appendix A

Highway Investment Analysis Methodology

Highway Investment Analysis Methodology

Investments in highway resurfacing and reconstruction and in highway and bridge capacity expansion are modeled using the Highway Economic Requirements System (HERS), which has been used since the publication of the 1995 C&P Report. This appendix describes the basic HERS methodology and approach in more detail than is presented in Part II, including the model features that have changed significantly from those used for the 2013 C&P Report: the valuation of travel time and the representation of pavement quality.

Highway Economic Requirements System

HERS begins the investment analysis process by evaluating the current state of the highway system using information on pavements, geometry, traffic volumes, vehicle mix, and other characteristics from the Highway Performance Monitoring System (HPMS) sample dataset. Using section-specific traffic growth projections, HERS forecasts future conditions and performance across several funding periods. As used in this report, the future analysis covers four consecutive 5-year periods. At the end of each period, the model checks for deficiencies in eight highway section characteristics: pavement condition, surface type, volume/service flow (V/SF) ratio (a measure of congestion), lane width, right shoulder width, shoulder type, horizontal alignment (curves), and vertical alignment (grades).

After HERS determines that a section's pavement or capacity is deficient, it identifies potential improvements to correct some or all of the section's deficient characteristics. The HERS model evaluates seven kinds of improvements: resurfacing, resurfacing with shoulder improvements, resurfacing with widened lanes (i.e., minor widening), resurfacing with added lanes (i.e., major widening), reconstruction, reconstruction with widened lanes, and reconstruction with added lanes. For reconstruction projects, the model allows for upgrades of low-grade surface types when warranted by sufficient traffic volumes. For improvements that add travel lanes, HERS further distinguishes between two capacity additions: those that can be made at "normal cost" and those on sections where obstacles to widening are present, making capacity additions feasible only at "high cost." HERS might also evaluate alignment adjustments to improve curves, grades, or both.

When evaluating which potential improvement, if any, should be implemented on a particular highway section, HERS employs incremental benefit-cost analysis. Such an analysis compares the benefits and costs of a candidate improvement to those of a less aggressive alternative—for example, reconstructing and adding lanes to a section could be compared with reconstruction alone. HERS defines benefits as reductions in direct highway user costs, agency costs, and societal costs. Highway user benefits include reductions in travel time costs, crash costs, and vehicle operating costs (e.g., fuel, oil, and maintenance costs); agency benefits include reduced routine maintenance costs (plus the residual value of projects with longer expected service lives than the alternative); and societal benefits include reduced vehicle emissions. Increases in any of these costs resulting from a highway improvement (such as higher emissions rates at high speeds or the increased delay associated with a work zone) would be factored into the analysis as a negative benefit ("disbenefit").

Dividing these improvement benefits by the capital costs associated with implementing the improvement results in a benefit-cost ratio (BCR) that is used to rank potential projects on different highway sections. HERS implements improvements in order of BCR, with the improvement having the highest BCR implemented first. Thus, as each additional project is implemented, the marginal BCR declines, resulting in a decline in the average BCR for all implemented projects. Until the point at which the marginal BCR falls below 1.0 (i.e., costs exceed benefits), however, total net benefits continue to increase as additional projects are implemented. Investment beyond this point is not economically justified because a decline in total net benefits would result.

Because HERS analyzes each highway section independently rather than the entire transportation system, it cannot fully evaluate the network effects of individual highway improvements. Although efforts have been made to account indirectly for some network effects, HERS is fundamentally reliant on its primary data source—the national sample of independent highway sections contained in HPMS. Fully recognizing all network effects would require developing significant new data sources and analytical techniques.

HERS Improvement Costs

For the 2004 C&P Report, significant changes were made to the structure of the HERS improvement cost matrix, the assumed unit costs in that matrix, and the manner in which those values were applied. The improved cost updates reflected in the 2004 C&P Report were based on highway project data from six States. The 2004 update disaggregated the improvement cost values in urban areas by functional class and by urbanized area size. Three population groupings were used: small urban (populations of 5,000 to 49,999), small urbanized (populations of 50,000 to 200,000), and large urbanized (populations of more than 200,000).

For the 2006 C&P Report, additional project cost data were collected for large urbanized areas, rural mountainous regions, and high-cost capacity improvements. These data were used to update the HERS improvement cost matrix, which was also modified to include a new category for major urbanized areas with populations of more than 1 million. The HERS improvement cost matrix was adjusted further for the 2008 C&P Report based on additional analysis of the data previously collected. For this 2015 C&P Report, the only change made to the cost matrix was an adjustment for the change in the National Highway Construction Cost Index between 2006 and 2012.

Exhibit A-1 identifies the costs per lane mile assumed by HERS for different types of capital improvements. For rural areas, separate cost values are applied by terrain type and functional class, while costs are broken down for urban areas by population area size and type of highway. These costs are intended to reflect the typical values for these types of projects in 2012, and thus do not reflect the large variation in cost among projects of the same type, even in a given year.

Such variation is evident in the project-level data on which these typical values are based and are attributable to several location-specific factors. For example, the costs assumed for highway widening projects are predicated on each section's having several bridges typical for the section's length, but in reality some sections will have more bridges than other sections of equal length, which adds to costs. Among other factors that could make costs unusually high are complicated interchanges, major environmental issues, and other extreme engineering issues.

Exhibit A-1 Typical Costs per Lane Mile Assumed in HERS by Type of Improvement

	Typical Costs (Thousands of 2012 Dollars per Lane Mile)								
Category	Reconstruct and Widen Lane	Reconstruct Existing Lane	Resurface and Widen Lane	Resurface Existing Lane	Improve Shoulder	Add Lane, Normal Cost	Add Lane, Equivalent High Cost	New Alignment, Normal	New Alignment, High
Rural									
Interstate									
Flat	$1,496	$977	$847	$347	$65	$1,923	$2,666	$2,666	$2,666
Rolling	$1,677	$1,003	$975	$370	$106	$2,085	$3,374	$3,374	$3,374
Mountainous	$3,180	$2,195	$1,615	$547	$223	$6,492	$7,600	$7,600	$7,600
Other Principal Arterial									
Flat	$1,169	$782	$706	$279	$43	$1,541	$2,205	$2,205	$2,205
Rolling	$1,319	$804	$803	$310	$72	$1,650	$2,662	$2,662	$2,662
Mountainous	$2,562	$1,810	$1,556	$438	$95	$5,824	$6,706	$6,706	$6,706
Minor Arterial									
Flat	$1,069	$687	$658	$247	$41	$1,400	$1,966	$1,966	$1,966
Rolling	$1,290	$761	$819	$266	$75	$1,605	$2,532	$2,532	$2,532
Mountainous	$2,143	$1,405	$1,556	$365	$168	$4,916	$5,900	$5,900	$5,900
Major Collector									
Flat	$1,125	$728	$680	$252	$52	$1,455	$1,965	$1,965	$1,965
Rolling	$1,232	$739	$765	$267	$70	$1,486	$2,418	$2,418	$2,418
Mountainous	$1,869	$1,157	$1,113	$365	$108	$3,147	$4,111	$4,111	$4,111
Urban									
Freeway/Expressway/Interstate									
Small Urban	$2,440	$1,690	$1,923	$410	$75	$3,061	$10,022	$4,126	$14,085
Small Urbanized	$2,623	$1,704	$1,989	$485	$99	$3,345	$10,991	$5,562	$18,986
Large Urbanized	$4,184	$2,790	$3,081	$651	$376	$5,598	$18,777	$8,158	$27,849
Major Urbanized	$8,368	$5,580	$5,979	$1,078	$752	$11,197	$46,691	$16,315	$62,414
Other Principal Arterial									
Small Urban	$2,127	$1,436	$1,760	$344	$76	$2,602	$8,500	$3,253	$11,102
Small Urbanized	$2,275	$1,453	$1,840	$406	$102	$2,819	$9,244	$4,013	$13,698
Large Urbanized	$3,251	$2,129	$2,692	$511	$328	$4,126	$13,786	$5,509	$18,804
Major Urbanized	$6,501	$4,259	$5,384	$825	$656	$8,252	$31,988	$11,018	$47,693
Minor Arterial/Collector									
Small Urban	$1,567	$1,084	$1,331	$252	$55	$1,922	$6,225	$2,347	$8,011
Small Urbanized	$1,642	$1,097	$1,343	$286	$68	$2,025	$6,580	$2,880	$9,830
Large Urbanized	$2,210	$1,466	$1,837	$351	$184	$2,807	$9,321	$3,748	$12,792
Major Urbanized	$4,421	$2,932	$2,779	$585	$368	$5,614	$31,988	$7,496	$39,585

Source: Highway Economic Requirements System.

The values shown in *Exhibit A-1* for adding a lane at "Normal Cost" reflect costs of projects for which sufficient right-of-way is available or readily obtained to accommodate additional lanes. The values for adding lane equivalents at "High Cost" are intended to reflect situations in which conventional widening is infeasible and alternative approaches are required to add capacity to a given corridor. Such alternatives include the construction of parallel facilities, double decking, tunneling, or the purchase of extremely expensive right-of-way. HERS models these lane equivalents as though they are part of existing highways, but some of this capacity could be from new highways or other modes of transportation.

Allocating HERS Results Among Improvement Types

Highway capital expenditures can be divided among three types of improvements: system rehabilitation, system expansion, and system enhancements (see Chapters 6 and 7 for definitions and discussion). Improvements selected by HERS that do not add lanes to a facility are classified as part of system rehabilitation. Highway projects that add lanes to a facility normally include resurfacing or reconstructing existing lanes; HERS therefore splits the costs of such projects between system rehabilitation and system expansion.

Pavement Condition Modeling

HERS incorporates information on pavement condition when evaluating deficiencies, determining speed, calculating vehicle operating costs, estimating agency maintenance costs, and forecasting pavement deterioration. Building from a multiyear research effort beginning in 2004, this C&P report reflects a new set of HERS pavement performance equations.

The new HERS procedures are based on a series of equations from a Mechanistic-Empirical Pavement Design Guide (MEPDG) formula sponsored by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) through the National Cooperative Highway Research Program. Previous editions of the C&P report relied on HERS equations derived from prediction models of pavement performance AASHTO developed in 1993, which are no longer considered representative of current pavement design practices.

The new HERS equations for pavement performance rely heavily on a set of new data items related to pavement characteristics and distresses that were added to the HPMS data reporting requirements in 2009 (*Exhibit A-2*). The equations also incorporate numerous default values for the multiple variables in the MEPDG algorithms; FHWA adopted this approach to reduce the number of new data elements that States would need to report. State Departments of Transportation (DOTs) provide default parameters for many of the variables. Additional data from the Long-Term Pavement Performance (LTPP) program and MEPDG supplement the HPMS sample data with required detail not available within the HPMS sample:

- LTPP climate and geographical data offer a finer level of detail used to supplement the broader climate zone values from the HPMS sample.
- LTPP and MEPDG soil data supplement the soil type indicators from the HPMS sample.
- LTPP and MEPDG data supplement HPMS sample data on base type.

Exhibit A-2 HERS Pavement Performance Equations Input Data by Type and Source

General Characteristics		
Data from HPMS	Location: State and county	
	Section length	
	Urban/rural status	
	Functional class	
	Facility type (e.g., one-way, two-way)	
	Number of lanes	
	Lane width	
	Speed limit	
	State ownership status	
Data from multiple sources (in parentheses)	Climate	Climate zone (HPMS)
		Rainfall (LTPP)
		Freezing index (LTPP)
		Air freeze-thaw cycles (LTPP)
		Mean monthly temperature (LTPP)
		Depth of ground water table (LTPP)
Travel Demand		
Data from HPMS	Annual average daily traffic (AADT)	
	Forecast AADT: forecast value and year of forecast	
Surface, Base, and Soil Characteristics		
Data from HPMS	Surface type	
	Year of last improvement	
	Year of last reconstruction	
	Thickness of rigid pavement: measured thickness and design/construction thickness	
	Thickness of flexible pavement: measured thickness and design/construction thickness	
	Previous overlay thickness (or typical design/construction thickness)	
	IRI (International Roughness Index)	
	PSR (Pavement Serviceability Rating)	
	Extent of fatigue cracking	
	Extent of transverse cracking	
	Average rutting	
	Average faulting (vertical displacement between adjacent panels)	
	Binder type	
	Typical joint spacing	
	Shoulder: type and tied shoulder status	
Data from multiple sources (in parentheses)	Dowel bar characteristics	Dowel bar status (HPMS)
		Dowel bar diameter (default)
	Soil	Soil type (HPMS)
		Sand fraction, by State and HPMS soil type (LTPP)
		Silt fraction, by State and HPMS soil type (LTPP)
		Clay fraction, by State and HPMS soil type (LTPP)
		Plasticity index, by State and HPMS soil type (LTPP)
		Soil resilient modulus, by HPMS surface type code and soil type code (MEPDG)
	Base characteristics	Base type (HPMS)
		Measured thickness (HPMS)
		Design/construction thickness (HPMS)
		Base material modulus (LTPP and MEPDG)
	Portland cement concrete properties	Portland cement concrete/base interface loss of friction age [debonding] (HPMS)
		Modulus, by State (LTPP)
		Compressive strength, by State (LTPP)
		Air content, by State (LTPP)
		Water-to-cement ratio, by State (LTPP)
	Asphalt layer	Gradation, by State (MEPDG and LTPP)
		Air voids, by State (MEPDG and LTPP)
		Binder content by volume, by State (MEPDG and LTPP)
		Air content, by State (LTPP)
		Asphalt PG (performance grade) model parameters, by high and low temperature grade (AASHTO)
		Asphalt viscosity grade model parameters, by asphalt binder grade (AASHTO)
Other data	Sealant type, by State (default)	

- For Portland cement concrete surfaces identified in the HPMS sample, data from the LTPP and Jointed Plain Concrete Pavement programs offer a range of attributes representing Portland cement concrete strength.
- For asphalt surfaces identified in the HPMS sample, MEPDG and LTPP data offer a range of attributes representing asphalt strength, while AASHTO model parameters governing asphalt performance grade and viscosity seed the pavement model equations directly.

The new HERS pavement performance equations project the level or severity of three distresses for concrete pavements—roughness, as measured by the International Roughness Index (IRI), faulting, and cracking, and three distresses for flexible composite pavements—roughness, rutting, and cracking. Among the pavement distresses HERS predicts, pavement roughness has the most direct influence on the model's calculations because the impact of pavement roughness on highway user costs is taken into account when HERS computes the benefit-cost ratio for potential improvements. Roughness, faulting, and cracking values do not directly influence HERS projections of user costs or agency maintenance costs. These distresses are taken into account in the computations indirectly, however, because they influence predicted pavement roughness.

The projected IRI values for rigid pavements are computed as a function of fatigue cracking, spalling, and faulting. Future IRI for flexible pavements is computed as a function of fatigue cracking, rutting, and transverse (low-temperature) cracking. The IRI for composite pavement is projected as a function of rutting, fatigue cracking, and reflective cracking. Each pavement type also has an age-based component and a climate-based component that are independent of individual distresses.

For each HPMS sample section analyzed, HERS first compares the State-reported IRI with a predicted IRI based solely on the characteristics of the pavement and the date the section was last constructed, reconstructed, or resurfaced as reported by the State. If the predicted IRI for the base year differs from the actual base-year IRI value, an adjustment factor is applied when predicting future IRI for that section. This procedure accounts for the impact of variables beyond those considered directly by HERS that might influence current pavement performance and is similar in concept to an adjustment procedure HERS uses when a State reports a different capacity for a sample section in HPMS than the software computes. This approach, however, makes the model highly dependent on the accuracy of the State-reported dates when each highway sample section was last improved.

Valuation of Travel Time Savings

HERS uses estimates of the value of travel time per vehicle hour for different vehicle types. FHWA recently conducted extensive research to expand and update to 2012 the estimated hourly values of travel time used in HERS. The primary objectives of this effort were to (1) identify reliable and recent sources of information on the major components of the values of travel time and (2) develop more comprehensive estimates of the value and amount of work-related business travel in light-duty passenger vehicles (automobiles and light trucks). This second objective required expanding previous estimates of business travel in HERS, which included only work-related trips using household vehicles (i.e., vehicles owned by households rather than by organizations), to include work-related travel using corporate and government fleet vehicles, rental cars, emergency vehicles, and taxi service. This update also sought to distinguish between hourly values of travel time for buses and those for three- or four-axle single-unit trucks, which were previously combined into a single vehicle class in HERS. Finally, this update ensured that the values of travel time for vehicle occupants used in HERS were consistent with DOT's most recent official guidance.

The vehicle types (VT) considered in HERS are:

- VT1: Small Auto
- VT2: Medium Auto
- VT3: Four-Tire Truck
- VT4: Six-Tire Truck
- VT5a: Three- or Four-Axle Truck
- VT5b: Bus
- VT6: Four-Axle Combination Truck
- VT7: Five- or More Axle Combination Truck

Several factors were considered in computing the value of time per vehicle hour for these VTs, including the value of vehicle occupants' travel time, vehicle occupancy, travel purpose (business or personal), capital costs for vehicles used for business, and inventory value of cargo carried by trucks.

The estimates of vehicle occupants' values of travel time, average vehicle occupancy, and the distribution of vehicle use between work-related and personal travel were constructed for individual vehicle classes as they are commonly identified in government and commercial information sources, surveys of vehicle ownership and use, and published research. These classes include passenger automobiles; light-duty trucks with different chassis and body configurations, such as minivans, SUVs (sport-utility vehicles), and pickup trucks; and various types of medium- and heavy-duty trucks usually identified by axle configuration, purpose, or body type.

For this update, values of vehicle occupants' travel time, average occupancy, and the amounts of work-related and personal travel were first developed for different categories of users for each vehicle class. The user categories used in this update include:

- households;
- businesses (those not primarily engaged in providing transportation services);
- rental agencies;
- government agencies;

- emergency service providers (such as police and fire departments);
- taxi operators;
- transit authorities;
- operators of intercity, charter, and tour bus services;
- school bus operators;
- freight carriers (including both for-hire carriers and private or in-house subsidiaries of other businesses); and
- a broad category of "commercial truck operators."

This approach was taken to enable ready use of data reported in government and industry publications, which typically report data for a single user category (such as rental companies, government agencies, or school bus operators), or obtained from surveys of vehicle use including the National Household Travel Survey (NHTS) and Vehicle Inventory and Use Survey (VIUS), which apply to clearly identifiable user categories. It also enabled incorporation of significant differences in the values of travelers' time, vehicle occupancy patterns, and the distribution of travel by purpose among different users of the same class of vehicles into the updated estimates.

Several of the HERS vehicle types correspond directly to a single class of vehicles for which such vehicle class data are commonly available, so the values of occupants' travel time, average vehicle occupancy, and the fractions of personal and business use for that vehicle class could be "mapped" readily to a single HERS vehicle type. These included VT1 (small automobiles), VT4 (six-tire trucks), VT5a (three- or four-axle single-unit trucks), VT5b (buses, including transit, intercity, charter and tour, and school buses), VT6 (four-axle combination trucks), and VT7 (combination trucks with five or more axles). This mapping was more complex for VT2 (medium automobiles) and VT3 (four-tire trucks), as each includes multiple classes of vehicles: VT2 includes automobiles and other light-duty vehicles used primarily to carry passengers such as minivans and SUVs; VT3 consists of large light-duty vehicles used to carry both passengers and cargo, including large passenger vans, cargo vans, and pickup trucks. Work-related and personal travel by all users of each vehicle class were totaled and used to determine the overall shares of these travel purposes for VT2 and VT3. The shares of work-related and personal travel for each vehicle class then were used to construct weighted-average values of occupant's values of time and average occupancy for VT2 and VT3.

Values of Vehicle Occupants' Travel Time

DOT's *Guidance on the Value of Travel Time in Economic Analysis*[1] outlines procedures for quantifying the value of time for vehicle occupants. For personal travel, this guidance recommends valuing vehicle occupants' time in local and intercity personal travel at different fractions of their hourly earnings rates. Because the data required to apportion nationwide travel between local and intercity trips are unavailable, however, this update adheres to the previous HERS practice of valuing personal travel time using the DOT recommendation for local travel. The value from DOT guidance was assumed to apply to drivers and to other occupants of all light-duty vehicles used for personal travel, including household vehicles, corporate fleet vehicles that employees are permitted to use for personal travel, rental vehicles, and taxis.[2] When multiple trip purposes were recorded, the distribution of person hours for the vehicle trip was applied to allocate vehicle hours recorded for the trip across reported trip purposes. The distribution also was used to value travel by bus passengers, including users of public transit, intercity, charter and tour, and school buses.

For business travel in light-duty vehicles (HERS VT1 through VT3) used by households, corporate fleets, and rental agencies, this update follows DOT guidance by valuing both drivers' and passengers' travel time at 100 percent of the average pre-tax hourly wage rate for all U.S. workers, including an allowance for the dollar value of fringe benefits. Wage rate and fringe benefit data for all U.S. workers and for the more detailed occupational categories used in the calculations described below were obtained for 2012 from U.S. Bureau of Labor Statistics (BLS) publications.[3] Travel in light-duty vehicles by government employees, which was assumed exclusively work-related, is valued at 100 percent of mean hourly earnings and fringe benefits for State and local government administrative workers. Similarly, travel in light-duty vehicles by police officers and fire department employees was assumed exclusively work-related and was valued at 100 percent of the mean hourly wage plus fringe benefits for police patrol officers. Taxi drivers' time is valued at 100 percent of the mean wage rate (plus the usual allowance for fringe benefits) as reported by BLS, while travel time for taxi passengers was valued identically to personal and business travel by household members in light-duty vehicles.

Travel time for drivers and other occupants of commercial vehicles (HERS VT4 through VT7) was valued at 100 percent of the average wage rate for corresponding occupational categories reported in BLS publications, including allowances for the hourly value of fringe benefits.[4] Drivers of vehicles included in HERS VT4 were assumed to have hourly wage rates corresponding to the BLS occupational category "light truck or delivery service drivers." Drivers of vehicles included in HERS VT5 through VT7 were assumed to earn wage rates reported by BLS for "heavy and tractor-trailer truck drivers." Other occupants of commercial trucks belonging to HERS VT4 were assumed to be paid work crewmembers engaged in work-related travel, whose travel time was valued using wage and fringe benefit rates for the BLS occupational category "general laborers." Travel time for bus drivers (HERS VT5) was valued using an estimate of the average hourly earnings rate (including wages plus the hourly value of fringe benefits) for public transit, intercity, and school bus drivers developed from BLS sources.[5]

Exhibit A-3 summarizes the resulting estimates of the average hourly values of individual vehicle occupants' time for business and personal travel using various classes of vehicles (in 2012 constant dollars). Although the entries in *Exhibit A-3* apply to each person hour of travel, they are average values that reflect the distribution of travel using vehicles in that class among various user categories (e.g., households, businesses, government agencies, commercial freight carriers), as well as their typical occupancies when used for business and personal travel by each category of user. For example, *Exhibit A-3* indicates that the average hourly value of travel time for business travelers representing all users of automobiles—including households, businesses, government agencies, and other user categories—is $31.65, while the corresponding average for all users of automobiles engaged in personal travel is $12.30. The entries for the "Bus" vehicle class in *Exhibit*

A-3 indicate that bus drivers' travel time, which represents business travel, is valued at an hourly rate of $23.79, while the travel time of bus passengers—who are traveling for personal reasons—is valued at $12.30 per hour.

Exhibit A-3 Average Hourly Value of Vehicle Occupants' Travel Time by User Category, Vehicle Class, and Travel Purpose (Values in Constant 2012 Dollars)

		Travel Purpose		
Vehicle Class	HERS Vehicle Type	Business	Personal	Total
Auto (small and medium)	VT1, VT2	$31.65	$12.30	$14.01
Minivan	VT2	$22.74	$12.30	$12.76
Large passenger van	VT2	$27.76	$12.30	$15.92
Cargo van	VT3	$27.52	$12.30	$27.43
SUV	VT3	$30.50	$12.30	$13.17
Pickup	VT3	$30.58	$12.30	$15.20
6-tire truck	VT4	$29.49	$12.30	$29.32
3- or 4-axle truck	VT5a	$30.29	$12.30	$30.28
Bus	VT5b	$23.79	$12.30	$13.18
4-axle combination truck	VT6	$28.00	$12.30	$27.92
5+-axle combination truck	VT7	$28.00	$12.30	$27.99

Source: U.S. DOT Revised Guidance on the Value of Travel Time in Economic Analysis (Revision 2 - 2015 Update), Bureau of Labor Statistics.

Vehicle Occupancy

For this update, average vehicle occupancy values were estimated by combining values obtained from the 2009 NHTS for household vehicles with detailed estimates of average vehicle occupancy for other vehicle types calculated from the National Highway Traffic Safety Administration's Fatality Analysis Reporting System (FARS) for 2010 to 2012.[6] In cases for which these estimates are not directly comparable, they appear to agree closely, suggesting that relying on occupancy counts from fatal accidents is unlikely to produce biased estimates of overall average vehicle occupancy.

These data were supplemented with estimates of the average number of qualified drivers carried by trucks and buses in long-haul service, where team or replacement drivers are occasionally used. These estimates were tabulated from approximately 3.5 million roadside inspection records for 2010 and 2011 obtained from the Federal Motor Carrier Safety Administration's Motor Carrier Management Information System.[7]

Corporate fleet and rental vehicles were assumed to have average occupancy identical to that of household vehicles of the same types (automobiles, mini vans, SUVs, and pickups) when used for the same travel purpose. Thus, for example, corporate fleet and rental automobiles were assumed to carry an average of 1.24 persons—the figure derived from the 2009 NHTS for work-related business travel using household automobiles—when used for work-related trips. No published estimates of occupancy were available for government and emergency service vehicles, which were assumed to be used exclusively for work-related travel; for this update, government fleet and emergency service vehicles were assumed to carry an average of one passenger in addition to the driver.

The number of fatal accidents involving buses reported in FARS was judged insufficient to yield reliable estimates of their average occupancy. Instead, average passenger occupancy estimates for intercity, charter, and tour buses were obtained from trade association publications.[8] Similarly, passenger occupancy estimates for transit buses were calculated from information reported by the American Public Transit Association.[9] No published estimates of occupancy were available for school buses, so these were assumed to carry 10 passengers on average. School and transit buses were assumed to carry a single driver, while roadside inspection records from the Federal Motor Carrier Safety Administration suggested that approximately 1 percent of intercity coaches carry a second driver.

Estimates of average occupancy for HERS VT4 (six-tire trucks) and VT5 (three- or four-axle single-unit trucks) obtained from FARS records suggest that these vehicles frequently carry occupants other than drivers. As indicated previously in the description of values of travel time, these additional occupants were assumed paid work crewmembers. Although FARS records also suggest that some combination trucks (HERS VT6 and VT7) carry occupants in addition to drivers, these additional occupants were assumed primarily companions to drivers or other passengers traveling for personal rather than work-related reasons. Inspection records from the Federal Motor Carrier Safety Administration indicated that approximately 2 percent of combination trucks carried a second qualified driver.

Exhibit A-4 summarizes the resulting estimates of average occupancy—including drivers and any passengers—for each vehicle class. It shows, for example, that automobiles operated by all categories of users (e.g., households, businesses, government agencies) carry an average of 1.24 occupants when used for business travel and 1.57 occupants when used for personal travel. These averages reflect variation in the typical occupancies of vehicles within each class when they are operated by different users, such as households, corporate fleets, government agencies, vocational operators (such as suppliers of construction materials and services), and freight carriers. The entries for the Bus vehicle class in *Exhibit A-4* indicate that buses are occupied by a single driver engaged in work-related travel, plus an average of 12.10 occupants engaged in personal travel.

Exhibit A-4 Average Vehicle Occupancy (Persons) by User Category, Vehicle Class, and Travel Purpose

		Travel Purpose		
Vehicle Class	HERS Vehicle Type	Business	Personal	Total
Auto (small and medium)	VT1, VT2	1.24	1.57	1.53
Minivan	VT2	1.39	2.27	2.21
Large passenger van	VT2	1.39	2.38	2.04
Cargo van	VT3	1.52	1.52	1.52
SUV	VT3	1.20	1.92	1.87
Pickup	VT3	1.29	1.50	1.47
6-tire truck	VT4	1.38	1.38	1.38
3- or 4-axle truck	VT5a	1.14	1.14	1.14
Bus	VT5b	1.00	12.10	13.10
4-axle combination truck	VT6	1.02	1.02	1.02
5+-axle combination truck	VT7	1.02	1.02	1.02

Sources: National Household Travel Survey, Fatality Analysis Reporting System, and Federal Motor Carrier Safety Administration.

Distribution of Vehicle Use by Purpose

The fractions of total vehicle use (represented in terms of vehicle hours traveled) that represent business (or work-related) and personal travel were used as weights to combine the separate hourly values of time for those two travel purposes into a single average hourly value for each HERS vehicle type. Ideally, the fractions of business and personal travel using vehicles assigned to each HERS vehicle type would be calibrated with respect to the number of vehicle hours traveled for these purposes, to improve their consistency with HERS' use of vehicle hours as a basis for estimating values of travel time. This calibration was possible only for household vehicles, for which measures of travel in vehicle hours were available from NHTS. This update used estimates of the number of vehicle hours that household automobiles, vans, SUVs, and pickups were used for work-related and personal travel tabulated from the 2009 NHTS to estimate the shares of use of these vehicles for each purpose.

For non-household vehicles, vehicle hours of work-related and personal travel were calibrated with respect to vehicle miles traveled, assumptions about the distribution of vehicle miles traveled between personal and business purposes, and estimates of average travel speed.

- Total vehicle miles driven by corporate fleet automobiles were estimated from the number of vehicles and their average monthly use for 2012 reported in trade association sources. Total vehicle miles were allocated between work-related and personal travel using the distribution of travel between those purposes by minivans and SUVs—the classes of vehicles for which use patterns appear to be most closely comparable to those of automobiles—reported in VIUS to be based at non-household locations.[10] Estimated vehicle miles were converted to vehicle hours by assuming that corporate automobiles used for business and personal travel achieved the same average speeds as household automobiles used for those same purposes.
- Vehicle miles of work-related and personal travel using all other light-duty vehicles—including minivans, large passenger vans, cargo vans, SUVs, and pickups—operated by corporate fleets were estimated from VIUS for vehicles reported to be based at non-household locations. Vehicle miles were converted to vehicle hours by assuming that these vehicles operate at the same average speeds as household vehicles of the same types when used for the same purpose.
- Total vehicle miles traveled using each class of light-duty vehicles—automobiles, minivans, large passenger vans, cargo vans, SUVs, and pickups—operated by Federal, State, and local government agencies and emergency service providers (police and fire) were estimated from the total number of such vehicles and their average annual use reported in published sources.[11] Average annual use of each vehicle type by State and local government agencies and by emergency service providers were assumed equal to those for Federal government fleet vehicles. All use of these vehicles was assumed to be for work-related purposes. Estimates of vehicle miles were again converted to vehicle hours by assuming that these vehicles operate at the same average speeds as household vehicles of the same types used for work-related travel.
- Total vehicle miles traveled using rented light-duty vehicles were estimated from the number of automobiles and light-duty trucks operated by rental agencies during 2012.[12] The total number of light-duty trucks owned by rental agencies was allocated among minivans, large

passenger vans, cargo vans, SUVs, and pickups using the distribution of all light trucks operated by corporate fleets among these same vehicle classes. Average annual utilization of rental vehicles was calculated from estimates of their average age and odometer reading at the time of their resale by rental agencies, and was assumed identical for automobiles and all types of light-duty trucks operated by rental agencies.[13] The distribution of rental vehicle use between business and personal travel was estimated from the reported distribution of rental transactions among the purposes of business, leisure (assumed to correspond to personal travel), insurance replacement, and service/maintenance reported in published sources.[14] Use of each type of vehicle (e.g., automobile, minivan) rented for insurance replacement and service/maintenance purposes was assumed distributed between work-related and personal travel in the same proportions as use of household vehicles of these same types because vehicles rented for these purposes are presumably temporary replacements for mainly household vehicles. Vehicle miles of personal and work-related travel using each type of rental vehicle were converted to vehicle hours by assuming that they operate at the same average speeds as household vehicles of the same type when used for the same purpose.

- Total vehicle miles of use by taxi operators were calculated from published estimates of the total number of vehicles in the U.S. taxi fleet and their average annual utilization.[15] The distribution of total vehicle hours of taxi use between business and personal travel was estimated by combining the estimates of annual taxi trips for each purpose, their average duration, and the average number of persons traveling together on work-related and personal taxi trips reported in the 2009 NHTS.
- Total use of each class of light-duty vehicles for work-related and personal travel was calculated as the sum of its use for each of those purposes by households, corporate fleets, government agencies, emergency responders, rental agencies, and taxi operators. *Exhibit A-5* shows the resulting shares of business and personal travel using different vehicle classes. For example, the exhibit indicates that 10.9 percent of travel by all users of automobiles represents work-related business travel, while the remaining 89.1 percent represents personal travel. The entry in *Exhibit A-5* for the Bus vehicle class indicates that 7.6 percent of total person hours of bus travel represents the time of bus drivers, who are assumed engaged in business travel, while the remaining 92.4 percent represents bus passengers' travel time, which is assumed exclusively personal travel.

In previous updates of HERS' travel time values, all use of medium and heavy trucks—those included in VT4 through VT7—was assumed work-related travel. As part of this update, this assumption was tested using estimates of personal and work-related use of medium and heavy trucks from VIUS, which asked survey respondents to report the percentage of each vehicle's use for personal transportation.[16] Almost no personal use of the classes of trucks included in HERS VT5 through VT7—single-unit trucks with three or four axles and combination trucks—was reported in the 2002 VIUS, so retaining the assumption used previously in HERS that use of single-unit trucks with three or four axles and combination trucks is exclusively work-related appears justified.

Exhibit A-5 Shares of Business and Personal Vehicle Use by User Category, Vehicle Class, and Travel Purpose

Vehicle Class	HERS Vehicle Type	Travel Purpose		
		Business	Personal	Total
Auto (small and medium)	VT1, VT2	7.8%	92.2%	100.0%
Minivan	VT2	4.8%	95.2%	100.0%
Large passenger van	VT2	5.7%	94.3%	100.0%
Cargo van	VT3	21.4%	78.6%	100.0%
SUV	VT3	99.1%	0.9%	100.0%
Pickup	VT3	11.6%	88.4%	100.0%
6-tire truck	VT4	100.0%	0.0%	100.0%
3- or 4-axle truck	VT5a	100.0%	0.0%	100.0%
Bus	VT5b	7.6%	92.4%	100.0%
4-axle combination truck	VT6	99.5%	0.5%	100.0%
5+-axle combination truck	VT7	99.9%	0.1%	100.0%

Sources: NHTS and VIUS.

The VIUS data indicated that some six-tire trucks were based at households and that their owners made some use of these vehicles for personal travel. The fraction of personal use for six-tire trucks vehicles was so small, however, that retaining the assumption that they are used exclusively for work-related travel appears justified. Government agencies also operate some six-tire trucks, but these are presumably used exclusively for work-related purposes.

Vehicle Capital Costs

Like other capital assets, vehicles depreciate over their lifetimes because of use and aging, which occurs independently of accumulating use. In addition, vehicle owners incur opportunity costs on the investment represented by vehicles' remaining value, and these costs continue throughout vehicles' useful lifetimes. The HERS procedure for estimating vehicle operating costs captures depreciation that occurs as a consequence of their use, but does not include depreciation related simply to their aging or the opportunity cost of the capital investment they represent. Although use-related depreciation occurs because of the number of miles or hours vehicles are operated, the decline in their value with the passage of time and the opportunity cost on their remaining capital value are more closely related to their original value. Thus, the magnitude of these latter two costs for a fleet of vehicles depends on both the number of vehicles it includes and their original purchase prices.

Many of the potential highway improvements evaluated by HERS would increase average travel speeds. For vehicle fleets with sizes determined primarily by the daily or weekly number of scheduled vehicle trips and their expected duration, improved travel speeds would shorten the time required by some trips and allow for a reduction in the required number of vehicles. Allowing some fleet operators to reduce the number of vehicles they employ would in turn lower both the time-related component of vehicle depreciation costs and the value of their investment in vehicles—and with the latter, the opportunity cost on that investment—although the use-related component of vehicle depreciation would not necessarily be reduced.

To capture this effect, the values of travel time for medium and heavy trucks (HERS VT4 through VT7), incorporate the hourly equivalent value of time-related vehicle depreciation and opportunity costs on capital investment in vehicles. Thus, any reduction in the number of hours that these vehicles are operated because of increased travel speeds will be reflected in savings in these components of hourly costs, in addition to the hourly value of their occupants' travel time. The following procedures and assumptions were used:

- Average purchase prices of new vehicles were obtained from published sources and converted to equivalent annual capital costs using estimates of expected vehicle lifetimes and the 7-percent real annual opportunity cost of private capital estimated by the White House Office of Management and Budget.[17] These estimates were constructed using annual capital recovery factors that incorporate each vehicle type's expected lifetime and the 7-percent opportunity cost of capital, and thus include both use- and time-related depreciation and opportunity costs on invested capital.
- Average annual miles of use were estimated from the 2002 VIUS and converted to average annual vehicle hours of use by dividing by average travel speeds for VT4 through VT7 derived from sample HERS outputs.
- Annual capital costs for each vehicle type were divided by its estimated average annual vehicle hours of use to determine total capital costs per hour of vehicle use.
- HERS estimates of use-related depreciation costs per vehicle mile for each vehicle type were converted to an hourly basis by multiplying by average speed. These results were subtracted from total hourly capital costs to determine time-related capital costs, including time-related depreciation plus opportunity costs on invested capital.

The results of these computations are shown in *Exhibit A-6*.

Exhibit A-6 Hourly Capital Costs by HERS Vehicle Type

Vehicle Class	HERS Vehicle Type	Costs in 2012 Dollars				
		Annual Capital Cost	Annual Hours of Use	Hourly Capital Cost	Use-Related Depreciation ($/hour)	Time-Related Capital Cost ($/hour)
6-tire truck	VT4	$4,883	284	$17.21	$4.76	$12.44
3+-axle single-unit truck	VT5a	$10,908	341	$31.98	$12.18	$19.81
All buses	VT5b	$14,497	1,164	$12.45	$4.61	$7.84
Transit bus	VT5b	$44,066	3,260	$13.52	$5.15	$8.37
Motorcoach	VT5b	$35,594	1,156	$30.78	$11.72	$19.06
School bus	VT5b	$9,439	1,200	$7.87	$2.99	$4.87
4-axle combination truck	VT6	$10,893	533	$20.43	$4.73	$15.70
5+-axle combination truck	VT7	$21,597	1,199	$18.01	$5.00	$13.01

Sources: VIUS and published vehicle purchase price data.

This procedure was not applied to VT1 through VT3, as the size of commercial vehicle fleets was assumed determined by considerations other than the number and duration of scheduled vehicle trips. The size of corporate automobile fleets, for example, seems more likely determined by peak demand for work-related travel during the typical workday and by corporate policies on employees' eligibility to use company-owned vehicles. Similarly, the size of rental vehicle fleets also seems likely affected by geographic and temporal (i.e., by time of day or day of week) variation in vehicle demand.

Value of Cargo Carried by Freight Vehicles

The final component included in HERS hourly vehicle costs is the inventory value of cargo carried by freight trucks, which is included only for VT6 and VT7. An important limitation of this approach is that the inventory value of cargo does not capture potential costs associated with delays of freight shipments outside of the direct accounting cost of holding cargo (e.g., disruptions of production schedules, spoilage). To estimate this value, large combination trucks of various sizes and configurations were first assigned to HERS VT6 and VT7. Detailed FHWA data on the distribution of vehicle miles by operating weight for each individual truck size and configuration were aggregated to produce distributions of total vehicle miles for HERS VT6 and VT7, and these distributions were used to compute the mileage-weighted average operating weight of trucks included in VT6 and VT7.[18] The empty weight of typical trucks included in each vehicle type was then subtracted from their average operating weight to yield an estimate of the average weight of cargo carried; these estimates were 22,900 pounds for VT6 and 36,800 pounds for VT7.

Data from the 2012 Commodity Flow Survey were used to estimate the average dollar value per pound for commodities shipped by truck, including those operated by for-hire freight carriers and trucks used for private or in-house freight carriage. These per-pound values were applied to the estimated shipment weights derived previously to calculate the total value of the typical cargo loads carried by combination trucks with three or four axles (HERS VT6) and those with five or more axles (VT7). Finally, the hourly values of cargo carried by trucks included in VT6 and VT7 were calculated by converting the 7-percent annual opportunity cost of capital used previously to its hourly equivalent and applying the result to the total value of cargo carried by trucks in VT6 and VT7. The resulting estimates were $0.11 per hour for VT6 and $0.17 per hour for VT7.

Estimated 2012 Values of Travel Time by Vehicle Type

Exhibit A-7 shows components of the hourly value of travel time for each HERS vehicle type, reports the overall average values of time per vehicle hour in 2012 dollars, and compares these to (1) the 2010 values used in the 2013 C&P Report and (2) the 2008 values used in the 2010 C&P Report. The estimated values of business travel time per vehicle hour presented in this report are higher than in the 2013 C&P Report for three key reasons. First, the estimated values of business travel time in this report are considerably higher than the 2010 values used in the 2013 C&P Report for all vehicle types except bus (which reflects only a small increase in the value of time for bus drivers). For all vehicle types except bus, the estimated value of business travel time per person hour is approximately $30 (ranging from $28.00 to $31.65), compared to a range of $22.98 to $23.98 in the 2013 C&P Report.

Additionally, the estimated average vehicle occupancy for business travel is also considerably higher for four-tire (VT3) vehicles and six-tire (VT4) trucks in this report. In the 2013 C&P Report, the estimates of vehicle occupancy for business travel were universally close to zero (ranging from

1.01 to 1.04); in this report, estimates of vehicle occupancy for business travel range from 1.24 (for small [VT1] and medium [VT2] automobiles) to 1.38 (for six-tire trucks). The estimated value of travel time per vehicle hour for business travel is the product of the estimated per-person hour value of time and vehicle occupancy. Both sets of estimates are higher for four-tire vehicles and six-tire trucks in this report than in the 2013 C&P Report, and the corresponding estimates of the value of time per vehicle hour are much larger, with increases ranging from around 34 percent for four-tire trucks to 74 percent for six-tire trucks.

Exhibit A-7 Estimated 2012 Values of Travel Time by Vehicle Type

2012 Travel Time Cost Element	VT1 Small Auto	VT2 Medium Auto	VT3 4-Tire Truck	VT4 6-Tire Truck	VT5a 3–4 Axle Truck	VT5b Bus	VT6 4-Axle Combination	VT7 5+-Axle Combination
Business Travel								
Value of time per person hour	$31.65	$30.70	$29.79	$29.49	$30.29	$23.79	$28.00	$28.00
Average vehicle occupancy	1.24	1.24	1.32	1.38	1.14	1.00	1.02	1.02
Vehicle capital cost per vehicle	N/A	N/A	N/A	$12.44	$19.81	$7.84	$15.70	$13.01
Inventory value of cargo	N/A	N/A	N/A	N/A	N/A	N/A	$0.11	$0.17
Value of time per vehicle hour	**$39.21**	**$38.15**	**$39.35**	**$53.15**	**$54.34**	**$31.66**	**$44.37**	**$41.75**
Personal Travel								
Value of time per person hour	$12.30	$12.30	$12.30	N/A	N/A	$12.30	N/A	N/A
Average vehicle occupancy	1.57	1.74	1.62	N/A	N/A	12.10	N/A	N/A
Value of time per vehicle hour	**$19.25**	**$21.40**	**$19.90**	**N/A**	**N/A**	**$148.85**	**N/A**	**N/A**
Share of vehicle use for personal travel	89.1%	90.1%	75.9%	0.0%	0.0%	92.4%	0.0%	0.0%
Average Values per Vehicle Hour								
2012	**$21.43**	**$23.06**	**$24.58**	**$53.15**	**$54.34**	**$180.51**	**$44.37**	**$41.75**
2010 (from 2013 C&P)	**$16.89**	**$16.92**	**$19.75**	**$30.47**	**$58.80**	**$58.80**	**$32.17**	**$31.44**
2008 (from 2010 C&P)	**$20.96**	**$21.00**	**$24.51**	**$29.88**	**$34.35**	**$34.35**	**$38.32**	**$38.00**

Source: U.S. DOT Revised Guidance on the Value of Travel Time in Economic Analysis (Revision 2 – 2015 Update) and internal DOT estimates.

Finally, the estimated vehicle capital cost per vehicle hour is approximately twice as large in this report as in the 2013 C&P Report. Vehicle capital cost is a component of the estimated value of time per vehicle hour for six-tire trucks, three- and four-axle trucks (VT5a), buses (VT5b), and all combination trucks (VT6 and VT7). Thus, in this report, the combined effects of increased value of time per person hour and vehicle capital cost per vehicle hour increase the estimated value of time per vehicle hour for business travel across all vehicle types, including vehicle types that do not have considerably larger estimated vehicle occupancy (three- and four-axle trucks, buses, and all combination trucks).

Exercising caution is essential when comparing the estimated values of time per vehicle hour for business travel for three- and four-axle trucks and buses across C&P reports. In the 2013 C&P

Report, three- and four-axle trucks and buses were reported in an aggregate category (i.e., buses were classified as three- and four-axle trucks). In particular, aggregating vehicle types obscures the impacts of changes to estimates of the value of time per person hour and vehicle capital cost for three- and four-axle trucks.

The estimated values of personal travel time per vehicle hour are also higher for small and medium automobiles in this report than in the 2013 C&P Report. The estimated increases are driven primarily by increases in estimated vehicle occupancy for personal travel (increasing from 1.38 to 1.57 for small automobiles and from 1.38 to 1.74 for medium automobiles). The estimated values of time per person hour for personal travel increased only slightly, from $11.89 per person hour to $12.30 per person hour. As with comparisons of the estimated changes to values of time per vehicle hour for business travel, comparisons of the estimated values of time per vehicle hour for personal travel for three- and four-axle trucks and buses across C&P reports also should be made cautiously. The estimates of average travel time cost per vehicle hour for each vehicle class in *Exhibit A-7* were specified as weighted averages of values of time per vehicle hour for business and personal travel, calibrated with respect to estimated shares of vehicle use for business and personal travel. For four vehicle classes—six-tire trucks, three- and four-axle trucks, four-axle combination trucks, and five- or more axle combination trucks—all travel was specified as business travel; for these vehicle classes, the estimated travel time cost per vehicle hour is equal to the estimated value of time per vehicle hour for business travel. For the other four vehicle classes, the estimated shares of vehicle use for personal travel range from 75.9 percent (for four-tire trucks) to 92.4 percent (for buses).

The estimated average travel time cost for small and medium automobiles increased from around $17 per vehicle hour in the 2013 C&P Report to $21.43 for small automobiles and $23.06 for medium automobiles in this report, as shown in *Exhibit A-7*. The larger increase for medium automobiles was driven chiefly by the larger increase in the estimate of average vehicle occupancy for personal travel in medium automobiles relative to small automobiles.

The relative increase in the current estimated average travel time cost for four-tire trucks ($24.58 per vehicle hour versus $19.75 in the 2013 C&P Report) is approximately equal to the corresponding increase for small automobiles. This result was driven by offsetting relative changes in estimated vehicle occupancy for business travel (a higher increase for four-tire trucks) and personal travel (positive for small automobiles). For four-tire trucks and small automobiles, the estimated average travel time costs in *Exhibit A-7* are similar to the corresponding estimates in the 2010 C&P Report; for medium automobiles, the current estimated average travel time cost is higher than in the previous two reports.

In the 2013 C&P Report, the estimated average travel time costs for six-tire trucks and for all combination trucks were similar ($30.47 per vehicle hour for six-tire trucks, $32.17 per vehicle hour for four-axle combination trucks, and $31.44 per vehicle hour for combination trucks with five or more axles). In *Exhibit A-7*, the estimated average travel time cost for six-tire trucks ($53.15 per vehicle hour) is between around $7 and $9 higher than the corresponding estimates for combination trucks ($44.37 and $41.75 for four-axle and five-axle combination trucks, respectively); this result was driven by a strong upward revision to estimated vehicle occupancy for business travel in six-tire trucks. For six-tire trucks and all combination trucks, the estimated average travel time costs in *Exhibit A-7* are higher than the corresponding estimates in the 2010 C&P Report.

Disaggregating buses and three- and four-axle trucks results in distinct estimated average travel time costs for these vehicles, relative to each other and to the aggregated estimates in previous reports. The estimated average travel time cost per vehicle hour for three- and four-axle trucks is more than $4 lower than the 2010 values from the 2013 C&P report ($54.34 versus $58.80), and much lower than the corresponding estimate for buses ($180.51). The estimate for three- and four-axle trucks represents only business travel with relatively few occupants, while the estimate for buses represents predominantly personal travel with many occupants. Although the estimated cost of business travel per vehicle hour is higher for three- and four-axle trucks, the large number of estimated bus occupants traveling for personal purposes on buses yields a much larger estimated average value of travel time for buses.

The estimated average travel time costs presented in *Exhibit A-7* represent the values of travel time HERS applies to base-year travel. DOT guidance directs FHWA to assume that values of travel time will grow at a rate of 1.2 percent per year when forecasting travel time impacts, to project the effects of real wage growth on travel time costs. Thus, the values of time specified in HERS for a given year, *t*, are equal to the base-year values in *Exhibit A-7*, multiplied by 1.012^{t-2012}.

Costs of Air Pollutant Emissions

Greenhouse Gas Emissions

Road traffic generates an appreciable share of anthropogenic emissions of greenhouse gases (GHG). In the United States, passenger vehicles alone account for roughly 20 percent of emissions of carbon dioxide, and CO_2 emissions account for about 95 percent of the total global warming potential from all U.S. emissions of GHGs. In line with CO_2 emissions as the dominant concern relating to global warming, HERS has the capability to quantify and cost these emissions starting with the version used for the 2010 C&P Report.

The quantification of CO_2 emissions from motor vehicle traffic is based on the amounts of gasoline and diesel fuel consumed (alternative fuels have yet to be incorporated into the model). Emissions directly from vehicles amount to 8,852 grams of CO_2 per gallon of gasoline consumed, and 10,239 grams per gallon of diesel fuel.[19] These emissions are often referred to as tailpipe emissions, because they result from the fuel combustion process in motor vehicles' engines. In addition to these direct emissions, the fuel production and distribution processes produce CO_2 emissions, which are often referred to as upstream emissions. For this report, the HERS analysis added upstream emissions, which quantitatively are more uncertain, to estimates of direct or tailpipe CO_2 emissions. The HERS estimates of upstream emissions are 2,072 grams CO_2 per gallon of gasoline consumed and 2,105 grams CO_2 per gallon of diesel fuel consumed.

HERS uses these estimates of CO_2 emissions per gallon of fuel consumed to convert consumption rates of vehicle fuel to CO_2 emissions per vehicle mile. The resulting estimates of CO_2 emissions per vehicle mile are then converted to dollar costs using estimates of climate-related economic damages caused by CO_2 emissions. A recent study by a Federal interagency working group (Interagency Working Group on Social Cost of Carbon 2010) estimated the costs to society from future climate-related economic damages caused by incremental CO_2 emissions. The group's estimates of this social cost of carbon were intended to include, at a minimum, the monetized impacts of emissions-induced climate change on net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. Low, medium, high, and very high estimates of the social cost per metric ton of carbon were developed for each year from 2010 through 2050 using alternative discount rates.

The analyses presented in this report use the medium estimates, updated to 2012 dollars using the gross domestic product price deflator (as was done in a recent analysis of corporate average fuel economy standards conducted by the National Highway Traffic Safety Administration). The adjusted values of CO_2 damage costs increase annually from $37 per metric ton in 2012 to $57 by 2032, the final year for which this report projects highway conditions and performance. For use as HERS inputs, the values were averaged to produce estimates of CO_2 damage costs for each 5-year HERS funding period; a 3-percent discount rate was applied to all estimated impacts on CO_2 emissions when calculating benefits associated with improvements in HERS.

Emissions of Criteria Air Pollutants

For the 2013 C&P Report, FHWA conducted new research to enhance and update HERS procedures for estimating economic damage costs from motor vehicle emissions of criteria air pollutants or their chemical precursors: carbon monoxide, volatile organic compounds, nitrogen oxides, sulfur dioxide, and fine particulate matter.

HERS estimates of economic damages from vehicle emissions of air pollutants were updated by first estimating new emission rates—measured in mass per vehicle mile traveled—for criteria pollutants and their precursors. These updated estimates were developed using the U.S. Environmental Protection Agency's (EPA's) Motor Vehicle Emission Simulator (MOVES) model. Average emissions per vehicle mile traveled of each pollutant vary among the roadway functional classes used in HERS because the typical mix of vehicles operating on each functional class varies and different types of vehicles emit these pollutants at different rates per vehicle mile traveled. The MOVES emission rates also vary with travel speed and other driving conditions that affect vehicles' power output.

Repeated runs of the MOVES model were conducted to develop a schedule of average emissions per vehicle mile traveled of each pollutant by travel speed for each roadway functional class during the midpoint year of each 5-year funding period used by HERS. Because MOVES uses different roadway classes than HERS uses, the most appropriate MOVES roadway class was used to represent each HERS functional class.

HERS combines these schedules of average emissions per vehicle mile traveled for different pollutants with estimates of the average dollar cost of health damages caused per unit mass of each pollutant to calculate damage costs per vehicle mile traveled for each pollutant. The dollar costs per unit of each pollutant used in HERS were updated using estimates for 2015, 2020, 2030, and 2040, supplied by EPA; these were interpolated to produce estimates for the midpoint of each 5-year funding period.[20] HERS then sums the estimates of damage costs for individual pollutants to calculate total air-pollution-related costs per vehicle mile traveled at different speeds. This process resulted in updated schedules of the average dollar cost of air-pollution-related damages per vehicle mile traveled by speed for each HERS functional class and funding period.

Motor vehicles emission rates for each criteria pollutant are projected to decline significantly in the future as new vehicles that meet more stringent emissions standards gradually replace older models in the vehicle fleet. At the same time, however, EPA projects that economic damage costs per unit of each criteria air pollutant (except carbon monoxide) will increase rapidly over time; projections of unit damage costs for nitrogen oxides, sulfur dioxide, and fine particulate matter are all projected to increase around 24 to 30 percent from 2015 to 2030.

Effects on HERS Results

Potential improvement projects evaluated by HERS can affect air pollution and CO_2 damage costs by increasing the volume of travel on a section during future funding periods and by increasing the average speed of travel on that section. Higher travel volumes invariably increase emissions and damage costs, but emission and fuel consumption rates are more complex functions of travel speeds, so increasing travel speed on a sample section can cause air pollution and CO_2 damage costs to either increase or decrease. Because the speed-mediated effect is often to reduce emissions, the overall effect of an improvement project on air pollution or CO_2 damage costs could be either an increase or a decrease. Net reductions in air pollution costs represent one component of the benefits from a potential improvement to a HERS sample section, while net increases represent one component of the costs (disbenefits).

Highway Operational Strategies

One of the key modifications to HERS featured in previous reports was the ability to consider the impact of highway management and operational strategies, including Intelligent Transportation Systems (ITSs), on highway system performance. This feature is continued in this report with only minor modifications. Current and future investments in operations are modeled outside of HERS, but the impacts of these deployments affect the model’s internal calculations and, thus, also affect the capital improvements considered and implemented in HERS.

Among the many operational strategies available to highway agencies, HERS considers only certain types based on the availability of suitable data and empirical impact relationships. Grouped by category, these are:

- Arterial Management
  - Adaptive Traffic Signal Control
  - Electronic Roadway Monitoring (considered a supporting deployment necessary to other operations strategies)
  - Variable Message Signs (VMS)
- Freeway Management
  - Adaptive Ramp Metering
  - Electronic Roadway Monitoring (considered a supporting deployment necessary to other operations strategies)
  - VMS
  - Integrated Corridor Management, with and without comprehensive deployment of Vehicle Infrastructure Integration (VII) technologies.[21] Integrated Corridor Management coordinates the operation of the infrastructure elements within a corridor—for example, the timing of traffic signals near freeway interchanges with freeway incident management and ramp metering.
  - Active Traffic Management, which includes lane controls (dynamic junction control, dynamic lane reversal/contraflow lane reversal, dynamic lane use control, dynamic merge control), queue warning systems, dynamic shoulder lanes, queue warning, and Variable Speed Limits (VSL), also known as "speed harmonization"
- Incident Management (freeways only)
  - Incident Detection (free cell phone call number and detection algorithms)
  - Incident Verification (surveillance cameras)
  - Incident Response (on-call service patrols)
- Traveler Information
  - 511 Systems
  - Advanced In-vehicle Navigation Systems with real-time traveler information (enabled by VII deployment)
  - Incident Response (on-call service patrols).

Creating the operations improvements input files for use in HERS involved four steps: (1) determining current operations deployment, (2) determining additional operations deployments for the HERS funding periods, (3) determining the cost of future operations investments, and (4) determining the impacts of operations deployments. Different levels and types of deployments can be selected for an individual scenario.

Current Operations Deployments

To determine current operations deployments on the HPMS sample sections, data from the ITS Deployment Tracking Survey (http://www.itsdeployment.its.dot.gov/) were merged with 2012 HPMS sample panel section data. The ITS data were assigned to HPMS sample sections for each urbanized area using existing congestion and traffic levels on those sections as criteria.

Future Operations Deployments

For future ITS and operational deployments, projections were developed based on two alternatives. For the "Continuation of Existing Deployment Trends" alternative, existing deployments in urban areas were correlated with the congestion level and area population to predict, based on these factors, where future deployments will occur. This alternative is reflected in the analyses presented in Chapters 7 and 8.

The "Aggressive Deployment" alternative is reflected in sensitivity analysis presented in Chapter 10. This alternative assumes that deployment accelerates above existing trends and expands to more advanced strategies. Under this alternative, advanced in-vehicle navigation systems that provide real-time traveler information would supersede the current 511 systems. *Exhibit A-8* identifies the strategies employed in each alternative.

Operations Investment Costs

The unit costs for each deployment item were taken from the DOT ITS Benefits Database and Unit Costs Database and supplemented with costs based on the ITS Deployment Analysis System model. Costs were broken down into initial capital costs and annual operating and maintenance costs. Additionally, costs were determined for building the basic infrastructure to support the equipment and for the incremental costs per piece of equipment deployed.

Impacts of Operations Deployments

Exhibit A-9 shows the estimated impacts of the different operations strategies considered in HERS. These effects include:

- Incident Management: Incident duration and the number of crash fatalities are reduced. Incident duration is used as a predictor variable in estimating incident delay in the HERS model.

Exhibit A-8 Types of Operations Strategies Included in Each Scenario

Operations Strategy	Scenario: Continue Existing Trends	Scenario: Aggressive Deployment
Arterial Management		
Signal control	•	•
Emergency vehicle signal preemption	•	•
Variable message signs		•
Advanced traveler information		•
Freeway Management		
Ramp metering	•	•
Variable message signs	•	•
511 traveler information	•	
Advanced traveler information		•
Integrated corridor management		•
Active traffic management		•
Incident Management (Freeways Only)		
Detection	•	•
Verification	•	•
Response	•	•

Source: Highway Economic Requirements System.

Exhibit A-9 Impacts of Operations Strategies in HERS

Operations Strategy	Impact Category	Impact Details
Arterial Management		
Signal control	Congestion/delay	Signal Density Factor = n(nx + 2)/(n + 2), where n = no. of signals per mile x = 1 for fixed time control 2/3 for traffic actuated control 1/3 for closed loop control 0 for real-time adaptive control/Split Cycle Offset Optimization Technique (SCOOT)/Sydney Coordinated Adaptive Traffic System (SCATS)® Signal Density Factor used to compute zero-volume delay due to traffic signals
Electronic roadway monitoring	Congestion/delay	Supporting deployment for corridor signal control (two highest levels) and traveler information
Emergency vehicle signal preemption	None	Reflected in costs but no impact currently simulated
Variable message signs	Congestion/delay	-0.5% incident delay
Freeway Management		
Ramp metering		
Preset	Congestion/delay	New delay = ((1 - 0.13)(original delay)) + 0.16 hrs. per 1000 VMT
Traffic actuated	Congestion/delay	New delay = ((1 - 0.13)(original delay)) + 0.16 hrs. per 1000 VMT
	Safety	-3% number of injuries and property damage only accidents
Electronic roadway monitoring	Congestion/delay	Supporting deployment for ramp metering and traveler information
Variable message signs	Congestion/delay	-0.5% incident delay
Integrated corridor management	Congestion/delay	-7.5% total delay without VII, 12.5% total delay with VII
Active traffic management	Congestion/delay Safety	-7.5% total delay -5% fatalities
Incident Management (Freeways Only)		
Detection algorithm/free cell	Incident characteristics Safety	-4.5% incident duration -5% fatalities
Surveillance cameras	Incident characteristics Safety	-4.5% incident duration -5% fatalities
On-call service patrols		
Typical	Incident characteristics Safety	-25% incident duration -10% fatalities
Aggressive	Incident characteristics Safety	-35% incident duration -10% fatalities
All combined	Incident characteristics Safety	Multiplicative reduction -10% fatalities
Traveler Information		
511 only	Congestion/delay	-1.5% total delay, rural only
Advanced traveler information (VII-enabled)	Congestion/delay	-3% total delay, all highways

Source: Highway Economic Requirements System.

- Signal Control: The effects of the different levels of signal control are directly considered in the HERS delay equations.

- Ramp Meters, VMS, ATM, Integrated Corridor Management, VSL, and Traveler Information: Delay adjustments are applied to the basic delay equations in HERS. VSL also is assumed to have a small impact on fatalities.

Based on the current and future deployments and the impact relationships, an operations improvements input file was created for each deployment scenario. Each file contains section identifiers, plus current and future values (for each of the four funding periods in the HERS analysis) for the following five fields:

- Incident Duration Factor
- Delay Reduction Factor
- Fatality Reduction Factor
- Signal Type Override
- Ramp Metering.

Future HERS Enhancements Currently Underway

As part of an ongoing program of model revisions and improvements, the matrix of typical costs per mile for the various types of highway capital improvements modeled in HERS as reflected in *Exhibit A-1* are currently being updated. As part of this effort, the matrix will be expanded to capture differences in costs associated with “typical reconstruction” versus “total reconstruction,” which would involve complete reconstruction of the roadway starting at the subgrade. The current distinction between “normal-cost” capacity expansion and “high-cost” capacity expansion will be broadened to consider the impact on expansion costs resulting from different types of obstacles to widening that are now coded by the States in HPMS. Other aspects of this research effort include developing procedures for adjusting the cost matrix to remove costs associated with culverts and bridge replacements in conjunction with highway widening projects in anticipation that future enhancements to the National Bridge Investment Analysis System will allow it to compute such needs more accurately than HERS can. Procedures also will be developed to facilitate analysis of the variable costs associated with different overlay depths.

Work is also underway to refine and update the new pavement performance equations recently introduced into HERS. These equations were based on an early version of the AASHTO Mechanistic-Empirical Pavement Design Guide algorithms, some of which have subsequently been revised. This research is also intended to address certain anomalies encountered in translating the simplified mechanistic-empirical equations into the HERS framework.

FHWA has initiated a major effort to update the equations for predicting vehicle fuel economy and other vehicle operating costs currently included in HERS and in several other public and private-sector tools for highway benefit-cost analysis. The current HERS procedures are based on a 1982 study and are not considered adequately reflective of current vehicle technology and driving patterns. The new study is building from the Strategic Highway Research Program 2 Naturalistic Driving Study and the Road Information Database to develop driving cycles that will be used to model the relationship between vehicle speed and fuel consumption. The impacts of road curvature and pavement roughness on fuel consumption also will be explored. This project includes modeling the relationships among pavement roughness, speed, roadway characteristics, and vehicle operating costs such as repair and maintenance, tire wear, mileage-related vehicle depreciation, and oil consumption.

Another research effort currently underway will update the costs and benefit associated with the types of operations strategies currently incorporated into the HERS operations preprocessor as referenced in *Exhibits A-8* and *A-9*. This effort includes an evaluation of the potential for simulating the impacts of connected vehicles and the potential for modeling the impacts of managed lanes.

FHWA is sponsoring research targeted at improving the specification of business travel time costs in HERS, including both refinements to the content and use of existing data sources and methodological improvements. A key data-centered effort involves identifying approaches for capturing and applying data on business travel from NHTS. The set of methodological improvements under investigation includes an effort to incorporate travel time reliability into the measurement of benefits associated with travel time improvements. HERS currently uses a proxy for reliability-based benefits, by adding a premium to account for lost time under unexpected delay due to traffic incidents. The premium for incident delay time also features in the ITS Deployment Analysis System model, which FHWA developed as a tool for benefit-cost analysis of ITS deployments.

FHWA sponsors research to develop and implement an updated plan for valuing personal travel time in HERS. Focal areas of the updated plan include the potential to differentiate values of travel time savings along dimensions such as trip length, the level of congestion, and trip purpose (e.g., commute travel versus discretionary travel). Consistent with the research on business travel time discussed above, this research includes efforts to incorporate travel time reliability into the measurement of benefits associated with travel time improvements.

A related research effort FHWA is sponsoring uses HERS outputs as inputs to a national economic model to capture the impact of highway investment on macroeconomic performance. After analyzing the capabilities of various macroeconomic models (econometric, input-output, and computable general equilibrium), the United States Applied General Equilibrium (USAGE) model was selected for further development and scenario analysis. USAGE is a 500-industry, dynamic computable general equilibrium model of the U.S. economy developed at Monash University (now housed at Victoria University) in collaboration with the U.S. International Trade Commission. USAGE was the only model among the candidates reviewed that satisfied all the following criteria considered important for estimating the economic effects of transportation investments:

- The freight-carrying transportation modes are represented as separate industries.
- Substitution between freight transportation modes can be represented.

- The model can represent changes in productivity in freight modes through changes in technical parameters defining the industry.
- Changes in prices of freight service influence demand for freight services, consistent with economic theory.
- Prices and demand can adjust in response to changes in fiscal and monetary policy (e.g., through changes in budget deficits, income taxes, and fuel taxes).
- Short-term Keynesian effects of government spending under the presence of slack resources (i.e., stimulus effects) can be represented.

The first phase of the research centered on the customization of USAGE to map outputs from HERS to impacts within the national economy. The customized version of the model, USAGE-Hwy, uses key outputs from HERS as model inputs, including levels of highway investment and impacts on travel time (specified separately for light-duty vehicles and heavy-duty trucks), operating costs (specified separately for light-duty vehicles and heavy-duty trucks), fuel consumption, vehicle miles traveled, and highway fatalities. FHWA anticipates including analyses based on USAGE-Hwy in future C&P reports to investigate the sensitivity of macroeconomic outcomes to changes in highway spending levels and to associated changes in highway travel costs and vehicle miles traveled.

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[1] See http://www.dot.gov/administrations/office-policy/2015-value-travel-time-guidance.

[2] Median household income data for 2012 were obtained from U.S. Bureau of the Census, Historical Income Tables – Households, Table H-6 (http://www.census.gov/hhes/www/income/data/historical/household/), and were converted to their hourly equivalent assuming 2,080 paid working hours per year.

[3] Hourly wage rates for All Occupations during 2012 are reported in Bureau of Labor Statistics, *Occupational Employment and Wages – May 2012*, March 29, 2013, Table 1 (http://www.bls.gov/news.release/ocwage.t01.htm). Hourly values of fringe benefits during 2012 were estimated from fractions of Total Compensation for Civilian Workers, reported in Bureau of Labor Statistics, *Employer Costs for Employee Compensation – June 2012*, September 11, 2012, Table 2 (http://www.bls.gov/news.release/archives/ecec_09112012.pdf).

[4] Hourly wage rates for 2012 were obtained from Bureau of Labor Statistics, *Occupational Employment and Wages – May 2012*, March 29, 2013, Table 1 (http://www.bls.gov/news.release/ocwage.t01.htm) for the occupational categories of light truck or delivery service drivers and heavy and tractor-trailer truck drivers. Hourly values of fringe benefits were estimated from fractions of Total Compensation for the "Transportation and material moving" occupational group, reported in Bureau of Labor Statistics, *Employer Costs for Employee Compensation – June 2012*, September 11, 2012, Table 2 (http://www.bls.gov/news.release/archives/ecec_09112012.pdf).

[5] Mean wage rate for bus drivers during 2012 was estimated using a weighted average of mean wage rates for BLS occupational categories Bus drivers – transit and intercity and Bus drivers – school or special client, reported in Bureau of Labor Statistics, *Occupational Employment and Wages – May 2012*, March 29, 2013, Table 1 (http://www.bls.gov/news.release/ocwage.t01.htm). Weights used in calculating this average are the product of employment in each category (reported in same source as wage rates) and estimates of average number of hours worked per week for school and all other bus drivers during May 2012, constructed using data tabulated from BLS Current Employment Survey (http://www.bls.gov/ces/data.htm).

[6] See http://www.nhtsa.gov/FARS.

[7] https://portal.fmcsa.dot.gov/login.

[8] ABA Foundation, Motorcoach Census 2013, February 27, 2014, Table 4-1, p. 19 (http://www.buses.org/assets/images/uploads/general/Report%20-%20Census2013data.pdf) suggests an average passenger occupancy of 36.5 persons.

[9] http://www.apta.com/resources/statistics/Documents/FactBook/2013-APTA-Fact-Book.pdf.
[10] These include vehicles reported to be based at a company office/headquarters, terminal, manufacturing plant, or distribution center; see definition of variable HB_TYPE, *Vehicle Inventory and Use Survey 2002, Microdata Data Dictionary*, p. 27. (https://www.census.gov/svsd/www/vius/datadictionary2002.pdf).
[11] Federal Fleet Report, Tables 2-5, 2-6, and 4-2 (http://www.gsa.gov/portal/category/102859), *Government Fleet Fact Book 2012*, *Fleet Size by Unit Type*, p. 28, and *State, County, and Municipal Vehicle Totals*, p. 30. (http://www.government-fleet.com/fileviewer/1556.aspx), and Automotive Fleet, U.S. Fleet Statistics by Industry Segment (http://www.automotive-fleet.com/statistics/statsviewer.aspx?file=http%3a%2f%2fwww.automotive-fleet.com%2ffc_resources%2fstats%2faffb12-9-fleetstats.pdf&channel).
[12] Automotive Fleet, U.S. Fleet Statistics by Industry Segment (http://www.automotive-fleet.com/statistics/statsviewer.aspx?file=http%3a%2f%2fwww.automotive-fleet.com%2ffc_resources%2fstats%2faffb13fleetstats.pdf&channel).
[13] Reported in http://online.wsj.com/news/articles/SB10001424127887324463604579040870991145200.
[14] *Auto Rental News*, Fact Book, various issues 2000–2003, http://www.autorentalnews.com/content/research-statistics.aspx.
[15] Automotive Fleet, U.S. Fleet Statistics by Industry Segment (http://www.automotive-fleet.com/statistics/statsviewer.aspx?file=http%3a%2f%2fwww.automotive-fleet.com%2ffc_resources%2fstats%2faffb13fleetstats.pdf&channel).
[16] See definition of variable OPCLASS _PSL, *Vehicle Inventory and Use Survey 2002, Microdata Data Dictionary*, p. 33 (https://www.census.gov/svsd/www/vius/datadictionary2002.pdf).
[17] See White House Office of Management and Budget, Office of Information and Regulatory Affairs, Circular A-4, *Regulatory Analysis: A Primer*, August 15, 2011 (https://www.whitehouse.gov/sites/default/files/omb/inforeg/regpol/circular-a-4_regulatory-impact-analysis-a-primer.pdf, p. 11. Purchase prices for trucks were obtained from IHS Automotive, Truck Pricing: GWV Class 3-8, 2013. Estimate for transit buses is total for Bus, Trolley Bus, Commuter Bus, and Bus Rapid Transit from American Public Transit Association, *Transit Fact Book 2013* Table 6, p.12 (data for 2011) (http://www.apta.com/resources/statistics/Documents/FactBook/2013-APTA-Fact-Book.pdf). Motor coach estimate from ABA Foundation, Motorcoach Census 2013, February 27, 2014 (http://www.buses.org/assets/images/uploads/general/Report%20-%20Census2013data.pdf), Table 4-1, p. 19 (data for 2012). School bus estimate from *School Bus Fleet 2015 Factbook*, Volume 60, No. 11, (http://digital.schoolbusfleet.com/2015FB/Default/3/0/2414989#&pageSet=0), *School Transportation Statistics: 2012–13 School Year*, pp. 29–30.
[18] Federal Highway Administration, *1997 Highway Cost Allocation Study*, Chapter II, Table II-8 (http://ntl.bts.gov/lib/5000/5900/5940/final.pdf).
[19] The chemical properties of fuels were obtained from Wang, M.Q., *GREET 1.5 — Transportation Fuel-Cycle Model: Volume 1, Methodology, Use, and Results*, ANL/ESD-39, Vol.1, Center for Transportation Research, Argonne National Laboratory, Argonne, Ill., August 1999, Table 3.3, p. 25 (available at http://greet.es.anl.gov/index.php?content=publications&by=date&order=up#Technical_Publications).
[20] For a description of these estimated damage costs, see U.S. EPA and National Highway Traffic Safety Administration, Joint Technical Support Document, Final Rulemaking for 2017–2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, August 2012, pp. 4-42 to 4-48 (available at http://www.nhtsa.gov/fuel-economy).
[21] The VII program at DOT has evolved into the Connected Vehicle Program: http://www.its.dot.gov/landing/cv.htm. As of this writing, for HERS, the strategy enabled by VII technologies is advanced traveler information. Additional strategies covered under the Connected Vehicle program have not been incorporated.