NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Built Environment Analysis Tool

April 2013

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Cambridge, Massachusetts

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1.0 Overview

This documentation describes the development of a tool created to evaluate the effects of built environment scenarios on transportation energy and greenhouse gas (GHG) emissions, and provides guidance on how to apply the tool. The tool was developed in support of the U.S. Department of Energy (DOE)'s Transportation Energy Futures (TEF) Study, which is being led by the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory. The tool is designed for scenario analysis at a national level. Key inputs include the amount of population by various land use characteristics that are related to travel behavior, including population density, employment density, urban vs. rural context, and pedestrian environment. Outputs include transportation energy use and GHG emissions. The tool includes a base year of 2010 and evaluation years of 2030 and 2050.

At the core of the tool is a set of linear regression models, developed from the 2009 National Household Travel Survey (NHTS), to predict daily person-miles of travel (PMT) per capita as a function of various sociodemographic and land use variables. Mode shares from the NHTS were used to convert total PMT into PMT by mode. Average vehicle occupancies were then used to convert PMT by mode into vehicle-miles of travel (VMT) by mode. Finally, energy and emission factors were applied to estimate energy consumption and GHG emissions. The model estimates full fuel-cycle energy and emissions, accounting for energy and emissions associated with fuel production as well as direct vehicle operations.

2.0 Tool Basis and Structure

The literature sources reviewed in a companion paper prepared for the TEF study, "Effects of Built Environment on Transportation Energy Use, Greenhouse Gas Emissions, and Other Factors," identify a variety of built environment factors that affect travel patterns and resulting energy use. The paper also identifies existing analysis tools, thereby suggesting opportunities for further development to create tools with functionalities not already available.

Many of the existing empirical studies of land use and travel behavior are based on analysis of travel survey data from particular locations, combined with detailed land use data that is collected through a combination of existing local and national sources and field studies. The data from these studies, however, are not readily transferable into a national-level sketch analysis tool. Furthermore, it was determined that this research method would be too resource-intensive to apply for the purposes of the current effort, given the need for a nationally-applicable model.

Instead, the 2009 National Household Travel Survey (NHTS) was used to develop a new set of models to serve as the core of the built environment analysis tool. The 2009 NHTS, administered from April 2008 through April 2009, contains travel information from nearly 150,000 households nationwide, capturing both work and nonwork travel to provide a snapshot of travel behavior in the U.S. Previous versions of the NHTS have been widely used for travel behavior analysis. The 2009 dataset expands the opportunities for examining built environment relationships with the addition of a limited number of urban form-related variables, including:

- Census tract population density;
- Census tract job density;
- Housing unit type; and
- Perceptions of the built environment such as walking routes and safety.

Use of the NHTS dataset also permits inclusion of other variables which affect travel patterns, such as household size, composition, worker status, and income.

While the NHTS does not identify the specific location of individual respondents in the public dataset, it does identify the metropolitan statistical area (MSA) in which the respondent is located, if that MSA is one of the 50 largest MSAs in the U.S.. This allows regional-level variables to be matched with NHTS records for residents of large MSAs. In this effort, a number of variables related to regional infrastructure supply were tested.

2.1 MODELS OF PERSON-MILES OF TRAVEL

At the core of the tool is a set of linear regression models, developed from the NHTS data, to predict daily PMT per person as a function of various sociodemographic and land use variables. Only trips less than 200 miles were included. Separate PMT models were developed for four travel segments:

- Work travel in the 50 largest MSAs;
- Non-work travel in the 50 largest MSAs;
- Work travel in other MSAs; and
- Non-work travel in other MSAs.

The following variables were included in all models. Breakpoints were set based on analysis of the relationship between the independent variable and the dependent variable (PMT).

- **Census tract population density** (persons per square mile). Various segmentations of this variable were tested. A three-level segmentation with breakpoints at 750 and 7,000 persons per square mile was used in the final model, with these breakpoints showing good relationships to changes in PMT.
- **Census tract employment density** (jobs per square mile). Various segmentations of this variable were tested. A three-level segmentation with breakpoints at 100 and 1,000 jobs per square mile was used in the final model, with these breakpoints showing good relationships to changes in PMT. Employment density is used in this model as a proxy for a mixed-use environment, with 100 jobs per square mile roughly corresponding to a modest threshold of mixed uses (e.g., neighborhood retail) and 1,000 jobs per square mile corresponding to larger employment and/or retail centers.[1]
- **Housing unit type**. A two-level segmentation was used: single-family vs. multifamily. This variable was insignificant in three of the four final models of PMT but was retained due to policy interest.
- **Gender** (male or female).

[1] In the literature, indicators of mix of uses, or diversity, have been developed based on relative proportion of population and employment, or of different employment categories. For example, a ratio of 1:1 population to employment would be considered well-mixed. The advantage of using employment density over a diversity index is that it keeps low-density tracts that have relatively equal levels of population and employment from being considered mixed-use, where the employment may be too spread out to support walk, bike, or transit trips even if total population and employment is relatively balanced.

- **Household income.** A three-level segmentation was used with breakpoints at $30,000 and $60,000.
- **Age of worker** (less than 36, 36 to 50, over 50) – for work-trip models only.
- **Number of work trips or non-work trips** – During estimation, this variable was used to normalize the number of work and non-work trips made by different individuals. The coefficient was applied to the average number of trips per worker per day (for work trips), or the number of nonwork trips per person per day, as calculated from the NHTS data.
- **Region of the country** (Northeast, Midwest, South, West, based on Census definitions).
- **Urban vs. rural location –** Households may be located in a "rural" area, even if they are located within a metropolitan statistical area.[2]
- **MSA size.** Within the top 50 MSAs, MSAs over 3 million population were separated from MSAs of less than this size. Within "other MSAs," a breakpoint was set at a population of 200,000.[3] The top 50 MSAs correspond roughly to those with a population of over 1 million.

The following regional-scale variables were included only in the models for the top 50 MSAs, since these were the only areas for which individual households could be associated with regions.

- **Travel Time Index** – The ratio of the travel time during the peak period to the time required to make the same trip at free-flow speeds, as defined and measured by the Texas Transportation Institute (TTI).[4]

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[2] MSAs are based on county boundaries, whereas urban areas are based on census tract/block geography. According to the U.S. Census Bureau, an "urban area" will comprise a densely settled core of census tracts and/or census blocks that meet minimum population density requirements, along with adjacent territory containing non-residential urban land uses as well as territory with low population density included to link outlying densely settled territory with the densely settled core. For the 2010 census, urban areas are based on an aggregation of census tracts with densities of at least 1,000 persons per square mile, along with adjacent tracts with densities of at least 500 persons per square mile. For a complete definition, see: "2010 Census Urban and Rural Classification and Urban Area Criteria," http://www.census.gov/geo/www/ua/2010urbanruralclass.html.

[3] The final model also included a breakpoint at 500,000 population, but the population data did not include this breakpoint and the difference in the coefficients for 200,000 – 500,000 and >500,000 was small, so the same coefficient was used for all "other MSAs" larger than 200,000 population.

4 Texas Transportation Institute. "Urban Mobility Information." http://mobility.tamu.edu/ums/media-information/faq/

- **Freeway dominance –** Ratio of freeway miles to total freeway + arterial miles, again based on data from TTI.

The following variables were tested as potentially being of policy interest in this tool, but discarded due to lack of significance or unexpected signs:

- **Existence of rail service in the region** (yes/no) – The coefficient on this variable was positive, possibly because of correlation between existence of rail service and size of the region, which was also associated with longer trip lengths.
- **Various metrics of transit supply and access**, including vehicle revenue-miles per capita (bus, rail, and total), and track-miles for areas with rail were tested. A consistently significant relationship between transit supply and PMT per capita could not be identified. It is hypothesized that transit primarily affects VMT through mode shares, rather than total distance traveled.

It was desired as much as possible to include variables with policy relevance and for which future changes in variables could be intuitively understood so that logical scenarios could be created. Population and employment density, and urban vs. rural setting, are the most directly relevant variables included for this purpose. The transportation variables (congestion index and freeway dominance) may be varied to assist in understanding how congestion reduction strategies, or transportation investment policy, might affect travel. The distribution of population by region of the country and MSA size could also be varied for sensitivity analysis, although these are not likely to be targets of policy initiatives. Other variables, including income, age, gender, would not normally be varied for the purposes of built environment scenario analysis, but are included as important controlling variables.

2.2 Computing PMT and VMT by Mode

To develop energy and GHG estimates, total PMT by trip type needs to be broken out into PMT and VMT by mode. Three modes are included: automobile, transit, and non-motorized transit (NMT). To do so requires data on mode shares (to calculate PMT by mode) and average vehicle occupancy (to calculate VMT by mode).

Mode shares were computed from the 2009 NHTS sample data and are expressed on the basis of *percent of PMT* (rather than percent of trips, which mode shares commonly refer to). Mode shares were differentiated by population density (three levels) and by trip type (work vs. other). Consideration was given to applying mode shares for additional dimensions (including employment density and MSA size). However, increasing the number of dimensions led to inconsistent mode share relationships in some cases (e.g., a higher transit mode share in low-density than medium-density locations for non-work trips in "other" MSAs), due to small sample sizes in some cells. The mode share relationships across two dimensions (Table 2.1) appear consistent and of reasonable magnitude.

Table 2.1 Mode Shares (Percent of PMT) from 2009 NHTS

	Home-Based Work Trips			Other Trips		
Population Density	Auto+Other	Transit	NMT	Auto+Other	Transit	NMT
High	78.6%	19.3%	2.1%	82.4%	13.8%	3.9%
Medium	96.1%	3.4%	0.6%	95.7%	3.0%	1.3%
Low	99.0%	0.7%	0.3%	96.7%	2.7%	0.6%

Total PMT is first calculated for 1) home-based work (HBW) trips and 2) other trips, using the PMT models. Total PMT by mode is then calculated by trip type as follows:

- Work-trip PMT = total HBW PMT * labor force participation rate * HBW auto mode share. The result is work-trip PMT *for the average person* (including non-workers). For automobiles, work-trip and other-trip PMT were retained as separate results so that different occupancy factors could be applied;
- Non-work trip PMT = total "other trip" PMT * "other trip" mode share.

The following calculations are then applied to compute VMT by mode:

- Automobile VMT = work-trip PMT / work-trip vehicle occupancy + other trip PMT / other trip vehicle occupancy;
- Transit VMT = total transit PMT / average transit load factor;
- NMT VMT = zero.

Automobile occupancies of 1.19 for work trips and 2.10 for nonwork trips were computed from the 2009 NHTS.[5] An average transit load factor was computed based on average load factors (passenger-miles per vehicle-mile) by transit submode from the 2010 National Transit Database, multiplied by total vehicle-miles by transit submode from the same source. (Details of transit data assumptions are provided on the "Energy" worksheet in the model.)

2.3 Allocation of U.S. Population

The calculations of PMT and VMT by mode, as described above, are performed for current and forecast U.S. population by population "cell." These cells have five dimensions, with the number of levels of each noted, corresponding to the previously-described model variables:

[5] These occupancies are based on the number of person-trips divided by the number of vehicle-trips, so they are not weighted by trip distance.

- Urban or rural (2);
- Region of the country (4);
- MSA population (2 each within "top 50" and "other" categories);
- Census tract population density (3); and
- Census tract employment density (3).

The base year (2010) distribution of population in these categories was estimated using Census 2010 population data combined with employment data from the Census' Longitudinal Employer-Household Dynamics (LEHD) dataset.[6] Tract-level population data from the Census was matched with tract-level job data compiled from LEHD so that joint distributions of population by both population and employment density could be computed. At the time of model development, LEHD did not include data for the District of Columbia, Massachusetts, or Puerto Rico, so the combined data for which both population and employment densities were available is not a complete representation of the U.S. population.[7] Therefore, the percentage of population in each cell for which both data items were available was applied to a control total population for all MSAs as determined from the 2010 Census.

The tool contains a total of 106 populated cells for the "top 50" MSAs and 98 populated cells for the "other" MSAs. The reason that there are not 144 cells in each category (2 x 4 x 2 x 3 x 3) is that some cells have no population. For example, there are no populated areas in the rural – high population and high employment density category.

Total daily automobile VMT is calculated for each cell by multiplying PMT by population, and was then summed across cells to obtain total daily VMT for the entire population of the MSA group. Total transit and NMT PMT are calculated by summing the product of population and modal PMT by cell. Daily PMT and VMT are annualized using a factor of 365 since the NHTS survey data covered all days of the week.

For comparison purposes, daily VMT per capita is also computed for all cells. For the top 50 MSAs, the minimum under baseline conditions is 57 percent of the average, and the maximum cell value was 130 percent of the average for this group. This range (a factor of about 2.3) is roughly comparable to the range of VMT per capita across different population density levels (five density ranges) from analysis of the 2001 NHTS data (see built environment issue paper,

[6] Source: http://lehd.did.census.gov/led/onthemap/. LODES 6.0 Workplace Area Characteristic data, jobs are totaled by work Census Block aggregated to the Census Tract level.

[7] A total of 70,750 tracts were identified with non-zero employment density compared to a total of 74,002 total tracts with population data.

Table 3.1). The range for "other MSAs" is 64 to 113 percent of the average value for this group.

2.4 CALCULATION OF ENERGY AND GHG EMISSIONS

Energy consumption and GHG emissions are calculated for both automobiles and transit vehicles. Both direct operating and life-cycle (full fuel cycle) energy and emissions are reported in the tool. Options are provided for a variety of fuel types in use today, including:

- Conventional and reformulated gasoline;
- Gasoline with 10 percent ethanol blend (E10);
- Conventional diesel;
- Biodiesel (20 percent blend, B20);
- Natural gas;
- A custom "renewable fuel" for which the user specifies carbon dioxide equivalent (CO_2e) emissions relative to conventional gasoline; and
- Electricity.

The tool includes the following parameters:

- Energy and carbon dioxide (CO_2) content of different fuels;
- Scale factors by fuel type, to convert direct energy and CO_2 emissions into both direct and fuel cycle energy and CO_2 equivalent emissions;
- Current and scenario year (2010, 2030, 2050) emission rates for electricity generation;
- Current and scenario year light-duty vehicle and transit vehicle energy consumption per vehicle-mile; and
- For transit, fraction of VMT, average load factors, and fuel type fractions by mode.

The assumptions are discussed in more detail below. Some of the data, especially for transit vehicles, were developed for a concurrent research project for the Federal Transit Administration to identify environmental impact factors for transit projects. The 2012 Annual Energy Outlook (AEO) Reference Scenario serves as the primary data source for current and forecast year assumptions.

Energy and CO_2 Content of Fuels

A key issue in deriving energy consumption rates is the appropriate factor for converting gallons of fuel consumed into British thermal units (Btu) of energy. Conversion factors exist for both low heating value (LHV) and high heating value (HHV) and much confusion and disagreement exists regarding which one is most appropriate for application to transportation fuels. GHG reporting protocols, including The Climate Registry – General Reporting Protocol[8] and the Energy Information Administration (EIA) Voluntary Reporting of GHGs Program,[9] use HHVs. However, LHVs are used in the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model) life-cycle emissions model developed by Argonne National Laboratory. We believe that the LHV values are more appropriate for use in internal combustion engines and propose to use these values.[10] Reported values of LHV and HHV also vary slightly by source; we proposed to use the values included in the GREET model (v. GREET1_2011) as shown in Table 2.2.

Table 2.2 Energy and CO_2 Content of Fuels

Fuel	Energy – Btu/gal (LHV)	CO2 – kg/gal	CO2 – kg/mmBtu
Conventional gasoline	116,090	8.91	76.75
Reformulated or low-sulfur gasoline	113,930	8.73	76.63
Ethanol = 10% of gasoline	112,110	8.02	71.54
Conventional diesel	128,450	10.15	79.02
Biodiesel (B20)	126,670	8.12	64.10
Natural gas (Btu/scf)	929		58.78
Electricity (Btu/kWh)	3,412		

Source: Btu content – All except natural gas from GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model, GREET 1.8d.1, developed by Argonne National Laboratory, Argonne, IL, released August 26, 2010. Ethanol and biodiesel blends calculated based on weighting of conventional gasoline and diesel with 100% ethanol and biodiesel. The natural gas HHV average for the U.S. is taken from the EIA Voluntary Reporting of GHGs Program (http://www.eia.doe.gov/oiaf/1605/emission_factors.html). This value was factored by the ratio of LHV to HHV in GREET (983/1,089), which provides values for natural gas at 32 degrees F instead of 60 degrees (the measurement point for a standard cubic foot).

CO_2 content – Conventional gasoline, diesel, and biofuel factors from EIA Voluntary Reporting of Greenhouse Gases Program. Reformulated gasoline calculated at 2 percent oxygenate blend. Ethanol and biodiesel blends calculated based on weighting of conventional gasoline and diesel with 100% ethanol and biodiesel. Natural gas is value of 53.06 kg/mmBtu from EIA (provided for HHV), multiplied by ratio of HHV to LHV energy content.

CO_2/mmBtu – calculated from Btu/gal and CO_2/gal.

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[8] The Climate Registry (2008). General Reporting Protocol, Version 1.1.

[9] http://www.eia.gov/oiaf/1605/.

[10] The HHVs assume that the energy used to vaporize water is recaptured when the water condenses. The LHVs assume that this energy is lost. Since most water vapor probably recondenses *after* leaving the car engine, we believe that the LHV is more appropriate. See http://en.wikipedia.org/wiki/Heat_of_combustion for a discussion.

In addition to conventional gasoline and diesel, values are shown for reformulated gasoline, ethanol, and biodiesel. Different blends of gasoline are sold in different parts of the country including gasoline-ethanol blends as well as the addition of other oxygenates to gasoline to improve air quality. For automobiles the following default assumptions are included in the model:

- 2010 – Average ethanol blend across the country of 6.1 percent by energy content, modeled as 61 percent E10/38.5 percent conventional gasoline. The remaining 0.5 percent of energy content is made up of diesel and natural gas.[11]
- 2030 and 2050 – diesel, natural gas, and electricity fractions are taken from the 2012 AEO Reference Scenario. The remainder (95.7 percent) is assumed to be E10.

For buses we use a mix of 10 percent biodiesel (B20) and 90 percent conventional diesel for all years. As of 2010, about 8 percent of diesel used by transit properties is biodiesel.[12]

Heating values for compressed natural gas (expressed per standard cubic foot or scf) and electricity (Btu per kilowatt-hour) are also shown in Table 3.1. The electricity conversion factor of 3,412 Btu per kilowatt-hour (kWh) is a universal unit that reflects point-of-use propulsion energy ("at the plug"); it does not account for upstream losses in electricity generation and transmission.

Full Fuel Cycle Energy and GHG

Full fuel-cycle energy consumption and GHG emissions includes energy used and GHG emitted in extracting, refining, and delivering fuel (for liquid and gaseous fuels) as well as energy losses in electricity generation and transmission.

The GREET model (v. GREET1_2011) was used to develop ratios of fuel-cycle energy consumption to energy consumed directly by the operation of the vehicle, as well as ratios of fuel-cycle CO_2e to direct CO_2 (these factors reflect scaling both for CO_2 to total CO_2e, and direct to fuel cycle emissions). These ratios were developed for 2020 for the fuels of interest as shown in Table 2.3. (The GREET model only allows analysis through 2020; factors are similar for 2013.) While the GREET model is intended for passenger vehicle assessment, the ratios should be similar for heavy-duty vehicles and electric transit since the fuel sources and production pathways are the same. For electricity, the scaling factors for fuel

[11] Source: Calculated from data in AEO 2012 Early Release tables "energy consumption by sector and source" (motor gasoline) and "renewable energy consumption by sector and source" (ethanol used in gasoline blending). Quadrillion Btu converted to gallons using LHV values. An ethanol content of 6.1 percent by energy content corresponds to 8.6 percent by volume.

[12] National Transit Database.

cycle to fuel CO_2 and CO_2e account for the emissions associated with fuel production and extraction, in addition to those produced by fuel combustion at the electricity generation plant.

Table 2.3 Fuel-Cycle Energy Factors

Fuel	FC to Operating Energy	FC to Fuel CO_2	FC to Fuel CO2e	FC CO_2e to Operating CO_2
Conventional gasoline	1.27			1.27
RFG or low-sulfur gasoline	1.27			1.27
Ethanol = 10% of gasoline	1.29			1.27
Conventional diesel	1.22			1.28
Biodiesel (B20)	1.20			1.09
Natural gas	1.17			1.47
Electricity	2.43	1.03	1.09	

Source: GREET1_2011, run for passenger car (PC) with default assumptions, outputs for year 2020.

Automobile Energy Consumption Rates

Energy consumption rates for automobiles (cars and personal light trucks) are derived from the AEO 2012 Early Release, Reference Scenario. This source provides total energy consumption and total miles driven for light-duty vehicles for future years through 2035. The projections reflect the impacts of adopted Federal fuel economy standards for Model Years 2012-2016, but not the impacts of additional standards proposed for Model Years 2017-2025. The assumed rates are shown in Table 2.4. Rates projected for 2035 were used to represent 2050 conditions.

Table 2.4 Energy Consumption Rates for Automobiles (Btu/mi)

	2010	2030	2050
Direct	6,025	4,521	4,365
Fuel-cycle	7,652	5,742	5,544

Source: Direct: AEO – Energy Information Administration, Annual Energy Outlook 2012 Early Release, Reference Scenario; calculated based on total energy consumption (quadrillion Btu) and total miles driven (billion vehicle-miles) for light-duty vehicles. Fuel-cycle = direct * scale factor from Table 2.3.

Transit Vehicle Energy Consumption Rates, Activity, and Load Factors

Energy consumption rates for a variety of transit modes are derived from 2010 National Transit Database (NTD) data reporting of fuel consumption and vehicle-miles traveled. While buses will be subject to Federal heavy-duty fuel economy requirements in the future, there is no similar controlling standard for rail energy use, and opportunities for improvements – especially for electric rail efficiency – are likely to be lower than for bus technology. Since there is no source of agreed-upon projections for future bus and rail efficiency, energy consumption rates in 2030 and 2050 were scaled from 2010 rates based on the following relative energy consumption rates reported in the 2012 AEO Reference Scenario:

- Buses – based on heavy-duty vehicles (trucks); and
- Rail – based on freight rail efficiency (per ton-mile).

Table 2.5 shows the calculated average energy intensity of the various modes reported in the NTD. The "efficiency factor" is the relative efficiency assumed in the forecast year vs. 2010.

Table 2.5 Energy Intensity of Transit Modes (Btu/vehicle-mile)

Mode	2010	2030	2050
Bus efficiency factor:	1.00	0.83	0.81
Rail efficiency factor:	1.00	0.97	0.97
Bus	33,964	28,190	27,511
Light rail	28,635	27,776	27,776
Heavy rail	19,239	18,662	18,662
Commuter rail – diesel	81,239	78,802	78,802
Commuter rail – electric	34,884	33,837	33,837

Source: 2010 – National Transit Database, for all systems reporting in U.S. Vehicle-miles are either the sum of passenger-car miles for rail modes, or the sum of vehicle-miles for non-rail modes. Reported gallons of diesel, gasoline, CNG, and biodiesel and kWh of energy consumption are converted to Btu using conversion factors shown previously. For CNG, the diesel conversion factor is used since transit agencies are asked to report CNG consumption in terms of gallons of either diesel or gasoline equivalent. 2030 and 2050 – adjusted from 2010 based on efficiency improvements for trucks (applied to buses) and freight rail (applied to rail) as derived from 2012 AEO Reference Scenario.

Transit vehicle activity (percent of vehicle-miles by mode) and average load factors (passenger-miles per vehicle-mile) were developed from the 2010 National Transit Database and represent U.S. averages. Assumptions are shown in Table 2.6. Default assumptions are held constant in 2030 and 2050, but the user is provided with the option of changing these assumptions for the purposes of scenario analysis. Demand-responsive transit, vanpools, and modes representing a very small fraction of service (e.g., monorail, ferry) are not included in this inventory and therefore their energy consumption is not reflected in the outputs of the built environment analysis tool.

Table 2.6 Default Transit Activity and Load Factors

Mode	% Vehicle-Miles by Mode	Average Load Factor
Bus	66.9%	9.2
Light Rail	3.0%	23.3
Heavy Rail	19.9%	24.6
Commuter Rail – Diesel	4.6%	31.5
Commuter Rail – Electric	5.6%	31.5

Source: 2010 – National Transit Database, for all systems reporting in U.S. Vehicle-miles are either the sum of passenger-car miles for rail modes, or the sum of vehicle-miles for non-rail modes.

GHG Emissions from Electricity Generation

GHG emissions from electricity generation are derived from 2012 AEO Reference Scenario forecasts through 2035 (2035 values are used to represent 2050). Intensity as expressed in terms of kg GHG emissions per kWh and per mmBtu is shown in Table 2.7. Emissions based on "point-of-use" energy are derived directly from AEO forecasts of total net generation (in kWh) and GHG emissions (in tons), and include a 7 percent adjustment for generating and transmission losses. GHG emissions per kWh are converted to GHG emissions per Btu using a factor of 3,412 Btu/kWh. These factors are applied to reported electric transit vehicle energy use (in Btu/mile) as calculated from the National Transit Database. Emissions are also calculated on a full fuel-cycle basis (i.e., net GHG emissions per kWh or Btu of fuel-cycle energy). This is so that emission factors for electric trolley buses can be developed assuming that an electric bus has the same life-cycle energy consumption as a diesel bus. (The NTD shows slightly higher energy consumption for trolley buses but this is based on reporting for only five systems which may have unique characteristics.)

Table 2.7 GHG Emissions from Electricity Generation

	2010	2030	2050
Point-of-Use Energy			
kg GHG/kWh	0.612	0.550	0.547
kg GHG/mmBtu	179.3	161.2	160.2
Fuel-Cycle Energy			
kg GHG/kWh	0.231	0.208	0.206
kg GHG/mmBtu	67.7	60.8	60.5
GHG intensity vs. 2010		90%	89%

Source: Cambridge Systematics, Inc. calculations based on 2012 AEO Reference Scenario, "total net generation" and "GHG emissions," and 7 percent generating/transmission loss; 2035 values shown for 2050.

It should be noted that 2012 AEO Reference Scenario shows only a very modest reduction in the GHG intensity of future electricity emissions. This could change substantially if more aggressive GHG reduction policies or other alternative energy programs are implemented in the future.

3.0 Tool Validation

A number of validation checks were applied to compare the output of the tool to other benchmarks of personal travel and energy use.

Total VMT and VMT per Capita

Total annual U.S. VMT is reported in the Federal Highway Administration (FHWA) Highway Statistics publication by vehicle type, including for all light-duty vehicles (LDV) and for short-wheelbase LDVs, which is probably the category most closely corresponding to personal travel. The VMT data are estimated by each state based on a network of traffic monitoring stations which is part of the Highway Performance Monitoring System (HPMS). Counts are multiplied by segment lengths for each monitored site and expanded to represent the entire roadway network. If the total of 2,026,396 million short-wheelbase LDV VMT reported in 2010 is divided by the U.S. population of 308.8 million, the average per capita VMT is 6,560. This compares with a modeled average of 7,592, about 16 percent higher.

There are a number of possible reasons for discrepancies between modeled VMT per capita and estimates from measured sources, including:

- The NHTS reflects 2008/2009 conditions, not 2010. (Comparing 2008 Highway Statistics VMT and the Census' estimated 2008 population reduces the difference by about 2 percent.)
- The model does not including travel by non-MSA residents. This group would be expected to have per-capita travel at least as high as MSA residents, so this factor should not account for the overestimation.
- The model does not account for trips over 200 miles (this should also lead to a small underestimation of VMT, although many of the longer trips will be taken by air, rail, or intercity bus).
- There may be errors introduced in Highway Statistics by state-level VMT measurement and estimation methods in the HPMS on which the VMT estimates are based.
- Short-wheelbase light-duty VMT does not completely correspond to travel in personal vehicles. Some such vehicles may be used for commercial purposes, while some larger vehicles may be used for personal travel. Even if the HPMS data were accurate, the fraction of VMT attributable to personal travel is not known with certainty.
- There may be errors in reported or observed distances traveled in the NHTS. Trip distances in NHTS are estimated, based on the reported origin and destination, rather than modeled network distances. The behavior of the NHTS survey sample may not be exactly representative of the U.S.

population as a whole. Differences may also be introduced by mode shares and vehicle occupancies calculated from the NHTS data and applied to the modeled PMT to obtain modeled VMT.

- Errors will be introduced by modeling (the regression models have relatively low goodness of fit to begin with) and will be combined with discrepancies introduced by extrapolating results modeled from NHTS sample to entire U.S. population subgroups.

Person-miles of travel by automobile were estimated from Highway Statistics VMT multiplied by average vehicle occupancy as observed in the 2009 NHTS. The observed value of 3.97 trillion compares with a modeled value of 3.29 trillion, about 17 percent lower. This is consistent with expected differences, given that PMT by the 15 percent of the population not in an MSA is not included. However it is subject to errors of the same nature as described above.

The fraction of VMT made of up work travel vs. all travel was modeled to be 36.3 percent in the top 50 MSAs, and 28.5 percent in other MSAs. This is reasonably close to data reported from the 2001 NHTS that 33 percent of all VMT is travel to work.[13] A better comparison could be made by examining the same statistic from the 2009 NHTS.

Energy Use and CO_2 Emissions by Personal Vehicles

The 2011 Annual Energy Outlook provides historical estimates of energy use by light-duty vehicles. This was reported as 16.2 quadrillion Btu in 2010. To adjust for LDV travel by commercial vehicles, this figure was multiplied by the ratio of short-wheelbase to total LDV VMT of 76.5 percent, as reported in Highway Statistics for year 2010, providing an estimate of 11.4 quadrillion Btu by short-wheelbase LDVs. Our modeled estimate of 12.0 quadrillion Btu from personal automobile travel is about 5 percent higher.

Some of the same factors identified for the VMT per capita comparison may also be leading to differences in the energy use estimates. The basis for the AEO estimates of LDV energy use is not known but is probably state-reported fuel sales data apportioned to vehicle type by type of fuel. If based on fuel sales, this is a reason for relative discrepancies between the energy estimates and VMT estimates. If based on VMT, a comparison would be required of VMT estimates and fuel economy assumptions. Note that Highway Statistics reports an average fuel economy for all light-duty vehicles of 21.6 mpg, while AEO reports an average of 20.8 mpg for the light-duty stock.

In a similar manner, CO_2 emissions from AEO were compared with our modeled CO_2 emissions (actually CO_2e with a minor scaling adjustment for CO_2 /CO_2e).

[13] Hu, P.S. and T.R. Reuscher (2004). "Summary of Travel Trends: 2001 National Household Travel Survey." U.S. Department of Transportation.

AEO reported total U.S. emissions in 2010 of 1,071 mmt for LDVs, which is about 755 mmt when adjusted for short-wheelbase LDVs as described above. Our modeled estimate of 919 mmt is about 22 percent higher.

The relative differences in modeled vs. observed (AEO) estimates for energy (5 percent higher) vs. CO_2 emissions (22 percent higher) can be explained easily by the difference in the heating value of fuels used. As noted in Section 2.4, we use the LHV and AEO appears to use the HHV. If AEO's reported LDV CO_2 emissions are divided by energy use, a carbon intensity of 66.2 kg CO_2 per mmBtu is obtained. Our model's carbon intensity is 73.5 kg/mmBtu. If we substitute HHV for LHV in our model for conventional gasoline and E10, we obtain a carbon intensity of 68.6 kg/mmBtu which is much closer to the AEO value.

Transit Ridership and Energy Use

Our model's estimated transit energy use of 0.72 quadrillion Btu compares against AEO's estimate of 0.27 quads used by buses and 0.05 quads used by passenger rail (0.32 quads total, or less than half). The AEO data may not include urban electric rail systems which could largely account for our model's overestimate compared to AEO. More investigation of the basis for AEO's transit estimates would be required to further examine this factor.

The National Transit Database reports a total of 50.8 million person-miles of travel on U.S. transit systems in 2010. This compares with our modeled estimate of 189 million PMT, which is over two and one-half times greater. Part of this discrepancy should be due to the inclusion of walk, drive, and other non-transit access and egress distance considered as part of transit trips in our model, whereas the NTD only reports passenger-miles actually traveled on the system. There may be errors introduced in reporting and measurement of trip distances for both the NTD and NHTS, although it is not likely that NTD systematically underreports PMT by a substantial amount.

Transit PMT in our model is a function simply of total PMT and transit mode shares by trip type. Total PMT has been investigated above and not found to differ significantly from national estimates based on observed VMT and occupancy data. We compared the work-trip mode shares that we use (from the 2009 NHTS) with mode shares from the 2009 American Community Survey (ACS). The mode shares we use average 5.9 percent when weighted across the three population density classes by the population in each class (calculations shown on the "FixedInputs" worksheet). This compares with 5.4 percent from the ACS (trip mode shares weighted by average trip length, and excluding work-at-home trips), so our calculation of transit PMT for work trips appears reasonable.

Unfortunately a national-level independent source similar to the ACS is not available for comparing non-work transit trips. Analysis of the 2001 NHTS did show that over half of transit PMT is for work trips, which is considerably greater than the 18 to 24 percent of PMT for work trips found in our model (values noted for top 50 and other MSAs, respectively).[14] Our model uses a weighted non-work transit mode share of 5.0 percent (observed from NHTS data), which seems high if work trips still make up a majority of all transit travel. If our model overestimates non-work transit PMT, that could also account for some of the difference between our estimate and the NTD estimate. To fully explain the difference between modeled transit PMT and PMT reported in the NTD would require further investigation.

[14] Hu and Reuscher, *op cit.*

4.0 Using the Tool

The primary purpose of the tool is to test the effects of built environment strategies on outputs including PMT, VMT, energy use, and GHG emissions. Built environment strategies are changed on the "Scenarios" worksheet. Various other parameters on the "FixedInputs" and "Energy" worksheets can be changed as well. The mechanics of each worksheet are described below.

Some cells have a colored background or text. Their meaning is identified in Table 4.1.

Table 4.1 Cell Formatting

Cell Formatting	Significance
Pale yellow background	User may change input
Blue background	Key intermediate output (useful for internal checking/QC)
Blue font	Data input from an external source
Yellow background with bold red font	Invalid data (conditional formatting)
Grey shaded	Data not used in final version of model

4.1 Tool Worksheets

Scenarios

The user should enter a scenario name, description, and date of analysis in cells E2:E4. These will carry through to other worksheets. The data describing the built environment scenarios are entered in the cells shown in Table 4.2, as described below.

Table 4.2 Cells for Entering Built Environment Scenarios

MSA Group/Scenario Year	Change in percent of population by population & employment density class	Change in pedestrian design index by population density class
Top 50 MSAs in 2030	J16:L18	P16:P19
Top 50 MSAs in 2050	J47:L49	P47:P49
Other MSAs in 2030	J80:L82	P80:P82
Other MSAs in 2050	J111:L113	P111:P113

Entering the "Change % of Population" by Population and Employment Density Class

The scenario tables for user input are dimensioned two ways: by population density class (three classes) and by employment density class (three classes). The thresholds for each class and a brief description of each are provided in Table 4.3. These dimensions represent the national distribution of population and employment density at a census tract level. Census tracts, which are set for a consistent population averaging around 4,000 residents, can vary in physical size from an urban neighborhood to a rural village or township. "Low" population densities generally reflect a rural environment, with "medium" densities reflecting a suburban environment (a wide range of characteristics is possible) and "high" densities a strongly urban environment (or suburban with extensive multi-story developments). "Medium" and "high" employment densities are intended to correspond to a mixed-use environment that supports shorter driving trips and possibly walk and transit trips, with high densities reflecting larger employment centers. The extent to which walk and transit trips are supported will depend not only upon densities, but also upon design characteristics and how well the commercial uses are integrated with the residential uses.

Table 4.3 Description of Dimensions for Built Environment Scenarios

	Employment Density[a]		
Population Density	**Low (<100 jpsm)**	**Medium (100 – 1,000 jpsm)**	**High (>1,000 jpsm)**
Low (<750 ppsm)	Low-density suburban or rural residential neighborhoods. Nearly all travel by auto.	Low-density suburban or rural residential neighborhoods with some commercial activity. Nearly all travel by auto.	CBD or other major employment center; possible focal point of transit trips.
Medium (750 – 7,000 ppsm)	Low- to medium- density suburban residential neighborhoods. Most travel by auto.	Urban or suburban areas with moderate-density residential neighborhoods and commercial activity. Some transit and walk trips may be possible with good design and well-mixed uses.	CBD or other major employment center, with some residential areas providing potential for local transit and walk travel.
High (>7,000 ppsm)	High-density residential, but not mixed-use. Transit use primarily for work trips.	High-density residential with neighborhood/small scale commercial. Good potential for transit use, some walk trip opportunities.	High-density employment centers and residential mixed or in close proximity. Many opportunities for walking and transit use.

[a] These descriptions are based on professional judgment and have not been validated against real-world data. However, as previously noted, the density thresholds were selected to correspond to observed differences in travel behavior.

The values entered into the table represent the percent of total population within the MSA group that is being "shifted" into or out of each density group. The user-entered values should be realistic, based on the baseline forecast percent of population in each class, as shown in columns D:G. The "scenario % of population" is shown in columns S:V and is computed as the "baseline % of population" minus the "change % of population" entered by the user. <u>In no case should the "scenario % of population" be less than zero</u>. Values less than zero in these tables will be highlighted in bold red font with yellow background.

Note that only eight cells are user-entered for each MSA group and scenario year. The ninth cell (not highlighted) is calculated from the remaining eight cells so that the total change in population is 0.0%.

Directly under the user-input table is shown the amount of population being "shifted" as a percentage of the total forecast population growth between 2010 and 2030 (or 2010 and 2050). While it is possible for this value to exceed 100 percent, it would mean that not only is all new population growth shifted, but some existing population is shifted (e.g., through redevelopment). A value in the range of 50 to 75 percent or less for this parameter is probably more realistic.

Below the total population for each MSA group/year are shown tables for population in urban areas vs. rural areas. The total user-entered change in each cell is allocated to urban vs. rural in proportion to the baseline distribution of urban/rural population for that cell.

The user should enter different population change scenarios for the top 50 MSAs vs. other MSAs because the baseline population distributions are quite different. (Other MSAs have less population in high-density areas and more population in low-density areas.) However, as a shortcut, the user may choose to scale the 2050 changes from the 2030 changes. For example, doubling the percent change in each cell between 2030 and 2050 would represent a continuation of present-2030 trends through 2050. Care must be taken to ensure that the "scenario % of population" in 2050 is not less than zero for any cell.

<u>Note that after the population distributions are changed, the orange "update data" button should be pressed so that outputs are correctly recalculated</u>. This command causes the pivot tables on the worksheet to be updated.

Entering the "Change in Pedestrian Design Index" by Population Density Class

The pedestrian design index is used to represent factors influencing walkability that are not captured in the population and employment density factors above. A positive change in the pedestrian design index indicates a more favorable environment for walking and transit access (e.g., more complete sidewalk network, smaller block sizes, a well-connected pedestrian network).

The impact of a change in pedestrian design is evaluated using elasticities entered on the "FixedInputs" worksheet (see below). The elasticity, combined with the percent change in the design index entered by the user on this (Scenario) worksheet, is used to calculate the percent change in person-travel for walk and transit modes. The specific index that is represented (e.g., sidewalk coverage, pedestrian environment factor) is entered by the user on the "FixedInputs" worksheet and carried through to cells P11 and P12. It can be different for walk vs. transit. However, only one percent change in design index can be applied by the user.

As with scenario population by cell, changes are expressed relative to baseline conditions, i.e., the change in both 2030 and 2050 is expressed relative to conditions extrapolated based on 2010 data. Therefore, scenarios would logically include a larger change in 2050 than in 2030.

FixedInputs

This worksheet contains various global inputs that should not normally be changed by the user. However, some inputs (pale yellow cells) may be changed to test the sensitivity of the model to different assumptions. Columns B:I store data that is referenced by other worksheets, while Columns K and beyond store original data (for values that may be changed by the user) and provide sources.

Note that if any values are changed in this worksheet, the orange "update data" button should be pressed so that outputs are correctly recalculated. This command causes the pivot tables on the "Scenario" worksheet to be updated.

Population and Workforce Control Data

This section includes population and labor force data for years 2010, 2030, and 2050 as derived from Census Bureau forecasts and other sources. The following variables are set to their current values as defaults, but may be changed by the user:

- **Labor force participation rate** – The default values for 2030 and 2050 are scaled from the current (2010) rate, as reported by the Bureau of Labor Statistics, based on the Census-projected percent of population in the 18-64 age group.
- **Change from Census growth** – This variable can be used to adjust 2030 and 2050 population relative to the Census forecast. A value of 0% means that the Census forecast is used. A value of -100% means no growth, and a value of +100% means a doubling of growth.
- **% of U.S. in MSA** – This variable represents the percent of U.S. population that lives in a Metropolitan Statistical Area (MSA). The value was 84.9 percent in 2010. The Census Bureau does not forecast population by MSA so the default is retained at the same value in 2030 and 2050.
- **% of MSA pop/workers in Top 50 MSAs –** This variable represents the percent of MSA population and workforce that lives or work in the 50 largest

MSAs. The value for population was 64.2 percent in 2010 and workers are assumed to have the same distribution as population.

The following other key assumptions are noted:

- The population by region of the country (four regions) is extrapolated from 2010 population by region, based on growth rates in regional forecasts produced by the Census Bureau in 2005 (the latest available). Population by region in 2050 is extrapolated. See cell comments and formulas for details of the extrapolation.

Coefficients for Fixed Variables in Model

The models of PMT (described on the "NHTSModel" worksheet) includes a number of demographic and regional infrastructure variables. Providing joint distributions of population by these variables, along with the built environment variables, would have required the creation of intractably complex scenarios. Instead, default distributions are provided for these variables (based on 2010 data), and the coefficient values are averaged based on these distributions and added to the fixed coefficient in the model. (The coefficients on these variables are imported from the "NHTSModel" worksheet and shown to the right of the distributions). However, the default distributions may be adjusted to test global sensitivity to changes in demographics and infrastructure supply. The specific variables are:

- **Demographics –** Household income (three categories), gender, and worker age (three categories). The primary change of interest here would be increasing or decreasing incomes. (Note that incomes are in constant dollars.)
- **Level of congestion** – This is the ratio of congested to normal travel time at the metropolitan area level, as described in Section 2.1. A higher value indicates higher levels of congestion. This variable could be changed to evaluate the global travel, energy, and GHG impacts of actions (such as infrastructure investment) that increase or decrease congestion. However, only impacts on PMT and VMT are captured, not impacts on mode share, or reduced vehicle efficiency under congested conditions.
- **Freeway vs. arterial dominance –** This is the ratio of freeway lane-miles to total freeway and arterial lane-miles in the metro area. A lower ratio (less than 25 percent) means relatively fewer freeways. This variable could be changed to test the global impacts of relative investment in freeways vs. arterials.

For both level of congestion and freeway vs. arterial dominance, default shares of one-third each are provided. The breakpoints were set to divide metro area population into roughly three equal groups according to these variables.

Other Inputs

This subsection includes the average number of trips per person or worker per day, vehicle occupancy, and mode shares. All of the values are taken from analysis of the 2009 NHTS and are not intended to be changed.

Pedestrian Design Elasticities

The impact of a change in pedestrian design is evaluated using elasticities of transit and walk mode share with respect to a pedestrian design factor. Different elasticities can be entered for low, medium, and high population density areas. (Impacts of a percent change in design might be expected to be lower in areas of low density where most destinations are not within walking distance.) Default values are provided based on an assessment of values found in the literature, as provided below the user-entry highlighted cells. If the user changes the elasticity he or she should also identify what aspect of pedestrian design the elasticity is applied with respect to.

Energy

This worksheet contains a variety of inputs required to calculate energy consumption and GHG emissions. Data taken from AEO, GREET, or another source as referenced are shown in blue font. AEO values for 2035, the last year in the 2012 forecast, are used to represent 2050. Other data are calculated.

Inputs that are allowed to be changed by the user include:

- **GHG emissions (CO_2e) from electricity generation – GHG intensity vs. 2010:** This factor represents the relative intensity of GHG emissions (GHG per unit of electricity generated) in 2030 and 2050, relative to 2010.
- **Light-duty vehicle energy & GHG – energy intensity vs. 2010**: This factor represents the relative energy intensity (Btu/mile) of light-duty vehicles in 2030 and 2050, relative to 2010. The default values from 2012 AEO Reference Scenario account for Model Year 2012-2016 Federal fuel economy standards, but not more stringent standards for years beyond 2016.
- **LDV % energy by fuel type:** This is the percentage of each fuel used in light duty vehicles in 2030 and 2050 (expressed as a percent of total energy content – not volume). The user can enter fractions for diesel, biodiesel (B20), compressed natural gas, renewable fuel (user-specified custom blend – see below), and electricity. The remaining fraction (not user-entered) is assumed to be a standard 90% gasoline/10% ethanol blend.
- **CO_2e ratio for renewable fuel vs. gasoline:** This allows the user to specify a custom-blend renewable fuel with lower emissions than conventional gasoline. The user can specify direct and life-cycle emissions relative to conventional gasoline (expressed as a percentage).

- **Transit improvement (relative energy consumption vs. 2010):** These factors are the relative energy consumption of bus and rail transit vehicles in 2030 and 2050, relative to 2010. The defaults shown for buses are from freight trucks, and for rail are from freight rail, from the 2012 AEO.
- **% of transit VMT by mode:** This is the fraction of national vehicle-miles traveled (passenger-car miles for rail) traveled by each mode as a percent of all the transit modes included. Default values are set at the 2010 values as determined from the National Transit Database.
- **Load factor vs. 2010:** This is the relative load factor for all transit vehicles in 2030 and 2050, expressed as a ratio to the 2010 load factor. It can be used to test policies that would increase the utilization of transit vehicles, such as transit-oriented development that balances jobs and housing along a transit corridor to increase loads on trips in the non-peak direction of travel. The load factor is defined as the ratio of passenger-miles to vehicle-miles, i.e., the average number of passengers per vehicle across all systems.
- **Transit fuel use:** These factors represent the fraction of each fuel (on an energy content basis) used in buses and in diesel commuter rail. Default values for 2030 and 2050 are set at the 2010 values.

Outputs

This worksheet summarizes the key outputs from the tool. Outputs are shown for 2010, 2030 baseline and scenario, and 2050 baseline and scenario. The outputs reflect only impacts associated with population living within metropolitan statistical areas (MSAs), since the tool does not provide for analysis of built environment scenarios in non-MSA areas where options for reducing travel are much more limited. As of 2010, about 85 percent of the U.S. population lived in an MSA.

Travel impacts are shown including VMT as well as PMT by mode. Per capita values of both are also provided as a benchmark, along with the percent of PMT by mode. Note that this percentage is not the same as “mode shares” that are typically reported, which represent the percentage of *trips* by mode.

Energy and GHG outputs include energy consumption in quadrillion Btu and GHG emissions in million metric tons of carbon-dioxide equivalents (mmt CO_2e). Outputs are shown for both direct and full fuel-cycle energy and GHG emissions.

‘MSA Top 50’ and ‘MSA Other’

These worksheets are where the calculations are performed for travel impacts by population cell. Rows 1:13 import the relevant model coefficients from the “NHTSModel” worksheet. These coefficients are referenced from VLOOKUP functions and must be kept in alphabetical order. None of the data on these worksheets should be changed by the user.

Rows 18:123 (MSATop50) and 18:117 (MSAOther) contain the calculations for the population cells. Columns B:F are the relevant cell class descriptions by urban/rural, region of the country, MSA size (MSApop), population density, and employment density. Column J contains the percent of U.S. metropolitan area population in each cell as of 2010. For the purposes of this model, workers (i.e., residents who travel to work – not the same as jobs) are assumed to be distributed in the same way as population. These percentages are used to calculate the baseline population by cell (columns G and h) using the worker and population control totals in the "FixedInputs" worksheet.

Columns K:P contain population and worker totals for the 2030 baseline and scenario conditions. The baseline population is scaled off the 2010 population, inflated by the growth rate for the respective region of the country from "FixedInputs." Workers are scaled from population based on the labor force participation rate from "FixedInputs." The scenario population is obtained from lookup functions referencing the relative change in population by density and urban/rural as calculated from the "Scenarios" worksheet. Columns Q:V repeat these calculations for 2050.

Columns X:Y are the daily modeled PMT by trip type: *PMT per worker* for work trips, and *PMT per person* for other trips.

In columns Z:AS, the PMT values are split out by mode and also determined for the future year baselines and scenarios. In these columns all PMT values are expressed *per person*. Notes on these calculations are as follows:

- The PMT values for transit and NMT in this block are the sum of work and other trip PMT. The baseline values for all modes reflect total PMT apportioned by mode shares by trip type from the "FixedInputs" worksheet.
- The scenario values for transit and NMT reflect adjustments for the "change in ped design index" factor from the "Scenarios" worksheet. The increase in transit and NMT PMT is then subtracted from the auto PMT so that total PMT is the same (for each population cell) for the baseline and scenario condition.
- With the default inputs, average PMT for work trips is lower in 2030 and 2050 than in 2010, because of the lower forecast labor force participation rate in these years. Average PMT for other trips is assumed to be the same as in 2010.

Columns AU:AY compute the total daily auto VMT for each population cell and scenario. This is done by multiplying auto PMT per capita by the population of each cell and dividing by average vehicle occupancy. Different occupancy factors are used for work vs. other trips. Note that *the largest difference in outputs between the baseline and scenario condition in each year will generally be caused by a redistribution of population across cells* – not by VMT changes within each cell, which are only affected by the pedestrian design factor.

Columns AZ:BE show the average VMT per capita in each cell, and compare the 2010 average as a percent of the average across the entire population. This calculation is performed to examine how the range of predicted VMT per capita varies across population cells. This block of output is provided for comparison purposes only and is not used in further calculations.

Column BG contains text strings used in the lookup functions.

Summary statistics across all population cells are computed in rows 125:154 (MSATop50) and in rows 119:148 (MSAOther). Blue highlighted cells are summary outputs that are of particular interest. These outputs are summed across the MSATop50 and MSAOther worksheets to provide the summary output on the "Output" worksheet. However, it can be useful for diagnostic purposes, or for research interest, to examine how these outputs differ for the 50 largest MSAs vs. other MSAs.

One important note is that *the total 2030 and 2050 population and workers, as computed across the summary cells in these worksheets, may not equal the control total population and workers as determined from the Census data*. This is a result of the algorithm used to forecast population in each cell based on growth rates by region of the country. While it would be possible to apply a "rebalancing" to match the control total population, as long as the scenario and baseline populations in each year are equal, the key model results (including differences between the scenario and baseline, and per-capita indicators) should not be significantly affected.

NHTSModel

This worksheet contains the coefficients for the daily PMT models developed from the 2009 NHTS data, as well as descriptive statistics for the models. The models are:

1. Home-based work PMT in the 50 largest MSAs;
2. All other PMT in the 50 largest MSAs;
3. Home-based work PMT in other MSAs; and
4. All other PMT in other MSAs.

None of the data on these worksheets should be changed by the user.

Checks

This worksheet contains various checks on the model's intermediate and final output as described in Section 3.0.

5.0 Limitations and Potential Enhancements

While an advancement over previous methods used for built environment analysis at a national scale, the tool still contains a number of limitations, and a variety of enhancements would be possible to further mine the NHTS data or take advantage of additional data from other sources.

One limitation of the models is that variables describing overall metropolitan area urban form/structure, such as average density or population-weighted density, were not included. Such variables could have been developed and appended to records from the 50 largest MSAs. However, overall average density has been found to be of questionable value in explaining travel behavior. Potentially more useful measures, such as population-weighted density, were not developed due to resource limitations. It was also not possible to include household-level variables such as regional accessibility (i.e., relative access to jobs and other destinations) or distance from the region's core, since the location of individual households was not known. Both of these variables have been found to be significant in predicting per-capita travel. To the extent that either is strongly correlated with variables included in the model (such as tract-level density), the model may therefore be picking up some of these confounding effects and overstating the contributions of the variables that were included.

Mode shares for auto, transit and NMT are applied based on population density, but are not modeled. Models could be tested to predict mode shares as a function of the joint population and employment density variables used for predicting PMT. This could further increase the sensitivity of the model to built environment scenarios.

The use of population and employment densities as the primary built environment descriptors is also fairly crude. Such measures do not capture more fine-grained relationships such as the extent of land use mixing, network connectivity, etc. within a census tract. The matching of local/neighborhood-level metrics with NHTS data would require geocoded data. Such data is potentially available from over 20 states that funded "add-on" samples for the 2009 NHTS. Additional place-specific metrics could be identified from a newly-developed U.S. Environmental Protection Agency (EPA) dataset, the Smart Location Database, that includes a variety of built environment measures for the entire nation. However some effort would be required to obtain geocoded NHTS data from a sample of states sufficient to represent the U.S., match these data with EPA's indicators, and re-estimate models.