18
Carbon Monoxide (CO)	0.01 <sup>(e)</sup>	13.64 <sup>(e)</sup>		1
Non-Methane Hydrocarbon (NMHC)	0.93	930.00		
Nitrogen Oxides (NO <sub>x</sub> )	16.00	21,500.00		215.00

- (a) (Funk and Rabl 1999)  
 (b) (Spadaro and Rabl 2001)  
 (c) (Ogden, Williams, and Larson 2004)  
 (d) Stationary emission sources; (Lewis et al. 1999)  
 (e) Calculated assuming 55% city driving and 45% rural

Two of the pollutants shown in Table 14 (NMHC and NO<sub>x</sub>) cause damage as a result of chemical interactions and transformation into secondary substances (such as ozone and nitrates) and have been treated as national, not local, stressors (Funk and Rabl 1999). Similarly, impacts of carbon dioxide emissions are considered relative to global effects such as global warming; therefore, damage cost values for carbon dioxide are not expected to vary at the local or regional level. However, carbon monoxide emissions are expected to result in local impacts and damage costs are expected to have location specific characteristics.

Published values for unit pollution costs were adjusted to reflect national average U.S. conditions are shown in Table 15.

**Table 15. Mobile Source Pollutant Unit Damage Costs,  $u_i$  (2002 \$/kg)**

Carbon Dioxide (CO <sub>2</sub> )	0.04
Carbon Monoxide (CO)	0.00 <sup>(a)</sup>
Non-Methane Hydrocarbon (NMHC)	0.34
Nitrogen Oxides (NO <sub>x</sub> )	5.87

(a) 0.04 ¢/kg

For our analysis the value of \$0.04/kg selected for CO<sub>2</sub> was suggested by Ogden et al. and is within the illustrative range of \$66-\$170/ton (carbon) considered by the European Commission (Ogden, Williams, and Larson 2004). CO, NMHC and NO<sub>x</sub> unit damage costs were scaled from published values based on the European Union ExternE methodology. The ExternE methodology results in values (such as those published by Funk and Spadaro) dependent on population density (Funk and Rabl 1999), (Spadaro and Rabl 2001). Population densities in Europe (105 persons/km<sup>2</sup>), and France (national average: 105 persons/km<sup>2</sup>, 6,240 persons/km<sup>2</sup> in Paris) specifically, are considerably higher than those in the U.S. (national average: 31 persons/km<sup>2</sup>, 157 persons/km<sup>2</sup> for cities with population over 100,000). The values shown in Table 15 have been adjusted based on relationships documented by Rabl and Spadaro (Rabl and Spadaro 1999) to account for the lower population density of the U.S.

To better characterize the impacts of pollution from stationary manufacturing sources, unit cost values proposed by Lewis et al. for utility plant emissions of CO and NO<sub>x</sub> are

used<sup>32</sup> (Lewis et al. 1999). The source data were shown in last column of Table 14. In terms of 2002 \$/kg these values are \$.001/kg and \$0.26/kg for CO and NO<sub>x</sub> respectively.

## 2.2 Results

### **2.2.1 VEHICLE OWNERSHIP COSTS**

The cost estimating methods described in the earlier sections were used to determine the total annual ownership cost for the generic sedan. Annual ownership costs were calculated based on the annual fixed and variable costs for generic vehicle operation described in section 2.1. The resulting total annual costs for the baseline generic vehicle are shown in Figure 8. These results highlight the strong additive impact of high depreciation and financing charges in the first years of vehicle ownership. While variable costs are relatively low during this period of low maintenance and repair cost, this effect is offset by the high cost of depreciation and financing.

Figure 9 provides the total annual cost for the generic vehicle under all of the scenarios considered (for complete scenario description see section 2.1.1). In many cases the relatively minor changes from the baseline had only limited impact on the overall annual costs, with key exceptions in specific years. For example, in year eight when the scenarios following the low durability pattern for unscheduled repair (unreliable scenario and high cost scenario) experience a peak in variable repair costs.

#### *Life Cycle Ownership Cost*

In addition to considering the costs to an owner who sells a vehicle to a new owner for the depreciated value at the end of the ownership period, costs were evaluated assuming the vehicle would have to be scrapped at the end of the ownership period. This is referred to here as the total life cycle ownership cost and includes purchase, operation, and disposal (salvage value to owner). As was the case in the Phase I Escort Study, the end of life value for a scrap generic vehicle is taken as \$80 (1997 \$) (Keoleian et al. 1997). Table 16 provides the total life cycle cost of generic vehicle ownership at 10 and 20 years.

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<sup>32</sup> CO<sub>2</sub> emission costs are not differentiated between stationary and mobile sources, no values were available for NMHC stationary emissions.

**Table 16. Total Per Mile Life Cycle Ownership Cost for a 2005 MY Generic Vehicle (constant 1985\$)**

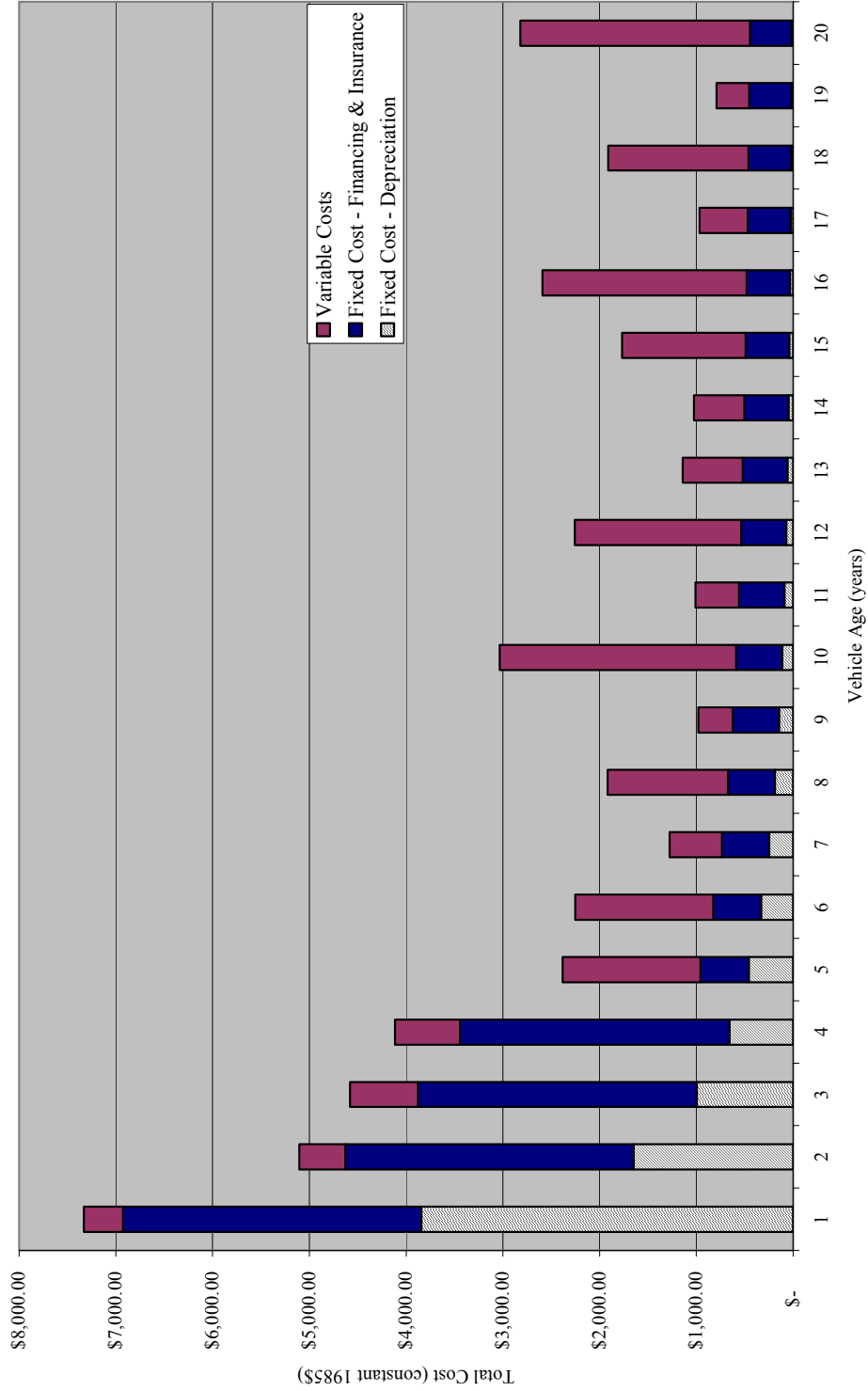
Scenario	Lifetime	
	10 years/ 120,000 miles	20 years/ 240,000 miles
Baseline	\$0.20	\$0.14
Durable	\$0.19	\$0.13
Unreliable	\$0.23	\$0.15
Improving	\$0.19	\$0.13
Cash Payment	\$0.19	\$0.14
Gas Tax	\$0.25	\$0.18
Advanced ICE	\$0.20	\$0.14
Accel. Advanced ICE	\$0.25	\$0.16
Accel. Adv. ICE with Gas Tax	\$0.27	\$0.18
External Cost	\$0.21	\$0.14
Slow Depreciation <sup>(a)</sup>	\$0.20	\$0.14
High Cost	\$0.28	\$0.20
Low Cost <sup>(a)</sup>	\$0.18	\$0.12

(a) For this table vehicle is assumed to be fully depreciated to residual scrap value at end of life in all cases.

The total life cycle results continue to emphasize the importance of fixed costs in overall ownership cost. Under the baseline conditions, after 10 years, fixed costs represent 70% of the total life cycle cost. After 20 years these costs (which occur mainly in the first 6-7 years<sup>33</sup>) represent 65% of the total life cycle ownership cost.

<sup>33</sup> 75% of the total 20 year fixed costs occur in years 1-7 under the baseline scenario. This is due largely to the impacts of financing (years 1-4) and depreciation.

**Fixed and Operating Costs for a 2005 MY Generic Sedan Under Baseline Conditions**



**Figure 8. Fixed and Variable Costs for a 2005 MY Generic Sedan Under Baseline Conditions (note financing charges are carried over the first four years of ownership)**

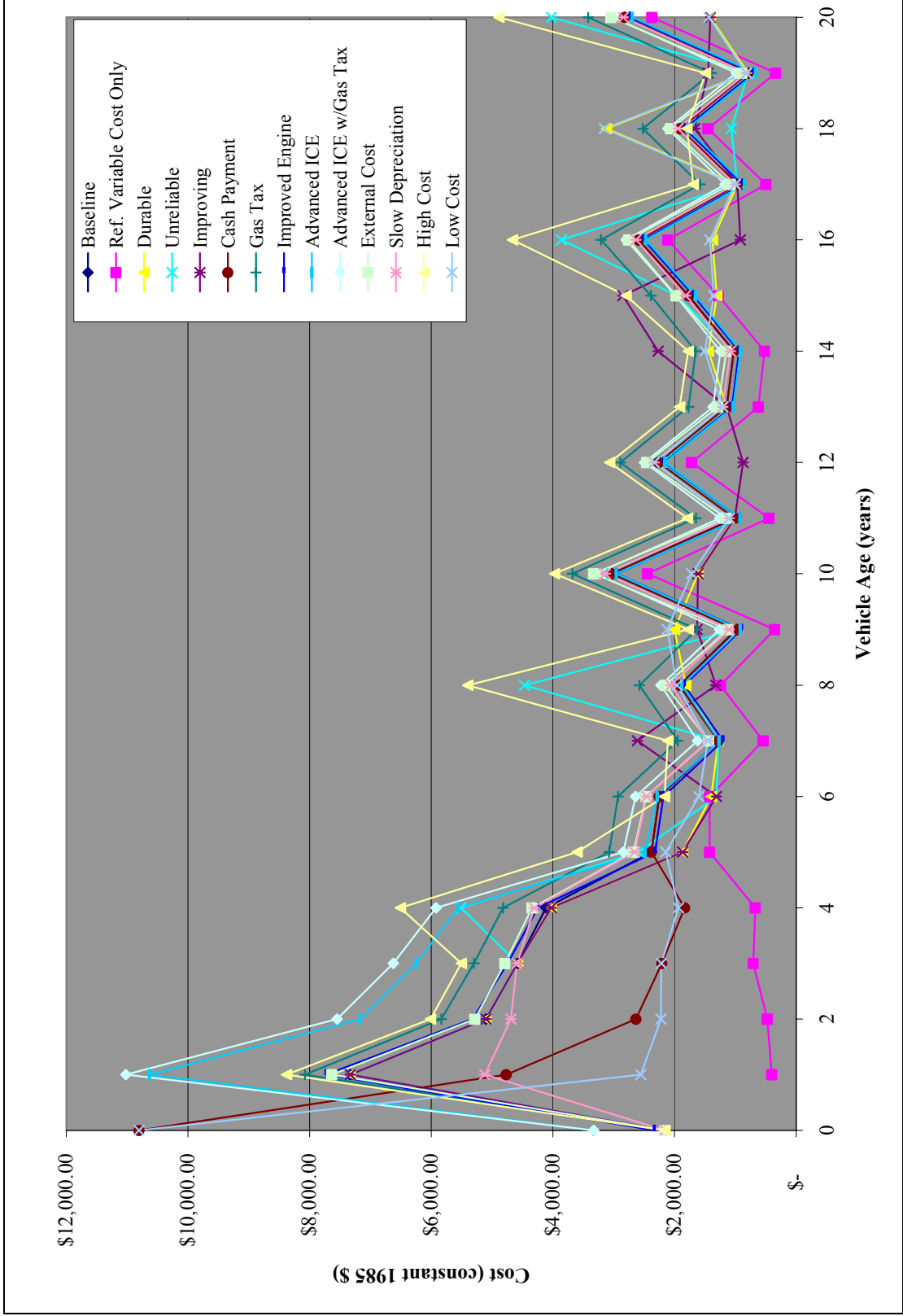


Figure 9. Total Annual Ownership Cost for a 2005 MY Generic Vehicle Under all Scenarios Investigated

*Used Vehicle Ownership*

In addition to economics and replacement policy for purchase of *new* vehicles, the potential economic impacts of *used* vehicle purchase were considered. While the dynamic replacement model did not allow the consideration of used vehicle purchase as an alternative to new vehicle purchase, the supporting economic data can provide insight with regard to used vehicle ownership costs. Using the generic vehicle economic data, the optimal ownership age for a used vehicle can be determined for any period of ownership. The central question here can be phrased as follows: if an individual were to purchase a used generic sedan, paying the depreciated price, at the end of year *n* and own it for *j* years selling it for the depreciated value, which combinations of *n* and *j* minimize ownership costs?

The answer to this question is dependent on the expected reliability of the vehicle purchased. The ideal times for vehicle ownership are years in which the vehicle is depreciating very little and few expensive components require repair. Identification of time periods that fit these criteria is dependent on component durability, corresponding replacement schedule and individual component costs. The potential 3, 4, 5 and 6 year ownership costs for generic vehicles were calculated for the baseline, durable and unreliable scenarios described above<sup>34</sup>. Results are shown in Table 17.

**Table 17. Low Cost Ownership Periods for Used 2005 MY Generic Vehicles**

Length of Ownership	Scenario Conditions	Optimal Years of Ownership	Average Per Mile Cost (1985\$)
3 years	Baseline	17-19	\$0.10
	Unreliable	17-19	\$0.08
	Durable	15-17	\$0.10
4 years	Baseline	11-14	\$0.11
	Unreliable	11-14	\$0.11
	Durable	14-17	\$0.11
5 years	Baseline	11-15	\$0.12
	Unreliable	11-15	\$0.12
	Durable	13-17	\$0.10
6 years	Baseline	14-19	\$0.13
	Unreliable	9-14	\$0.13
	Durable	12-17	\$0.12

These results continue to emphasize the importance of depreciation as a driving factor in economic decisions. All scenarios favor older, more fully depreciated vehicles that have had some major repairs completed. In other words, it is economically advantageous to purchase an older vehicle in good working condition and pay for any additional repairs while avoiding the low repair but high depreciation newer vehicles. However, this discussion ignores an individual’s apprehension with regard to potential future repairs on a used vehicle and overall preference for new vehicle features, styling and performance.

<sup>34</sup> These scenarios are considered here without financing charges that would increase costs during the first years of ownership. Similarly, used vehicles are purchased with cash.

### New Vehicle Premium

The results discussed above have focused on evaluations of total lifetime ownership costs and identifying patterns or low points within a 20 year ownership horizon. The next section (2.2.2) will examine the optimal vehicle replacement intervals that minimize total ownership costs over a 36 year period (1985-2020). Both analysis methods suggest that long term (more than 14 years) ownership is economically advantageous. However, anecdotal evidence, such as the popularity of vehicle lease programs<sup>35</sup>, suggests that owners exhibit a strong preference for ownership periods substantially shorter than ideal. Potential explanations include aversion to potential repairs or breakdowns, interest in new vehicle features, and overall enhanced pleasure of driving a new vehicle (Porter 1999).

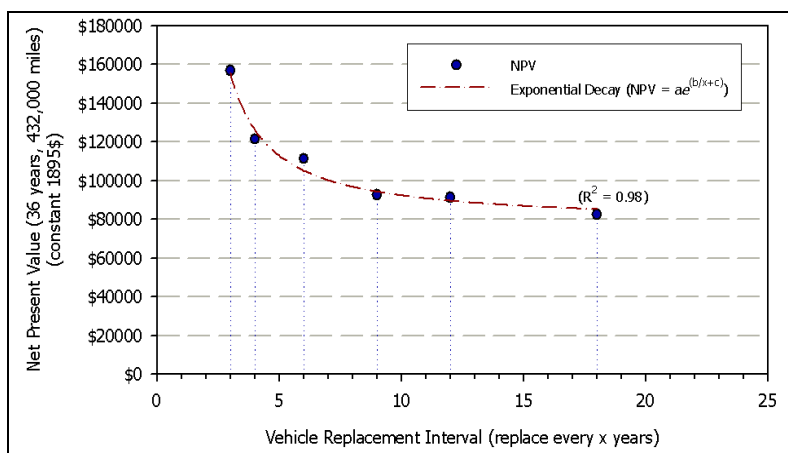
Individuals that replace vehicles more often than the economic ideal could be thought of as paying a premium for vehicle operation. Table 18 provides the per mile premium for more frequent vehicle turnover based on conditions and assumptions in the baseline generic vehicle scenario.

**Table 18. Premium Paid for Higher Turnover of a Baseline Generic Vehicle Over 36 Years of Operation (1985-2020)**

Vehicle Turnover	Ownership Cost (constant 1985 \$/mile)	Per Mile Premium
Ideal <sup>(a)</sup>	\$0.19	-
Every 12 years	\$0.21	\$0.02
Every 9 years	\$0.21	\$0.03
Every 6 years	\$0.26	\$0.07
Every 4 years	\$0.28	\$0.09
Every 3 years	\$0.36	\$0.17

<sup>(a)</sup> Replacement after 17 years and 19 years as discussed in section 2.2.2

These values suggest an exponential decay in the 36-year net present value of vehicle ownership with increasing ownership periods as shown in figure 10.



**Figure 10. Net Present Value of Ownership Costs Associated with Decreasing Vehicle Replacement**

<sup>35</sup> The popularity of leasing has increased from 25% of all purchases in 1994 to an expected level of 39% in 2005 (Richardson et al. 1997).

### 2.2.2 REPLACEMENT INTERVALS

A C program was developed to solve a dynamic program minimizing cost for each of the 13 scenarios. The optimal vehicle replacement policy over the 1985-2020 time horizon for each scenario, and the corresponding cumulative cost, is displayed in Table 19.

**Table 19. Generic Vehicle Life Cycle Cost Scenario Results**

Scenario Name	Optimal Replacement Policy	Total Cost (1985 \$)
"Baseline"	17 years, 19 years	\$81,687
"Durable"	17 years, 19 years	\$75,368
"Unreliable"	19 years, 17 years	\$91,603
"Increasing Durability"	19 years, 17 years	\$83,649
"Cash Payment"	17 years, 19 years	\$79,038
"Gas Tax"	15 years, 20 years, 1 year	\$86,984
"Advanced ICE"	17 years, 19 years	\$81,687
"Accel. Advanced ICE"	17 years, 19 years	\$81,687
"Accel. Adv. ICE w/Gas Tax"	15 years, 20 years, 1 year	\$87,516
"External Cost"	17 years, 19 years	\$90,402
"Slow Depreciation"	17 years, 19 years	\$81,309
"High Cost"	14 years, 19 years, 3 years	\$104,368
"Low Cost"	1 year, 17 years, 17 years, 1 year	\$71,918

ICE = Internal Combustion Engine

Similar to the Escort results, many policies were unchanged by varying the conditions examined. With the *Unreliable* and *Increasing Durability* scenarios<sup>36</sup>, the optimal policy required keeping the first vehicle longer than the *Baseline* case, in order to avoid higher maintenance costs as the second vehicle aged. The three scenarios in which the substantially increased gasoline tax was introduced (*Gas Tax*, *Accelerated Advanced ICE*

<sup>36</sup> In both the *unreliable* and *increasing durability* scenarios vehicle repair costs are relatively low in years 17,18, and 19 as shown in Figure 9.



*with Gas Tax*, and *High Cost*) were the only scenarios that induced a third vehicle purchase to take advantage of the improving fuel economy in newer vehicles.

Across all scenarios, the economic life of vehicles extends well beyond ten years of use. Despite increasing maintenance costs over time and varying purchase options, it is still preferable to postpone the high cost of purchasing a new vehicle.

## **Conclusions**

Overall, this analysis provides substantial evidence for the importance of fixed costs, and depreciation specifically, in total life cycle vehicle economics. Dynamic replacement modeling for both the Ford Escort and generic sedan suggested long replacement intervals (of 15 years or more) were economically ideal despite varying repair, and finance costs. In the generic vehicle study, additional variations in finance methods, gasoline price, powertrain availability, and external societal costs made little change to the ideal replacement intervals.

### *National Ownership Patterns*

Analysis by Oak Ridge National Laboratory suggests that 1990 MY vehicles will remain on the road for 16.8 years before retirement (Davis and Diegel 2002). Interestingly, this is consistent with the economically ideal replacement policy for a baseline generic vehicle in the current study (17 years). However, a portion of vehicle owners in the U.S. are willing to pay a substantial premium to own a new vehicle. Every year, 4.6 million vehicles less than four years old (3.4% of all registered vehicles in the U.S.) are sold on the used car market in the U.S. (Lescota 2003). The results presented in Table 18 suggest<sup>37</sup> that keeping these vehicles as little as one additional year (replacement every four years) could reduce ownership costs by 8 cents/mile. Further extending the ownership period to 18 years would reduce ownership costs by nearly 50% per mile – a 17 cents/mile savings.

This observation suggests that for many U.S. drivers, vehicle ownership (and new vehicle ownership specifically) has substantial hidden value. Some examples of potentially hidden values include dependability/ reliability, societal status, and new features/ functionality. In other words, mobility, for many Americans, is more than just getting from point A to point B at the lowest cost. These hidden values have potential policy implications for delivering mobility solutions to lower-income households, reducing national emissions, and alleviating congestion problems in cities.

### *Ownership Costs for the Ford Escort Wagon vs. the Generic Sedan*

Not surprisingly, the generic sedan with a higher purchase price and lower fuel economy is expected to incur higher lifetime ownership costs than an Escort wagon. Table 20 provides the life cycle ownership costs for the Escort wagon and the baseline generic vehicle.

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<sup>37</sup> This hypothetical discussion treats all U.S. vehicles as baseline generic sedans.

**Table 20. Life Cycle Costs for Generic Sedan and Escort Wagon**

Vehicle	Lifetime	
	10 years/ 120,000 miles	20 years/ 240,000 miles
Escort Wagon <sup>(a)</sup>	\$0.16	\$0.12
Generic Vehicle (baseline)	\$0.20	\$0.14
Generic Vehicle (low – high range)	\$0.18 - \$0.28	\$0.12-\$0.20

<sup>(a)</sup> Escort data presented here are based on constant 12,000 miles/yr

Despite differences in repair cost profiles, purchase price, vehicle class, etc., both the specific Escort studied and the generic vehicle exhibited identical ideal replacement intervals of 17 years and 19 years. While the limited number of vehicles considered here and the potential real world variability in vehicle ownership costs suggest that this is not a “universal” replacement interval result, long ideal replacement intervals are expected for all potential ownership scenarios.

#### *Emissions-Based Replacement Intervals*

Previous studies have examined the life cycle energy and emissions associated with generic vehicles and their replacement (Ecobalance and National Pollution Prevention Center 1999), (Kim et al. 2003). Kim et al. determined the optimal replacement interval for a generic vehicle with regard to life cycle energy and emissions. Independent optimizations were conducted to minimize energy use, CO<sub>2</sub> emissions, CO emissions, NMHC emissions, and NO<sub>x</sub> emissions. Generic vehicle replacement intervals that minimize environmental factors are shown in Table 21 along with the baseline per mile cost determined in the current study.

**Table 21. Environmental Burdens and Ownership Cost Associated with Emissions-Based Replacement Policies.**

Objective	Optimal Vehicle Lifetimes (years)	Environmental Burdens <sup>(a)</sup>					Ownership Cost (1985 \$ /mile)
		Energy (10 <sup>3</sup> GJ)	CO <sub>2</sub> (10 <sup>5</sup> kg)	CO (10 <sup>6</sup> g)	NMHC (10 <sup>5</sup> g)	NO <sub>x</sub> (10 <sup>5</sup> g)	
Minimize CO <sub>2</sub> emissions and Energy Use <sup>(b)</sup>	18,18	3.34	2.18	4.95	6.18	6.52	\$0.19
Minimize CO emissions	3,3,4,6,6,7,7	3.84	2.46	2.76	4.29	4.54	\$0.27
Minimize NMHC emissions	6,6,10,14	3.53	2.29	2.96	4.07	4.47	\$0.23
Minimize NO <sub>x</sub> emissions	5,5,6,6,14	3.65	2.36	2.86	4.14	4.32	\$0.24

NMHC = Non Methane Hydrocarbon

(a) Source: (Kim et al. 2003)

(b) Energy minimum and CO<sub>2</sub> minimum occur simultaneously.

The results in Table 21 suggest current economic parameters governing vehicle replacement are consistent with optimal replacement intervals to minimize carbon dioxide emissions and life cycle energy use. However, replacement policies that

minimize other specific pollutants, such as CO, NO<sub>x</sub>, or NMHC, could increase baseline generic vehicle ownership costs as much as four to eight cents/mile over a 36 year period.

As was the case for external cost scenario described earlier, the additional variable costs associated with expected societal damage caused by pollutants does not offset the higher fixed costs of more frequent vehicle replacement. Pollutant damage costs and ownership costs for the policies in Table 21 are shown in Table 22. The pollutant damage costs shown in Table 22 were calculated using the procedure described in Section 2.1.10 above.

**Table 22. Total Pollutant Damage Costs and Total Ownership Cost Associated with Emissions-Based Replacement Policies.**

Objective	Optimal Vehicle Lifetimes (years)	Pollutant Damage Cost (1985\$)	Ownership Cost (1985\$)	Total Damage + Ownership (1985\$)
Minimize CO <sub>2</sub> emissions and Energy Use	18,18	\$29,300	\$82,100	\$111,000
Minimize CO emissions	3,3,4,6,6,7,7	\$22,700	\$118,000	\$141,000
Minimize NMHC emissions	6,6,10,14	\$22,000	\$98,400	\$120,000
Minimize NO <sub>x</sub> emissions	5,5,6,6,14	\$21,600	\$104,000	\$126,000

The NO<sub>x</sub> emissions resulting from vehicle operation dominate the pollutant damage costs shown in Table 22. While the total mass of NO<sub>x</sub> emissions is less than one percent of the CO<sub>2</sub> emission levels, the unit damage cost for NO<sub>x</sub> is 147 times that for CO<sub>2</sub>. The cost of NO<sub>x</sub> emissions contributes between 70% and 78% of the total pollutant damage cost for the four optimization scenarios shown.

While policies optimal for reducing NO<sub>x</sub> emissions will minimize total pollutant damage costs to society (a 26% reduction in pollutant damage costs from CO<sub>2</sub> minimum levels), this same policy increases private vehicle ownership costs 27% over the minimum levels. These results suggest that vehicle scrappage programs could simultaneously minimize total ownership costs, energy use, and CO<sub>2</sub> emissions; however, such a program would need to be tailored to the specific vehicle conditions and costs of the fleet in question<sup>38</sup>.

<sup>38</sup> For a complete discussion of fleet replacement programs please see (Kim 2003).

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All vehicle names used in this document are trademarks of their respective manufacturers.

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## Appendix A. Scheduled Maintenance

Data sources for the consideration of generic vehicle scheduled maintenance costs are as follows:

I	University Chevrolet	Ypsilanti, MI
II	Varsity Ford	Ann Arbor, MI
III	McDonald Pontiac GMC	Saginaw, MI
IV	Gene Butman Ford	Ypsilanti, MI
V	USAMP Study Documentation	

**Table A-1. Groups of recurrent scheduled items (Data Source I)**

	Maintenance Item(s):	Frequency (miles)	Cost (constant 2000 \$)
Group 1:	Lubricate/inspect front suspension Change Oil (5 quarts) Change Oil filter Refill windshield wiper fluid	Every 3000	23.20
Group 2:	All of Group 1 Safety Inspection Rotate Tires	At 6000/21,000/36,000/ 51,000/66,000/81,000...	49.95
Group 3:	All of Group 1 Tire rotation and wheel balancing Clean, inspect and adjust brake system Inspect cooling system, tighten hoses Inspect exhaust system and heat shields	At 15,000/45,000/75,000 /105,000...	169.95
Group 4:	All of Group 1 Replace air filter and PCV filter Replace fuel filter Inspect vacuum hose and EGR system Check engine timing Inspect cooling system, tighten hoses Inspect fuel tank cap and lines Tire rotation and wheel balancing Clean, inspect and adjust brake system Inspect exhaust system and heat shields	At 30,000/60,000/90,000 /120,000...	279.95



**Table A-2. Single Items (data sources as noted)**

Data Source	Maintenance Item:	Frequency (miles)	Cost (constant 2000 \$)
I, V	Replace spark plugs, inspect wires	Every 30,000	59.99
I, V	Replace windshield wiper blade inserts	Every 12,000	19.99
I, IV, V	Auto. Transmission/Transaxle service (Replace filter, pan gasket and fluid)	Every 30,000	79.95
I, V	Power cooling system flush (Includes coolant recycling)	36,000/75,000/105,000	79.95
I, V	Replace front disc brakes (dealer parts)	Every 60,000	179.95
I, V	Replace rear brake pads/shoes (dealer parts)	Every 60,000	149.99
II, III, V	Replace tires (set of four)	Every 40,000	400.00
III, V	Replace muffler, exhaust pipe	Every 60,000	276.00
II, V	Replace Battery	Every 60,000	84.95
II, III, V	Replace struts/shocks	Every 80,000	600.00