Research Report
KTC-05-07/PL5-03-1F

KENTUCKY TRANSPORTATION CENTER

College of Engineering

SPEED ESTIMATION FOR AIR QUALITY ANALYSIS

UNIVERSITY OF KENTUCKY

Our Mission

We provide services to the transportation community through research, technology transfer and education. We create and participate in partnerships to promote safe and effective transportation systems.

We Value...

Teamwork -- Listening and Communicating, Along with Courtesy and Respect for Others
Honesty and Ethical Behavior
Delivering the Highest Quality Products and Services
Continuous Improvement in All That We Do

For more information or a complete publication list, contact us

176 Raymond Building
University of Kentucky
Lexington, Kentucky 40506-0281

(859) 257-4513
(859) 257-1815 (FAX)
1-800-432-0719
www.ktc.uky.edu
ktc@engr.uky.edu

Research Report
KTC-05-07/PL5-03-1F

SPEED ESTIMATION FOR AIR QUALITY ANALYSIS

By

Mei Chen, Ph.D.
Assistant Professor
Department of Civil Engineering

and

Huafeng Gong
Graduate Research Assistant
Department of Civil Engineering

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

in cooperation with
Transportation Cabinet
Commonwealth of Kentucky

and

Federal Highway Administration
U.S. Department of Transportation

May 2005

1. Report No. **KTC-05-07/PL5-03-1F**	**2. Government Accession No.**	**3. Recipient's Catalog No**
4. Title and Subtitle Speed Estimation for Air Quality Analysis		**5. Report Date** May 2005 **6. Performing Organization Code**
7. Author(s) Mei Chen and Huafeng Gong		**8. Performing Organization Report No.** KTC-05-07/PL5-03-1F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** P5
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet 200 Mero Street, Frankfort, KY		**13. Type of Report and Period Covered** Final **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

Average speed is an essential input to the air quality analysis model MOBILE6 for emission factor calculation. Traditionally, speed is obtained from travel demand models. However, such models are not usually calibrated to speeds. Furthermore, for rural areas where such models are not available, there has not been a reliable method for estimating speed.

In this study, a procedure was developed based on the Highway Economic Requirement System (HERS) speed model to estimate average speed using as input various data such as roadway characteristics and traffic conditions. This procedure was coded in MS Excel macro and can be attached to a workbook that contains the roadway inventory data in the HPMS format.

The comparison between the measured speeds and those estimated by the model demonstrated the strong performance of the model. The data availability and accuracy issue during the implementation stage was discussed.

17. Key Words Speed Estimation, Air Quality, Free-flow Speed, Delay		**18. Distribution Statement** Unlimited	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 43	**22. Price**

EXECUTIVE SUMMARY

Average speed is an essential input to the air quality analysis model MOBILE6 for emission factor calculation. Traditionally, speed is obtained from travel demand models. However, such models are not usually calibrated to speeds. Furthermore, for rural areas where such models are not available, there has not been a reliable method for estimating speed. In this study, a procedure was developed based on the Highway Economic Requirement System (HERS) speed model to estimate average speed using as input various data such as roadway characteristics and traffic conditions.

The HERS speed model first examines the three controlling factors for free-flow speed on a roadway segment; they are curvature, pavement condition, and the speed limit. Then the free-flow speed is obtained through combining their impact. For the roadways with heavy vehicles traveling on the uphill direction, free-flow speed is then adjusted to account for the speed reduction for these vehicles.

The next step is to estimate the delay caused by congestion and traffic control devices. Roadways are categorized into four groups; they are (1) multi-lane highway which includes freeway and other multilane highway on which traffic control devices are not present; (2) signal controlled facilities; (3) stop sign controlled facilities; and (4) rural two-lane highways. The HERS speed model contains various procedures for estimating delays on each of these facilities. The parameters in the model were determined through extensive simulation.

The HERS model was applied to the 2002 HPMS extract provided by the KYTC. The estimated speeds were then compared with two independent sets of speed data collected in the field. One set of speed data was collected during a 1997 study conducted by the Kentucky Transportation Center to evaluate the impact of speed limit on highway crash rate. Statistical comparison between the estimated and measured speeds showed that the estimated speeds are within close proximity to the measured speeds

The other set of speed data used to validate the HERS speed model was collected during the summer of 2004 from Christian County, Kentucky. Christian County was recently designated by EPA as non-attainment for the 8-hour ozone standard. Speed data together with some parameters required by HERS that are not available from the HPMS extract (e.g., speed limit, shoulder width, lane width for county roads and city streets) were collected during the field trip made by KYTC personnel. Analysis showed that the HERS speed model is capable of generating a statistically accurate estimate of speed for the set of roadways on which speed data were collected.

The HERS software package calculates speed as an intermediate variable as required by the ultimate economic analysis. It does not export the speeds at the level required by air quality analysis. Therefore, the HERS speed model was programmed exclusively in this study to create a tool on the MS Excel platform.

The success of the HERS speed model relies heavily on the accuracy of input data. During the study process, several problems with respect to the data quality were noticed. For example, the

curvature and grade information may be missing for certain roadways. Data quality screening should be conducted prior to the application of the algorithm.

The HERS speed model was applied to the Kentucky statewide highway inventory data in HPMS format. Average speeds were then grouped by county and by functional class, as shown in the table on the next page. Although Kentucky is largely a rural state, it has three major metropolitan areas (Louisville, Northern Kentucky, and Lexington) with typical urban traffic pattern. On the other hand, the eastern Kentucky area is mostly mountainous with high presence of coal trucks on the highways. Therefore, the statewide speed distribution was obtained for three types of areas: urban, mountainous, and other rural areas. We believe this grouping method preserves the characteristics of each area while ensuring relatively larger sample size to smooth out the impact of stochastic variation. Also shown in the table are the statewide average speeds obtained through the HMPS AP package in 1998 and those estimated by Rich Margiotta of Cambridge Systematics using the 2000 HPMS data.

STATEWIDE AVERAGE SPEEDS

HPMS Functional Class			1998 statewide HPMS average	HERS (RM) average speeds 2000 HPMS data	HERS daily speed model average speeds 2002 HPMS data Statewide-All Roads	HERS daily speed model average speeds 2002 HPMS data SW-Urbanized	HERS daily speed model average speeds 2002 HPMS data SW-Mountainous	HERS daily speed model average speeds 2002 HPMS data SW-Other	Bell County Measured Speed Mountainous	Bell County Measured Speed Rolling
01	Rural	Interstate	50.4	71.0	69.2	70.0	68.5	69.2	NA	NA
02	Rural	Principle Arterial	47.4	51.6	55.4	59.1	52.4	56.6	NA	NA
06	Rural	Minor Arterial	34.9	42.3	45.2	47.0	39.7	46.5	NA	NA
07	Rural	Major Collector	31.5	46.1	44.3	46.8	38.9	46.2	37.3	36.0
08	Rural	Minor Collector	31.5	NA	NA	NA	NA	NA	33.0	32.5
09	Rural	Local	31.5	NA	NA	NA	NA	NA	29.8	30.9
11	Urban	Interstate	49.0	62.9	60.1	58.6	71.6	70.6	NA	NA
12	Urban	Freeway	50.5	58.8	62.6	61.0	NA	65.4	NA	NA
14	Urban	Principle Arterial	28.0	38.9	25.4	21.1	36.2	30.5	NA	NA
16	Urban	Minor Arterial	20.6	37.1	23.1	20.3	26.3	27.9	NA	NA
17	Urban	Collector	21.1	37.0	31.0	29.4	32.2	33.1	NA	NA
19	Urban	Local	21.1	NA	NA	NA	NA	NA	NA	NA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 BACKGROUND

The increasing vehicle miles traveled has resulted in a much degraded air quality in recent decades. The Clean Air Act requires transportation planners to monitor and assess the performance of transportation system regularly; while the enactment of the Clean Air Act Amendments of 1990 signified the importance of combining travel demand and air pollutant emission forecasting.

The commonly used air quality analysis model MOBILE6 provides estimates of current and future emissions from highway motor vehicles. It has been employed by most states in compliance with the requirement of the Environmental Protection Agency. MOBILE 6 is an emission factor model which requires as input information such as vehicle classification and age distribution, and average operating speed. The outputs of the model include emission factors for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) , carbon dioxide (CO2), particulate matter (PM), and toxics from cars, trucks, and motorcycles under various conditions (Cook and Glover, 2002). Even though MOBILE 6 has national default values for each category, area-specific inputs on a variety of parameters such as annual mileage accumulation by vehicle class, average speed distribution by hour and roadway type, distribution of vehicle miles traveled by roadway type, distribution of vehicle miles traveled by vehicle class, and so on, give more accurate results.

Among these parameters required by the model, average speed is the most significant one since the emission rates are highly sensitive to its change. Furthermore, the emission rates of the three major pollutants, CO and NOx are also very sensitive to vehicle miles traveled by time of day and average speed (Tang et al, 2003). Therefore, an accurate estimate of average operating speed is called for.

Various methodologies can be applied to speed estimation. For a comprehensive review of such methods, NCHRP report 387 (Dowling et al 1997) would be a good resource. Here, we briefly discuss several commonly used methods.

The standard BPR equation used in most travel demand models was developed in 1960s. Even though it does not accurately reflect existing relationship between volume and speed, it has been widely used as a simple tool to predict mean speed, as shown in the following equation.

$$S = \frac{S_f}{1 + a(v/c)^b}$$

Where
S = predicted mean speed
S_f = free-flow speed
v = volume
c = practical capacity

$a = 0.15$
$b = 4$

The free-flow speed, capacity, and volume can be determined by creating various look-up tables based on area type and facility type. The uniform parameter values for a and b do not distinguish facilities in different types. This method could result in an estimation error of approximately 40 percent (Dowling et al, 1997).

Several improvements have been made to enhance the accuracy of the standard BPR equation. Separate curves were fitted for urban interrupted facilities. Facility averages were replaced by data on critical segment of facility. Based on an updated speed-flow relationship, the value of a was set as 0.05 for signalized facilities and 0.20 for all other facilities; while the value of b was set as 10. Furthermore, free-flow speed was estimated using an equation instead of the look-up table.

Although the enhanced BPR technique has made a significant improvement in accuracy of speed estimation over the standard BPR technique, it is still not suitable for facilities with interrupted flows. Generally, BPR-type equations are not capable of addressing the spill-back of physical queues formed at such facilities. Therefore, it was recommended that the BPR equation usage should be limited to long range planning applications which usually do not require high precision (Dowling et al, 1997).

The ARTPLAN technique is a planning procedure developed by Florida DOT which is powerful in dealing with urban facilities controlled by signals. Subsequently, the model was expanded to cover urban street with stop sign control and conditions in which demand exceeds capacity. A similar procedure for rural facilities with interrupted flows was also created.

Even though the ARTPLAN technique outperforms the enhanced BPR technique for mean speed estimation, it is still produces large errors. For example, it was observed that for urban arterials the prediction error could be between 25 percent and 33 percent of the true mean speed (Dowling et al, 1997).

In Kentucky, travel demand models are the primary tool for obtaining average speed estimates. The enhanced BPR function is used in most models currently being developed (Bostrom and Mayes, 2003). The Kentucky Travel Demand Model (TDM) Forecast process does not presently include procedures for calibrating to speed. Furthermore, Kentucky currently has no reliable procedure for estimating speeds in areas without a TDM.

The objective of this research is to develop a procedure to estimate average speed on different roadway types. The performance of such procedure will be evaluated by comparing the estimated speeds with speed data collected in the field.

CHAPTER 2 RESEARCH APPROACH

Based on the requirements of the air quality analysis and available data, a procedure was developed based on the speed model within the Highway Economic Requirement System (HERS).

The HERS is a cost and benefit analysis tool which uses engineering standards and economic criteria to provide decision support on future infrastructure investment level. HERS consists of a number of internal models which generate intermediate parameters for the cost and benefit analysis. One of them is the HERS speed model which calculates average effective speed (AES) for each segment of a roadway. This information would subsequently be used to calculate the costs of travel time, the external costs, and the total vehicle operating costs.

The HERS speed model (FHWA, 2003) requires many data items on the facility and traffic. Such information includes roadway geometric parameters, pavement condition, speed limit, traffic control devices, and traffic composition. Since HERS was designed to run based on the format of the HPMS (Highway Performance Measurement System) data, most data items required are readily available.

However, the HERS software package does not output speed estimates for each roadway segment since they are only intermediate results. In this study, the HERS speed model was adapted to the data set in Kentucky and was coded as a standalone program to calculate average speeds by segment and then aggregate them by county and functional classes.

In the HERS speed model, free-flow speed (FFS) is controlled by geometric condition, pavement condition, and posted speed limit. AES is the speed based upon FFS and the delays due to congestion or traffic control devices (stop signs and signals). The model first calculates FFS (and adjusts FFS if a positive grade is present), and then estimates the delay due to congestion or traffic control devices. Finally, the average effective speed is obtained from the free-flow speed and the delay. Figure 2-1 shows the general procedure to estimate AES.

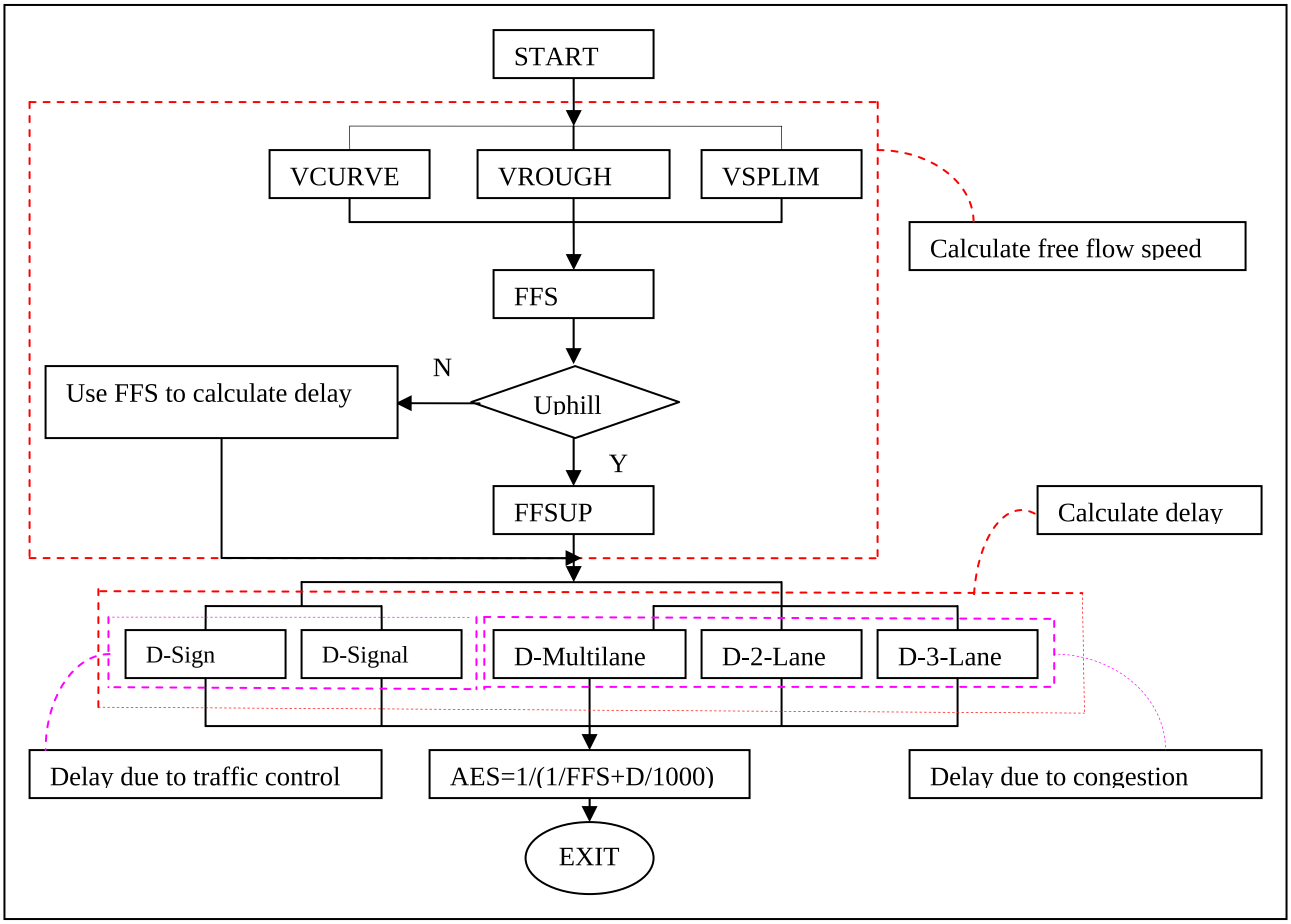

Figure 2-1 General framework of the HERS speed model

The general concept of HERS speed model is briefly explained below. The source of this documentation is the HERS Technical Report (FHWA, 2003).

2.1 Free-Flow Speed

The HERS speed model starts with calculating the free-flow speed. FFS is determined using three parameters, the maximum allowable speed on a curve (VCURVE), the maximum allowable ride-severity speed (VROUGH), and the maximum speed resulting from speed limit (VSPLIM).

$$FFS = ((1/VCURVE)^{10} + (1/VROUGH)^{10} + (1/VSPLIM)^{10})^{-0.1}$$

VCURVE represents the effect of curves on vehicle speed. It is related to the maximum perceived friction ratio, superelevation, and degrees of curvature. Friction ratio values are set in accordance with vehicle types. If a section has no curves, the VCURVE does not influence the FFS. Overall effect of curves in a section is the weighed average effect on different vehicle classes. The equation in miles per hour is:

$$VCURVE = 292.5 \times \sqrt{(FRATIO + SP)/(DC)}$$

Where

FRATIO = maximum perceived friction ratio
0.103 for combination trucks;
0.155 for automobiles; and
0.155 for single-unit trucks

DC = degrees of curvature

SP = superelvation
0 if DC<=1;
0.1 if DC>=10; and
$0.0318 + 0.0972 \times \ln(\mathrm{DC}) - 0.0317 \times \mathrm{DC} + 0.007 \times \mathrm{DC} \times \ln(\mathrm{DC})$, otherwise

VROUGH represents the effect of pavement roughness on speed. HERS speed model uses pavement serviceability rating (PSR) to measure pavement roughness. VROUGH's value is determined by the following formulas:

$$VROUGH = 5 + 15 \times PSR \qquad \text{if PSR<=1.0}$$

$$VROUGH = 20 + 32.5 \times (PSR - 1.0) \qquad \text{if PSR>1.0}$$

The effect of speed limits on vehicle speeds is represented by VSPLIM. The operational speed is assumed to be 9.323mph greater than the posted speed limit for urban freeways and rural multilane roads with partial or full access control and a median which is either a positive barrier or has a width of at least 4 feet. For all other roads, it is assumed to be 6.215mph greater than the posted speed limit.

2.2 Free-Flow Speed Uphill

For those segments with positive grade, the free-flow speed should be adjusted to account for the impact of grade. The delay due to grade, DGRADE, is determined based on vehicle characteristics and the average grade of a section. The HERS speed model first estimates the crawl speed for a section and then calculates the delay due to grade for each vehicle type. The overall delay due to grade is then weighed by vehicle classes. The relevant equations are:

$$DGRADE = a*(1 - \exp(b/a)) + b \qquad \text{if CRAWLS<FFS}$$

$$DGRADE = 0 \qquad \text{otherwise}$$

where

a = $-0.05*(1/CRAWLS - 1/FFS)^2$

b = SLEN*(1/CRAWLS-1/FFS)

CRAWLS = 1 / (j+k*GRADE)

j, k = constants based on vehicle types, as shown in Table 2-1

GRADE = the average grade of the section

Table 2-1 Crawl speed constants by vehicle type

Vehicle Type	j	k
6-Tire Truck	0.0090	0.0815
3-4 Axle Truck	0.0090	0.2755
4 Axle Combination	0.0090	0.2755
5 Axle Combination	0.0090	0.2755

FFSUP represents the free-flow speed on an uphill section. Assuming that downhill does not influence FFS of any vehicle class, and uphill only affects the speeds of those vehicle types listed in Table 2-1, HERS speed model uses the following equation to calculate FFSUP.

$$FFSUP = 1/(1/FFS + DGRADE/SLEN))$$

Where

DGRADE = delay in hours

SLEN = length of the section

This FFSUP value shall replace FFS on those segments with positive grade and truck volumes in the future effort of estimating average speed.

After obtaining the free-flow speed, the next task is to estimate delay experienced on each roadway segment. The HERS speed model classifies the causes of delay into two categories: one is congestion caused by the presence of other vehicles; the other is the presence of traffic control devices. The model uses either congestion delay or traffic control device delay, but not both. For instance, the delay due to congestion is considered only when the section does not have traffic control devices.

2.3 Delay Due To Congestion

The delay due to congestion is related to numbers of lanes, type of facilities, and the ratio of annual average daily traffic to its peak capacity. When a section is one-way one-lane or two-way two-lane, HERS speed model uses the following equations to calculate delay (D).

$$D = 0.432 \times ACR \qquad \text{if ACR<=10}$$

$$D = 9.953 - 1.66 \times ACR + 0.109 \times ACR^2 \qquad \text{if ACR>10}$$

Where

ACR = the AADT/Capacity ratio for the section

While calculating ACR, if the section is two-way urban road or multilane rural road, ACR equals to half of AADT/Capacity. This is because while AADT is a two-way figure, the peak capacity refers to the hourly capacity of the peak direction, as defined in the HPMS field manual (FHWA, 2000).

When a section is a multilane road (two or more lanes per direction) without any traffic signals or stop signs, the HERS speed model uses the following equations to calculate the delay.

$D = 0.0797 \times ACR + 0.00385 \times ACR^2$ if ACR <=8

$D = 12.1 - 2.95 \times ACR + 0.193 \times ACR^2$ if 8<ACR<=12

$D = 19.6 - 5.36 \times ACR + 0.342 \times ACR^2$ if ACR>12

For three-lane, two-way roads without traffic control devices, it is assumed that the total volume splits evenly between the two directions and the capacity splits 7:5 in favor of the two-lane direction. In this case, the AADT/Capacity ratios for the two directions should be calculated separately. Specifically, one needs to multiply the section's AADT/Capacity ratio by 0.875 as the ratio in the two-lane direction, and by 1.2 to calculate the ratio in the one-lane direction. HERS speed model then uses the equations for two-lane roads to calculate the delay in the single-lane direction, and uses the multilane equations in the two-lane direction. The total delay of a section is the weighed average of the two.

2.4 Delay Due To Stop Signs

For roads with traffic control devices, the delay depends on the number of signal and/or stop signs per mile and the AADT/Capacity ratio. If a section contains only stop signs, the equations listed in Table 2-2 are used to calculate the delay.

Table 2-2 Calculating delay due to stop signs

ACR Range	Stop Signs per mile	Equation
<=6		$D_{ss} = N_{sspm} \times (1.9 + 0.067 \times FFS + 0.103 \times ACR + 0.0145 \times ACR^2)$
>6 and <=15	<=10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS - 0.029 \times (ACR - 6)^2 + 0.354 \times (ACR - 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.064 \times (ACR - 6)^2$
>15	<=10	$D_{ss} = N_{sspm} \times (0.691 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2 - 23.49$

Where
Dss = delay due to stop signs in hours per 1000 vehicle miles
Nsspm = number of stop signs per mile
ACR = the AADT/Capacity ratio for the section
FFS = free-flow speed or free-flow speed uphill. Note that if the segment is uphill, FFS is replaced by FFSUP.

2.5 Delay Due To Signals

If a segment only has traffic signals, HERS speed model uses the following equations to calculate the delay.

$$D_{ts} = (1 - \exp(-N/24.4)) \times (68.7 + 17.7 \times ACR) \quad \text{if ACR<=7}$$

$$D_{ts} = (1 - \exp(-N/24.4)) \times (192.6 + 14.4 \times (ACR - 7) - 1.16 \times (ACR - 7)^2) + 0.16 \times (ACR - 7)^2 \quad \text{if 7<ACR<=13.2}$$

$$D_{ts} = 237.3 \times (1 - \exp(-N/24.4)) + 0.16 \times (ACR - 7)^2 \quad \text{if ACR>13.2}$$

Where
N = number of signals per mile

If a roadway segment has both stop signs and signals, a special procedure should be followed to calculate AES directly. First, consider all devices (both signals and stop signs) as stop signs, and use appropriate equation(s) in Table 2-2 to calculate delay. AES can then be calculated using the method introduced in the next section. Second, consider all devices as signals and use the corresponding equation(s) to obtain delay and then AES. The final average speed for the segment is then obtained by weighing the two average effective speeds by the percentage of each type of device.

2.6 Average Effective Speed

The HERS speed model uses the following equations to calculate average effective speed.

$$AES = 1/(1/FFS + D/1000) \quad \text{if no uphill}$$

$$AES = 1/(1/FFSUP + D/1000) \quad \text{if uphill}$$

Where
AES = Average Effective Speed
FFS = Free-flow Speed
FFSUP = Free-flow Speed Uphill
D = Average delay in hours per 1000 vehicles miles, with delay due to congestion and/or traffic control devices

Based on this model, an excel macro was programmed to calculate the AES for each roadway segment. Based upon the calculation results, the AES was then grouped by county and function class.

CHAPTER 3 HERS SPEED MODEL VALIDATION

3.1 Input Data

The HERS speed model was tested using the data extracted from the 2002 HPMS submission. This data set covers state-maintained roadways with a total of over 9000 segments which cover over 13,500 miles. Table 3-1 shows the summary of the input data to the HERS speed model.

Table 3-1 Input data summary

Functional Class	Numbers of Segments	Mileage
1	115	533
2	822	2052
6	979	1633
7	3138	6932
8	0	0
9	0	0
11	91	229
12	48	87
14	1270	661
16	2009	996
17	535	411
19	0	0
Total	9007	13534

3.2 Model Validation

In order to evaluate the performance of the speed estimation model, the estimates were compared to the field data collected through various efforts. There are two primary sources of speed data in Kentucky that can be used for the validation purpose. One is a study regarding the impact of speed limit change on highway safety, in which extensive speed data were collected on various roads in Kentucky (Agent et al, 1997). Another is a recent effort to collect speed data in Christian County, Kentucky.

3.2.1 Speed Limit Study

In the 1997 study, speed data were collected on 86 segments (routes) which cover all highway functional classes except for local roads and rural minor collectors. The data for the same set of highway segments were then extracted from the 2002 HPMS database and fed into the HERS model to provide speed estimates for each segment. Table 3-2 lists the set of roadways for which the comparison between measured and estimated speeds was made.

Table 3-2 Comparison between 1997 field measurements and average effective speed

Location/Route	Function Class*	Speed Limit (mph)	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
I-24	1,11	65	68.5	71.2	2.7	3.9
I-64	1,11	65	68.4	69.7	1.3	1.9
I-65-6lane	1,11	65	68.5	68.3	-0.2	-0.3
I-65-4lane	1,11	65	68.3	69.2	0.9	1.3
I-71	1,11	65	68.3	69.1	0.8	1.2
I-75-6lane	1,11	65	68.5	70.9	2.4	3.5
I-75-4lane	1,11	65	68.7	69.4	0.7	1
I-265	11	65	65.6	68.3	2.7	4.1
I-275	1,11	65	64.7	70.6	5.9	9.1
I-64 Jefferson	11	55	61.2	50.9	-10.3	-16.8
I-65 Jefferson	11	55	59.8	60.7	0.9	1.5
I-71 Jefferson	11	55	63.1	60.5	-2.6	-4.1
I-75 Boone Kenton	11	55	62.5	51.1	-11.4	-18.2
I-264-6lane	11	55	61	53.9	-7.1	-11.6
I-264-4lane	11	55	60.4	56.2	-4.2	-7
I-275 Kenton	11	55	61.6	60.7	-0.9	-1.5
I-471 Campbell	11,12	55	59.6	61.8	2.2	3.7
I-65 Jefferson	11	50	55.8	52.3	-3.5	-6.3
Audubon 9005	2,12	65	66.7	70.9	4.2	6.3
Bluegrass 9002	2,12	65	68.6	72.3	3.7	5.4
Cumberland 9008	2,12	65	67.6	70.9	3.3	4.9
Mountain 9000	2	65	68.3	64.4	-3.9	-5.7
Natcher 9007	2,12	65	68.9	66.8	-2.1	-3
Pennyrile 9004	2,12	65	67.9	69.8	1.9	2.8
Purchase 9003	2,7,12	65	67	71.7	4.7	7

[*] Different segments of a route may belong to different functional classes.

Location/Route	Function Class*	Speed Limit (mph)	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
W Kentucky 9001	2,12,14	65	69.2	71.3	2.1	3
Daniel Boone 9006	2,12,14	55	61	52.6	-8.4	-13.8
Mountain 9009	2	55	63.8	54.9	-8.9	-13.9
US23,South of Pikeville	2,14	55	57.6	57.7	0.1	0.2
US23,Pikeville-Prestonsburg	2,14	55	59.9	56.7	-3.2	-5.3
US23,Pres-Ashland	2,14	55	58.8	52.6	-6.2	-10.5
US23,Ash-South shore	2,14	55	56.9	48.9	-8	-14.1
US25e,Middlesboro-Corbin	2	55	58.9	55.4	-3.5	-5.9
US27,Nicholasville-Lexington	2,14	55	57.9	51.5	-6.4	-11.1
US31w,Elizabethtown-Louisville	2,7,14,16	55	57.7	54.1	-3.6	-6.2
US41a,Fort cam-Hopkinsville	2,14	55	59.4	55.4	-4	-6.7
US45,Mayfield-Paducah	2,14	55	60.2	59.6	-0.6	-1
US60, Frankfort-Versailles	2,14	55	58.9	57	-1.9	-3.2
US60,Versailles-Lexington	2,14,16	55	59.1	52.4	-6.7	-11.3
US60,Owendboro-Hawesvill	2,14	55	57.2	59.5	2.3	4
US60b,Owendboro	2	55	58.1	63	4.9	8.4
US127,Danville-Frankfort	2,14	55	59.5	53.3	-6.2	-10.4
US150,Dancille-Stanford	2	55	58.7	60.3	1.6	2.7
US641,Murray-Benton	2,14	55	59.7	59.4	-0.3	-0.5
KY4,Lexington	12,14	55	59.8	53.2	-6.6	-11
KY9,Campell	2	55	60.1	60.4	0.3	0.5
KY61,Hodgencille-Elizabeth	6,14	55	60.7	50.8	-9.9	-16.3
KY80,Somerset-London	2	55	59.6	45.1	-14.5	-24.3
KY80,Hazard-Prestonsburg	2	55	60.3	59.5	-0.8	-1.3
KY645, Inez-Ulysses	2	55	58.3	59	0.7	1.2
KY841,Louisville	12	55	62.4	63.4	1	1.6
US27,Paris-Alexandria	6,14	55	55.1	54.6	-0.5	-0.9
US60,Hawesville-Muldraugh	2,14	55	58.5	54.3	-4.2	-7.2
US60,Grayson- Ashland	7	55	54.7	54.9	0.2	0.4
US127, Russell -Danville	2	55	59.2	52.7	-6.5	-11
US150,Bardstown- Danville	2,6,14	55	59	54.3	-4.7	-8
US460, Salyersville- Paintsville	2,6	55	60	52.5	-7.5	-12.5
KY9,Alexandria- Maysville	2	55	60.1	55.7	-4.4	-7.3
KY9,Mayscille- Vanceburg	2	55	57.3	54.6	-2.7	-4.7
KY10, Vanceburg -Us23	2	55	57.6	55.4	-2.2	-3.8
KY15,Whitesburg-Campton	2,7,14	55	58.5	53.9	-4.6	-7.9

Location/Route	Function Class*	Speed Limit (mph)	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
KY34,Danville-Us27	2,7,16	55	58.9	56.7	-2.2	-3.7
KY55,Lebanon-Springfield	2,7,14	55	58.1	57.1	-1	-1.7
KY80,Somerset-London	2,7	55	60.2	53.1	-7.1	-11.8
KY114,Salyersville-Prestonsburg	2	55	60.2	56.8	-3.4	-5.6
KY461,Shopville-Mt.vemon	2	55	59.4	54.9	-4.5	-7.6
KY555,Springfield-Bluegrass pkwy	2	55	59.2	57	-2.2	-3.7
US25,Corbin-Lexinton	2,7,14,16	55	54.5	53.9	-0.6	-1.1
US27,Smerset-Nicholasville	2,14	55	57.5	55.5	-2	-3.5
US27,Paris-Alexandria	6,14	55	55.7	54.6	-1.1	-2
US31e,Scottsville-Glasgow	2,6,7,14,16	55	57.3	52.2	-5.1	-8.9
US51,Fulton-Wicklife	2	55	56.5	58.8	2.3	4.1
US60,Paducah-Owensboro	2,6,14,16	55	58.4	55	-3.4	-5.8
US60,Hawesville-Muldraugh	2,14	55	57	54.3	-2.7	-4.7
US60,Luisville-frank	6	55	56.6	56.2	-0.4	-0.7
US60,Lexington-Mt.sterling	7,16	55	55.4	55.6	0.2	0.4
US60,Morehead-Grayson	7,16	55	51	54.7	3.7	7.3
US62,Elizab-Bardstown	7,16	55	54.7	57.4	2.7	4.9
US150,Danville-Bardstown	2,6,14	55	57.6	54.3	-3.3	-5.7
US231,Scottsville-Bowling green	2,7,16	55	52.2	50.5	-1.7	-3.3
US421,Lexington-Frank	6,7,16	55	58.1	52.3	-5.8	-10
KY15,Campton-Winchester	2,7	55	50.8	55.5	4.7	9.3
KY11,Mount sterling-Flemingsburg	6,7	55	55	56.9	1.9	3.5
KY32,Morehead-Flemingsburg	6,7,17	55	56.3	54.2	-2.1	-3.7
KY80,London-Hazard	2,7	55	50.8	50	-0.8	-1.6
KY185,Bowling Green-Caneyville	7,16	55	54.4	57.9	3.5	6.4

It was observed that the difference between the estimated and measured speeds ranged from -0.2 to 5.9 mph for rural interstates which have a speed limit of 65 mph. For urban interstates and other arterials with a speed limit of 55 mph, such difference ranged from -11.4 mph to 2.2 mph.

A paired t-test was conducted to test the equality of underlying population means for the model output and measured samples, respectively. Prior to the test, preliminary analyses were conducted to ensure that the data do not violate the assumptions. First, the independence of paired differences should be satisfied since the speed data come from different roads. Second, the paired differences should be normally distributed. The normal probability plot for the paired differences was constructed as shown in Figure 3-1. After the close agreement with the straight line in the normal probability plot was observed, the Lilliefors test for goodness of fit to a normal distribution was conducted. Under the significance level $\alpha = 0.05$, the null hypothesis that the paired difference has a normal distribution was accepted.

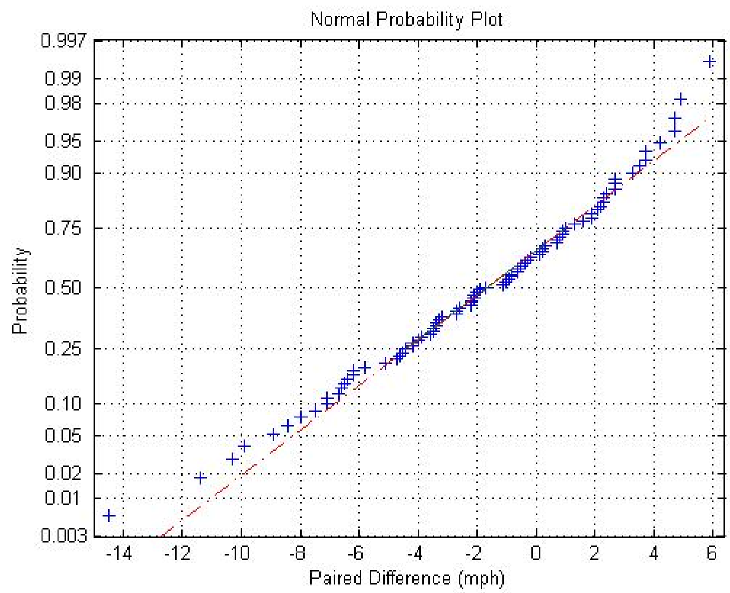

Figure 3-1 Normal probability plot for paired differences

After the assumptions were confirmed, the paired t-test was conducted for the whole data set shown in Table 3-2 to test the hypothesis that the measured speeds and the estimated speeds come from distributions with equal means. The t-statistic can be calculated as

$$t = \frac{\bar{x} - m}{s / \sqrt{n}}$$

where s is the standard deviation of paired differences and n is the number of observations in the sample set (i.e., the number of roadway segments from which speeds are collected and for which speeds are estimated). A generalized null hypothesis is that the mean of the paired differences $\bar{x}$ is equal to m.

Under the null hypothesis that $\bar{x} = m = 0$, the data set in Table 3-2 produced a p value of 5.6×10^{-5} which is much lower than the pre-specified significance level of $\alpha = 0.05$. This infers that we should reject the null hypothesis that the two sets of speeds are from populations with equal means.

However, through varying the m value, we observed that the difference in means between the measured and estimated speeds was less than 1.1 mph when $\alpha = 0.05$. The p value at this time is 0.08 and the calculated t statistic is 1.77 and is lower than the critical t statistic (1.99 in this case). The 95% confidence interval for the average difference between the measured and estimated speeds is (0.18, 3.59). Theses statistical analyses showed that the differences between estimated speeds and measured speeds on the same facility are relatively small.

To reduce the potential impact of speed limit on the sample means, we split the samples into two groups based on the speed limit. Under the significance level of 0.05, paired t-test results showed that the average estimated speed was approximately 1 mph higher for facilities with a speed limit of 65 mph, and 2 mph lower while speed limit is 55 mph, than that of the measured speeds. The 95% confidence intervals for the difference between the measured and estimated speeds are (-2.97, -0.69) and (1.74, 3.84) for a speed limit of 65 mph and 55 mph, respectively. In other words, the HERS model is likely to overestimate speed for rural interstates (with a speed limit of 65mph) and underestimate the speed on other roads. Nevertheless, in either case, the paired difference was not significant based on the boundary values of the confidence intervals.

We believe that the larger difference for roads with lower functional classes is primarily attributable to the model's sensitivity to various factors such as traffic signal density. Detailed discussion on this topic will be presented in section 4.3.2.

3.2.2 Christian County Speed Data

In 2004, Christian County in Kentucky was designated by EPA as non-attainment area. It became crucial to obtain accurate speed estimates for different types of roadways in this county in order to establish the future emission budget. Speed data were collected during a three-month period in the summer of 2004 on a number of roadways throughout the county. The effort covered approximately 50% of the total mileages and over 70% of state-maintained facilities in the county. The sample segments were selected based on the recommendation in the FHWA's Travel Time Collection Handbook (Turner et al, 1998). Each road was traveled on at least twice, once during the peak period and once during the off-peak conditions.

The HERS model was tested on the same highway segments in Christian County on which the speed survey was conducted. Table 3-3 shows the comparison between measured and estimated speeds for several sample roadways in the county. The complete comparison is shown in Appendix A. The differences between the two sets of speeds are mostly within 5 mph with few exceptions. However, the paired t-test could not be applied in this case because the data violated the assumption that the paired differences between the two sets of speeds should be normally distributed, as evidenced by Figure 3-2.

Therefore, nonparametric tests need to be used since they usually do not make distributional assumptions. The most commonly used alternatives for the paired t-test are the Wilcoxon paired signed rank test and the paired sign test. Wilcoxon paired signed rank test performs a paired, two-sided test of the hypothesis that the difference between the estimated and measured speeds comes from a distribution whose median is zero. The paired differences are assumed to come from a continuous distribution that is symmetric about its median. This assumption basically enables us to test the hypothesis about mean since when the distribution is symmetrical, the mean should coincide with the median. The paired sign test conducts the same test of hypothesis with a further relaxation of the requirement for symmetrical distribution of the paired difference. Therefore, it is not as sensitive to the Wilcoxon signed rank test.

Table 3-3 Sample speed comparison based on the 2004 Christian County survey

Route	Functional Class	Speed Limit (mph)†	Measured Speed (mph)	Estimated Speed (mph)
I24	1	65	71.8	72.0
EB9004	2	65	72.1	68.5
US41	6	25/35/45/55	51.1	53.1
KY91	7	55	58.5	58.0
KY164	7	45	47.8	51.2
KY1026	8	35	46.7	40.5
KY1027	8	40	42.7	38.4
CR1031	9	40	39.9	38.9
CR1053	9	45	47.5	44.8
I24	11	65	72.0	74.3
US41A	14	25/35/45/55	35.6	42.3
US68B	14	45	60.8	55.1
KY115	16	35/45	39.8	39.1
KY380	16	35	25.2	30.8
KY911	17	35	34.9	36.8
KY1007	17	45	27.3	32.2
KY400	19	35	37.9	32.4

In this study, we used the Wilcoxon paired signed rank test to compare the estimated and measured speeds. The test procedure starts with calculating the absolute paired differences. Those sample roadway segments with the same values for estimated and measured speeds are excluded from consideration. Rank the remaining absolute differences from smallest to largest. Assign each such rank a "+" sign when estimated speed is higher than the measured speed on a roadway and a "–" sign otherwise. Then compute W_+ and W_- as the sums of the positive and negative ranks respectively. The number of signed ranks, n_{sr}, is equal to the number of paired samples minus the number of pairs with same measured and estimated speeds. When n_{sr} is relatively large (e.g., greater than 30), the Wilcoxon test value $W = \min(W_+, W_-)$ approaches a

† Multiple speed limits may be observed for one route.

normal distribution with a mean of $\mu_W = n_{sr}(n_{sr} + 1)/4$ and a standard deviation of $\sigma_W = \sqrt{n_{sr}(n_{sr} + 1)(2n_{sr} + 1)/24}$. For a two-sided test under significance level of α, if $\mu_W - \sigma_W \Phi^{-1}(\alpha/2) < W < \mu_W + \sigma_W \Phi^{-1}(\alpha/2)$, in which Φ^{-1} is the normal distribution function, then reject the null hypothesis that the two sets of speeds have the same mean.

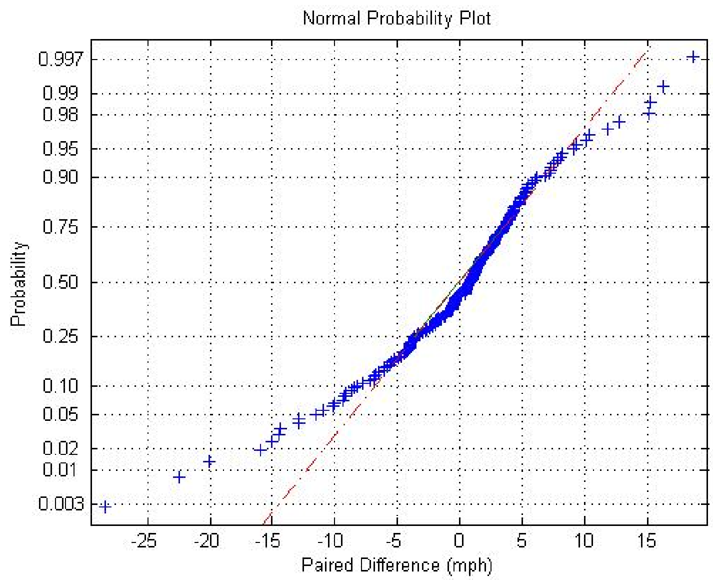

Figure 3-2 Normal probability plot for paired differences for Christian County

For all the samples collected in Christian County, no significant evidence was found from the Wilconxin paired signed rank test to reject the null hypothesis that the average speeds have the same mean.

Considering the speed variation among highway under various functional classes, the speed samples were grouped according to roadway functional class. Table 3-4 illustrates the speeds collected during field test and the speeds estimated by the model for the same set of roads in Christian County.

Table 3-4 Christian County speeds comparison

Functional Class	Sample Size	Mileage	Measured Speed (mph)	Estimated Speed (mph)
1	2	17.3	71.2	70.7
2	6	35.1	60.3	56.4
6	2	7.6	53.1	51.1
7	6	52.4	54.7	54.0
8	30	175.6	48.5	47.1
9	74	188.6	41.2	35.7
11	1	3.3	74.3	72.0

12	-	-	-	-
14	7	15.9	38.8	35.7
16	26	51.6	30.5	31.2
17	7	15.6	32.5	29.6
19	64	68.2	23.2	23.0

It should be noted that US68 and EB9004 (Breahitt Parkway) were excluded from the data set in calculating the measured speeds and estimating speeds for roads driven because the data collected was considered flawed. However, they were included in the calculation for speeds based on information from all roads from which data are available. For comparison purpose, the countywide estimated speeds by functional class are also shown in Table 3-4.

The Wilcoxon paired signed rank tests were conducted for those functional classes with at least ten samples. None of them found enough evidence to prove there is a difference between the measured speeds and estimated speed under the 0.05 significance level. However, because the sample sizes in many functional classes are relatively small, it is difficult to find this inference convincing. In the absence of large amount of data collected in the field, it would be premature to draw statistically valid conclusions concerning the model performance within each functional class. Nevertheless, the overall performance of the HERS model based on the Christian County data set is encouraging.

CHAPTER 4 IMPLEMENTATION ISSUE

4.1 Software Tool

An Excel-based software tool was developed to implement the HERS speed model on highway data stored in HPMS format. The program is embedded in an MS Excel worksheet. It is included in a CD ROM as Appendix B. The tool calculates the average effective speed for each segment and then aggregates them to county level for each functional class. The instructions for running the software tool are included in the Appendix B.

The application of the software tool is not limited in Kentucky. Because of the standard format of the HPMS data file, the tool can be applied in any states.

4.2 Data Requirement

The majority of the data items required by the HERS speed model are available from the HPMS data file. Additional data items such as truck percentage breakdowns by truck type will need to be prepared in advance. Specifically, the heavy vehicles are classified into four different groups, as described in Chapter 2. The truck percentage for each category needs to be estimated. In this study, the statewide average truck percentage by functional class and truck type (KYTC, 2002) was used as the data source. The four truck types required by HERS are grouped based on the FHWA vehicle classifications, as indicated in Table 4-1. The last column of the table indicates the statewide average truck percentage by functional class. The "%" column for each HERS truck type represents the percentage of trucks of this type in all trucks. Such percentages were then used to generate the actual percentage of trucks in all vehicle population using the data from the HPMS file.

Table 4-1 Truck percentage conversion for the HERS model

HERS Truck Type		6-Tire Truck				3-4 Axle Truck				4-Axle Combination Truck		5-Axle Combination Truck							TOTAL (%)
FHWA Truck Type		Bus (4)	2-Axle Single Unit (5)	Sub-total	%	3-Axle Single Unit (6)	4-Axle Single Unit (7)	Sub-total	%	4 or Less Axle Truck & Trailer (8)	%	5-Axle Truck & Trailer (9)	6+Axle Truck & Trailer (10)	5 or Less Axle Truck & Multi-Trailer (11)	6-Axle Multi Trailer (12)	7+Axle Multi Trailer (13)	Sub-total	%	
Functional Class	1	0.30	3.40	3.70	13.12	0.70	0.10	0.80	2.84	1.00	3.54	21.30	0.30	1.00	0.10	0.01	22.71	80.50	28.21
	2	0.40	3.10	3.50	25.89	1.30	0.30	1.60	11.83	1.20	8.88	5.70	1.40	0.10	0.01	0.01	7.22	53.40	13.52
	6	0.50	2.60	3.10	37.61	1.30	0.30	1.60	19.41	1.00	12.13	2.20	0.30	0.03	0.01	0.01	2.54	30.85	8.24
	7	0.60	2.60	3.20	40.12	1.30	0.20	1.50	18.80	0.80	10.03	2.00	0.40	0.06	0.01	0.01	2.48	31.05	7.98
	8	0.80	2.70	3.50	36.15	1.30	0.10	1.40	14.46	0.70	7.23	3.60	0.40	0.07	0.01	0.00	4.08	42.15	9.68
	9	0.90	5.00	5.90	32.35	3.50	1.70	5.20	28.51	1.30	7.13	3.90	0.80	0.20	0.04	0.90	5.84	32.02	18.24
	11	0.20	2.70	2.90	20.41	0.70	0.20	0.90	6.33	0.50	3.52	9.30	0.10	0.40	0.10	0.01	9.91	69.73	14.21
	12	0.30	2.40	2.70	31.32	0.90	0.20	1.10	12.76	0.60	6.96	4.00	0.10	0.10	0.01	0.01	4.22	48.96	8.62
	14	0.40	2.20	2.60	43.72	0.70	0.20	0.90	15.13	0.40	6.73	1.80	0.20	0.04	0.01	0.00	2.05	34.42	5.95
	16	0.40	2.10	2.50	46.21	0.70	0.40	1.10	20.33	0.50	9.24	1.10	0.10	0.03	0.04	0.04	1.31	24.21	5.41
	17	0.90	2.90	3.80	48.41	1.00	0.10	1.10	14.01	0.80	10.19	1.90	0.10	0.10	0.03	0.02	2.15	27.39	7.85
	19	0.90	5.00	5.90	32.35	3.50	1.70	5.20	28.51	1.30	7.13	3.90	0.80	0.20	0.04	0.90	5.84	32.02	18.24

The data items required by the speed model are listed in Table 4-2. The data file used in this study is also included in the CD ROM.

Table 4-2 Data items required

HPMS Item No.	HPMS Item	Field Name in the Input File	Date Type	Comments
1	Year of data	Year_Record	Numeric; integer	
4	County code	County_Code	Numeric; codes	
5	Section identification	Section_ID	Character field	
13	Rural/urban designation	Rural_Urban	Numeric; codes	
17	Functional system code	F_System	Numeric; codes	
27	Type of facility	Type_Facility	Numeric; codes	
30	Section length	Section_Length	Numeric; decimal	
33	AADT	AADT	Numeric; integer	
34	Number of through lanes	Through_Lanes	Numeric; integer	
35	Measured pavement roughness	IRI	Numeric; decimal	
50	Pavement type	Pavement_Type	Numeric; codes	
55	Median type	Median_Type	Numeric; codes	
55	Access control	Access_Control	Numeric; codes	
56	Median width	Median_Width	Numeric; decimal	
63	Length class A curves	Curves_A	Numeric; decimal	
64	Length class B curves	Curves_B	Numeric; decimal	
65	Length class C curves	Curves_C	Numeric; decimal	
66	Length class D curves	Curves_D	Numeric; decimal	
67	Length class E curves	Curves_E	Numeric; decimal	
68	Length class F curves	Curves_F	Numeric; decimal	
72	Length class A grades	Grades_A	Numeric; decimal	
73	Length class B grades	Grades_B	Numeric; decimal	
74	Length class C grades	Grades_C	Numeric; decimal	

for roads in lower functional classes. The 2002 HPMS extract used in this study does not contain any roads within the categories of rural minor collector (FC8), rural local (FC9), and urban local (FC19). Intensive effort might be necessary to populate those empty fields in the data file. For example, in order to evaluate the performance of HERS model on lower functional class roadways, we constructed a sample file in HPMS format for those roads test-driven by KYTC during the data collection effort in summer 2004. Based on the field observation, required data items such as curve length, grade length, number of lanes, present serviceability rating (of pavement), density of traffic control devices, speed limit, AADT, and peak capacity were estimated to populate the fields in the data table. Table 4-3 lists those data items that were estimated for Christian County based on field observations.

Table 4-3 Data items estimated for Christian County

Item	Solution
AADT	Estimated based on the field observation as well as the combined consideration of congestion level and capacity
PSR	Estimated according to the HPMS Field Manual based on field observation
Curve Lengths	According to the terrain type definition in HPMS, add the section length to “Curve A” column if terrain type is 0 or 1; “Curve C” if terrain type is 2; “Curve E” if terrain type is 3
Grade Lengths	According to the terrain type definition in HPMS, add the section length to “Grade A” column if terrain type is 0 or 1; “Grade C” if terrain type is 2; “Grade E” if terrain type is 3
Speed limit	Use the field observation when posted speed limit is no higher than the design speed; otherwise, use the lower on between the two
Peak Capacity	Calculated based on the HPMS Field Manual, Appendix N, for those roadways with basic highway inventory data; Estimated based on the Statewide Traffic Model Calibration Report (1997).
Density of Stop Signs	Estimated from the field observation
Density of Signals	Estimated from the field observation
Truck Percentages	Estimated based on the 2003 Traffic Forecasting Report as 6.9% for city streets (FC19) and 8.6% for county roads (FC9)

4.3.2 Accuracy

The accuracy of input data directly affects the quality of the model output. Quality assurance procedures will be necessary prior to the application of the HERS model. During the model testing process, it was noticed by the research team that several problems were often present in the 2002 HPMS extract.

The HERS model requires information about the length of sections of a roadway that fall under different curvature and grade levels. The curvature information is required to calculate the free-flow speed, while the grade information is necessary to adjust the free-flow speeds for heavy vehicles traveling at the uphill direction. In theory, these section lengths should add up to the total length of the roadway segment. However, the total section length is often much shorter than the segment length. Further examination of the data revealed the fact that for many roadways especially those in lower functional classes, such detailed curve and grade information are just not available. However, there is no special coding for such situations other than a "0" in the table. This could easily be mistaken as the roadway being straight or level.

Special attention should be paid to data items such as the density of traffic control devices that tend to have significant impact on the delay estimates. During the model validation process, significant differences between the measured and estimated speeds were observed on several roads. Table 4-4 lists several roads in Christian County with "Initial AES" estimates significantly different from the observed speeds at the same sites. Further investigation revealed that there are some differences in the density of traffic control devices, speed limit, and lane width between the 2002 HPMS data and information collected in the field. After these changes were accounted for in the input file, the HERS model produced an updated output which is also shown in Table 4-4. One can observe significant improvement of estimation accuracy on many of these roads.

Table 4-4 Speed comparison with changes in traffic control devices

Route	Function Class	Measured Speed (mph)	Initial AES (mph)	Updated AES (mph)	Change
US 41A	2	43.7	60.4	41.3	12 Signals added
US 68	2	47.9	59.9	46.1	9 Signals added, lower speed limits (up to 30mph reduction)
KY 107	7	47.4	52.3	52.4	2 Stop signs added
KY 109	7	46.2	59.6	55.6	11 Signals added
KY 164	7	51.2	56.5	48.2	Lower speed limit (up to 10mph reduction)
KY 380	16	32.0	23.2	25.2	1 Signal removed
US 41	16	31.6	39.5	35.2	1 Signal added, lane width reduced
KY 911	17	36.8	30.0	34.9	1 Signal removed
KY 1007	17	32.0	27.9	32.0	Speed limit increased (up to 10mph)

The HERS model is also quite sensitive to speed limit, which is one of the three parameters used to calculate the free-flow speed. However, there are many rural highways in the mountainous areas of eastern Kentucky that have a speed limit of 55 mph with a much lower design speed (e.g., 40 mph). This implies that the posted speed limits may not always be a binding constraint for driving speed. Direct application of the speed limit figures in the HPMS data would cause the estimated free-flow speeds and average speeds to be unrealistically high in the mountainous areas. Therefore, it is recommended that the effective speed limit should be used in this case. Therefore, the lower value between the posted speed limit and the design speed was chosen as the effective speed limit.

The accuracy of many other data items such as capacity, AADT, and truck percentage could also affect the model output. However, because of the extremely limited data availability, a complete sensitivity analysis based on field data would not be possible. Instead, a small scale sensitivity analysis was conducted based on the theoretical relationships between the average speed and some of the input variables as defined by the equations in the HERS speed model. The variables selected are speed limit, truck percentage, AADT-to-capacity ratio, curvature, grade, signal density, and stop sign density.

The functional relationship between the average speed and each input can be obtained through substituting all intermediate variables defined in the HERS model. For example, the average speed can be expressed as a function of the free-flow speed (FFS) and other variables. The FFS is a function of VSPLIM, which in turn is a function of the speed limit. Therefore, one can substitute the intermediate variables VSPLIM and FFS with their equivalent functional expressions in the equation that estimates average speed.

The sensitivity of the model output (i.e., average speed) with respect to an individual input (e.g., speed limit, signal density) can be estimated by calculating the partial derivative of the output with respect to the input when the input takes its current value. For each input variable of interests as mentioned above, the sensitivity measure was estimated for each segment of the roadway in the database. Table 4-5 shows the average sensitivity values (by functional class) for these variables. The numerical values in the table can be interpreted as the change in average speed resulted from the change of input variable in one unit. The units are "number per mile" for signal and stop sign densities, "mph" for speed limit, "%" for truck percentage and grade, "degree" for curvature, and none for ACR. For example, average speed is expected to drop about 1.76mph if signal density increases by 1 per mile on an urban arterial (FC14). A one degree increase of curvature will likely to cause a decrease of 1.02mph in average speed on a rural freeway (FC1).

One can observe that among the selected variables, the signal density has a more significant impact on average speed for higher functional class roads (e.g., FC2, FC14), while the density of stop signs is more significant for roads with lower functional classes (e.g., FC7, FC 17). The speed limit and the ACR (AADT to peak-capacity ratio) have comparable impact (in extent) on the average speeds on all functional classes. However, the influence of ACR tends to be slightly stronger for roads with lower functional classes (e.g., FCs 6, 7, 14, 16, 17). The roadway geometry (curve and grade) only tends to be significant for roads in higher functional classes.

It can also be observed from Table 4-5 that the percentage of trucks is not very significant compared to other variables such as signal density. The impact is only noticeable on the roads in higher functional classes. However, one should note that this only means that the average speed is not very sensitive to the change in truck percentage at it current level. Since the truck percentages were estimated based on the statewide average, additional scrutiny may be necessary for those coal truck routes in the mountainous area. Area-specific or even facility-specific data may be needed in order to ensure a more accurate sensitivity analysis.

Table 4-5 Average sensitivity values as defined by HERS speed model

FC	Signals per Mile	Stop Signs per Mile	Speed Limit	Average Curvature	Average Grade	Truck Percentage	ACR
1	N/A	N/A	0.68	-1.02	-0.95	-0.01	-0.58
2	-1.37	-0.42	0.76	-0.31	-0.08	0.00	-0.84
6	-0.31	-0.50	0.72	-0.27	-0.01	0.00	-0.96
7	-0.23	-1.24	0.75	-0.26	-0.01	0.00	-0.97
8							
9							
11	N/A	N/A	0.75	-0.72	-0.26	-0.01	-0.77
12	-0.19	N/A	0.79	-0.56	-0.13	-0.01	-0.47
14	-1.76	-0.03	0.52	-0.07	0.00	0.00	-0.81
16	-0.93	-0.29	0.64	-0.04	0.00	0.00	-0.75
17	-0.66	-1.34	0.64	-0.03	0.00	0.00	-0.78
19							

Some of the problems encountered by the research team with respect to the data quality are listed in Table 4-6. Countermeasures were taken to "correct" the errors, as indicated in the table. However, one should note that this is only a temporary improvement of the data consistency. A continuous effort to guarantee the accuracy of highway inventory data is necessary.

Table 4-6 Data quality problems and countermeasures

Data Item	Problem	Countermeasure
Curve Length	Total curve length less than the segment length	According to the terrain type definition in HPMS, add the difference in length to "Curve A" column if terrain type is 0 or 1; "Curve C" if terrain type is 2; "Curve E" if terrain type is 3
Grade Length	Total grade length less than the segment length	According to the terrain type definition in HPMS, add the difference in length to "Grade A" column if terrain type is 0 or 1; "Grade C" if terrain type is 2; "Grade E" if terrain type is 3
Speed limit	Higher than design speed	Use lower between the posted speed limit and the design speed

CHAPTER 5 STATEWIDE AVERAGE SPEEDS

The HERS speed model was applied to the Kentucky statewide highway inventory data in HPMS format. Average speeds were then grouped by county and by functional class, as shown in Table 5-1.

Table 5-1 Average speeds by county and by functional class

County	Average Effective Speed (mph)											
	1	2	6	7	8	9	11	12	14	16	17	19
Adair		47	36	48								
Allen		50	55	41								
Anderson		64	46	55					39	25	37	
Ballard		37	35	41								
Barren	70	73	49	48				73	20	32		
Bath	69		40	40								
Bell		53		50					35	26	31	
Boone	70			45			65			28	26	
Bourbon		45	49	51					38	28		
Boyd	70	56		47					30	25	36	
Boyle		55	49	47					35	33	34	
Bracken		56		41								
Breathitt		46		41								
Breckinridge		50	45	45								
Bullitt	64	48	48	42			69		36	23	45	
Butler		73		53								
Caldwell	69	72	49	59					70	35	25	
Calloway		50	56	44					30	28	34	
Campbell		60	52	50			64	59	26	27	22	
Carlisle		34	59	42								
Carroll	70			42								
Carter	70	46	36	40								
Casey		48		44								
Christian	71	63	51	56			72	73	36	31	26	
Clark	71	67	59	56			71		36	27	27	
Clay		53	30	46								
Clinton		37	57	44								
Crittenden			37	42								

County	Average Effective Speed (mph)											
	1	2	6	7	8	9	11	12	14	16	17	19
Cumberland			44	48								
Daviess		62	56	50				64	26	36	38	
Edmonson	71		43	56								
Elliott			48	42								
Estill				44								
Fayette							71	58	23	40	49	
Fleming		57	51	36								
Floyd		55	41	40								
Franklin	69	46	53	52					29	24	26	
Fulton		61	43	41								
Gallatin	68		37	44								
Garrard		49	47	47								
Grant	69			35								
Graves		63	52	43				73	32	30		
Grayson		70	28	46								
Green			43	55								
Greenup		51		46					39	11	29	
Hancock		48		49								
Hardin	70	63	59	48			72	72	33	35	31	
Harlan		54	30	41								
Harrison			53	48					24	28	27	
Hart	69			42								
Henderson		62	55	53				56	32	37	36	
Henry	69		38	41								
Hickman		54	49	48								
Hopkins		69	50	49				69	38	25	38	
Jackson			40	44								
Jefferson	68	58	44	56			58	68	20	22	38	
Jessamine		53	52	40					39	25	33	
Johnson		58	56	41								
Kenton	71			49			50		18	9	26	
Knott		57		39								
Knox		54		39					29	30	30	
Larue	69		44	50								
Laurel	69	54	38	28			72		27	23	32	
Lawrence		59		35								
Lee			45	36								

County	Average Effective Speed (mph)											
	1	**2**	**6**	**7**	**8**	**9**	**11**	**12**	**14**	**16**	**17**	**19**
Leslie		53	43	47								
Letcher		52		42								
Lewis		54		43								
Lincoln		50	45	43								
Livingston	71		40	46								
Logan		55	49	55					36	30	34	
Lyon	71	73	55	57								
McCracken	72	59		48			71		31	35	36	
McCreary		51	51	45								
McLean			52	48								
Madison	71	52	48	55			71		29	30		
Magoffin		54	35	40								
Marion		57		47					31	28	34	
Marshall	72	55	56	47								
Martin		35	57	40								
Mason		56	53	43					38	34	35	
Meade		54	48	43					46			
Menifee			43	43								
Mercer		58	53	45					31	30		
Metcalfe		73	52	49								
Monroe				44								
Montgomery	71		49	54					33	32	32	
Morgan		57	50	45								
Muhlenberg		69	46	45								
Nelson		72	51	49				72	28	36	35	
Nicholas		55		38								
Ohio		70		47								
Oldham	68		35	43						26	40	
Owen			42	40								
Owsley			55	46								
Pendleton		55	43	44								
Perry		55		38					42	28	24	
Pike		44		42					48	31	35	
Powell		73	39	38								
Pulaski		55	48	45				44	28	25	27	
Robertson		57		40								
Rockcastle	69	51	36	48								

Table 5-2 Statewide average speed by area

HPMS Functional Class			1998 statewide HPMS average	HERS (RM) average speeds 2000 HPMS data	HERS daily speed model average speeds 2002 HPMS data Statewide-All Roads	HERS daily speed model average speeds 2002 HPMS data SW-Urbanized	HERS daily speed model average speeds 2002 HPMS data SW-Mountainous	HERS daily speed model average speeds 2002 HPMS data SW-Other	Bell County Measured Speed Mountainous	Bell County Measured Speed Rolling
01	Rural	Interstate	50.4	71.0	69.2	70.0	68.5	69.2	NA	NA
02	Rural	Principle Arterial	47.4	51.6	55.4	59.1	52.4	56.6	NA	NA
06	Rural	Minor Arterial	34.9	42.3	45.2	47.0	39.7	46.5	NA	NA
07	Rural	Major Collector	31.5	46.1	44.3	46.8	38.9	46.2	37.3	36.0
08	Rural	Minor Collector	31.5	NA	NA	NA	NA	NA	33.0	32.5
09	Rural	Local	31.5	NA	NA	NA	NA	NA	29.8	30.9
11	Urban	Interstate	49.0	62.9	60.1	58.6	71.6	70.6	NA	NA
12	Urban	Freeway	50.5	58.8	62.6	61.0	NA	65.4	NA	NA
14	Urban	Principle Arterial	28.0	38.9	25.4	21.1	36.2	30.5	NA	NA
16	Urban	Minor Arterial	20.6	37.1	23.1	20.3	26.3	27.9	NA	NA
17	Urban	Collector	21.1	37.0	31.0	29.4	32.2	33.1	NA	NA
19	Urban	Local	21.1	NA	NA	NA	NA	NA	NA	NA

CHAPTER 6 CONCLUSION AND FUTURE RESEARCH

The speed estimation procedure developed in this study is based upon the HERS speed model. It uses the HPMS data format to compute speed on each roadway segment. The free-flow speed is first estimated and then adjusted based on delay experienced by each vehicle in order to obtain the average speed estimate. Even though a large number of data items are required as input, such data are available from the annual HPMS submission which is mandatory for all states. However, for those roadways that do not belong to the HPMS sample set (primarily local roads and rural minor collectors), additional data collection effort may be necessary.

The performance of the model was evaluated by two independent speed data sets collected in the field. Various statistical analyses attested the power of the model to produce accurate speed estimates. Tests also showed that the model was quite sensitive to a number of factors such as the density of traffic control devices. Periodic review and update of such information in the inventory data file may be required to ensure the accuracy of input data to the speed model. Further investigation on the model's sensitivity showed that the density of signal and/or stop sign is the most significant factor to the variation of average speed. Further analysis is recommended on the model's performance in urban areas where most roadways are controlled by signals or stop signs.

6.1 Potential Applications

The average speed estimates obtained from the HERS model can be used in various applications. The speed estimates can be used as an input to the MOBILE6 model to compute the emission factors for various automobile related pollutants for the current year.

If we update the input data items such as pavement condition and AADT using their projected values for future years, the HERS speed model can produce the projected average speeds on these roads. Such speeds can be used to estimate the vehicle emission factors for future years.

In addition to emission factor estimation, the model can be used to answer the "what if" type of questions. For instance, one can estimate the future speeds based on various infrastructure investment decisions. Such quantified estimates could provide valuable decision support to transportation authorities.

In addition to air quality related analysis, the speed data can also be used as part of the highway congestion management performance measures based on travel times. Theses travel time performance measures (such as the travel time index) supplement the traditional level of service measures.

6.2 Future Research

Although default speed distribution by hour is available in MOBILE6, the area specific hourly speed estimates are desired for improved prediction accuracy in calculating emission factors.

Furthermore, the analysis of bottleneck requires delay and queue length by time of day. Effort will be made to adapt the concept of the HERS speed model to the estimation of hourly speeds.

ACKNOWLEDGMENTS

The research team wishes to express our sincere gratitude to the members of the Study Advisory Committee (SAC) for sharing their expertise and valuable advice with us during the course of the study. Particularly we'd like to thank Mr. Jesse Mayes (the SAC Chair) and Mr. Rob Bostrom (the SAC Vice-Chair) for their guidance throughout the study.

The research team also would like to thank Mr. David Hamilton and Ms. Maria Bostrom for their assistance in data cleanup and preparation, as well as Ms. Lynn Soporowski for her support

REFERENCES

Agent, K., J. G. Pigman and J. M. Weber (1997) *Evaluation of Speed Limits in Kentucky*, Final Report, KYSPR-96-172, Kentucky Transportation Center.

Bostrom, R. and J. Mayes (2003) Highway Speed Estimation for MODILE6 by Kentucky, available at transportation.ky.gov/Multimodal/ doc/M6_speed_estimation_paper.doc

Cook, R., and E. L. Glover (2002) Technical Description of the Toxics Module for MOBILE6.2 and Guidance on Its Use for Emission Inventory Preparation, EPA420-R-02-029, U. S. Environmental Protection Agency.

Dowling, R. G., W. Kittelson, J. Zegeer, and A. Skabardonis (1997) National Cooperative Highway Research Report 387: Planning Techniques to Estimate Speeds and Service Volumes for Planning Applications, Transportation Research Board.

Federal Highway Administration (2000) *HPMS Field Manual*, OMB No. 21250028, available at http://www.fhwa.dot.gov/ohim/hpmsmanl/hpms.htm.

Federal Highway Administration (2003) *Highway Economic Requirements System-State Version Technical Report*, FHWA-IF-02-060, available at http://isddc.dot.gov/OLPFiles/FHWA/010945.pdf.

Kentucky Transportation Cabinet (KYTC) (2002) Traffic Forecasting Report 2002, available at http://transportation.ky.gov/Multimodal/pdf/TFR%202002.pdf.

Transportation Research Board (2000) Special Report 209: Highway Capacity Manual.

Tang, T., M. Roberts and C. Ho (2003) *Sensitivity Analysis of MOBILE6 – Motor Vehicle Emission Factor Model*, FHWA-RC-Atlanta-03-0007, Federal Highway Administration.

Turner, S., W. Eisele, R. Benz, and D. Holdener (1998) *Travel Time Data Collection Handbook*, FHWA-PL-98-035, Federal Highway Administration.

APPENDIX A
CHRISTIAN COUNTY SPEED COMPARISON
(ROADS DRIVEN ONLY)

Roadway/Segment	Functional Class	Speed Limit (mph)[‡]	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
I0024 069830	1	65	70.2	70.7	-0.5	-0.6
I0024 089211	1	65	71.8	72.0	-0.2	-0.3
E9004 011697	2	65	72.1	68.5	3.7	5.3
U0041A012157	2	55	36.8	56.8	-20.1	-35.3
U0068B000000	2	55	53.3	43.2	10.1	23.4
U0068B002866	2	55	48.2	52.6	-4.3	-8.3
K1682 000640	2	55	52.9	61.1	-8.2	-13.5
U0041 004964	6	55	51.1	53.1	-2.0	-3.7
K0091 000679	7	--	58.5	58.0	0.5	0.8
K0107 012566	7	55	53.4	51.3	2.1	4.1
K0109 018813	7	55	50.3	52.8	-2.4	-4.6
K0164 007290	7	45	47.8	51.2	-3.4	-6.7
KY1026	8	55	46.7	40.5	6.2	15.3
KY1027	8	--	42.7	38.4	4.4	11.3
KY117	8	--	52.5	51.9	0.6	1.1
KY124	8	--	41.6	34.9	6.8	19.4
KY1296	8	--	44.0	42.0	2.0	4.8
KY1348	8	55	42.1	39.3	2.8	7.2
KY1687	8	--	44.0	39.8	4.2	10.6
KY1914	8	--	41.8	46.0	-4.1	-9.0
KY272	8	--	53.5	52.0	1.6	3.0
KY287	8	55	41.8	40.5	1.4	3.4
KY287	8	25/30	34.4	40.5	-6.0	-14.9
KY345	8	--	48.8	49.4	-0.6	-1.1
KY398	8	55	41.8	36.9	4.9	13.4
KY398	8	35	37.9	36.9	1.0	2.8
KY407	8	55	57.5	45.6	11.9	26.0
KY407	8	35	39.5	45.6	-6.1	-13.3
KY507	8	55	56.7	48.9	7.9	16.1
KY507	8	35	26.4	48.9	-22.4	-45.9
KY507	8	55	38.9	46.6	-7.7	-16.6
KY508	8	55	50.7	55.2	-4.5	-8.1
KY508	8	45	48.4	55.2	-6.8	-12.3
KY800	8	35/25	44.7	50.5	-5.8	-11.5
KY800	8	--	26.4	23.8	2.5	10.6
C Williams	9	--	34.9	30.6	4.3	14.1
Combs	9	35	39.5	30.3	9.1	30.1

[‡] Multiple speed limits may be observed for the same route.

Roadway/Segment	Functional Class	Speed Limit (mph)‡	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
CR 1031	9	--	39.9	38.9	1.0	2.7
CR 1033	9	--	32.8	29.0	3.8	13.0
CR 1047	9	--	17.8	26.8	-9.1	-33.8
CR 1052	9	--	16.8	27.7	-10.9	-39.5
CR 1061	9	--	30.8	25.3	5.5	21.8
CR 1062	9	--	18.4	31.3	-12.9	-41.3
CR 1161	9	--	34.9	30.1	4.8	15.9
CR 1164	9	--	19.1	27.9	-8.7	-31.4
CR-1010	9	--	37.1	33.8	3.3	9.9
CR-1011	9	--	35.6	32.7	2.9	8.9
CR-1017	9	--	19.6	29.8	-10.2	-34.3
CR-1019	9	--	19.1	28.3	-9.2	-32.5
CR-1053	9	--	47.5	44.8	2.7	6.0
CR-1060	9	--	19.0	34.0	-15.0	-44.1
CR-1064	9	--	44.6	25.9	18.7	72.4
CR-1068	9	--	18.2	29.7	-11.5	-38.8
CR-1070	9	--	17.9	27.3	-9.4	-34.4
CR-1079	9	--	19.4	35.4	-16.0	-45.2
CR-1088	9	--	34.9	33.7	1.2	3.4
CR-1093	9	--	47.6	45.2	2.4	5.3
CR-1099	9	--	48.5	52.5	-4.0	-7.7
CR-1101	9	--	18.3	23.8	-5.5	-23.0
CR-1157	9	--	42.9	41.2	1.7	4.2
CR-1192	9	25	29.1	27.8	1.3	4.5
CR-1195	9	--	20.0	21.0	-1.0	-4.5
CR-1200	9	--	42.2	43.5	-1.3	-3.0
CR-1206	9	--	48.0	46.5	1.6	3.4
CR-1216	9	--	44.4	45.1	-0.7	-1.5
CR-1221	9	--	40.0	38.9	1.1	2.9
CR-1265	9	--	31.7	27.4	4.3	15.7
CR-1284	9	--	19.6	34.1	-14.5	-42.5
CR-1289	9	--	44.6	44.1	0.5	1.1
CR-1292	9	--	18.8	26.0	-7.2	-27.7
CR-1293	9	--	16.9	16.2	0.7	4.1
CR-1299	9	35	39.5	31.4	8.1	25.8
CR-1302	9	--	19.6	26.5	-6.9	-26.0
CR-1306	9	35	39.5	42.2	-2.7	-6.4
CR-1307	9	--	19.2	29.2	-10.0	-34.1
CR-1308	9	--	39.5	36.8	2.7	7.3
CR-1315	9	--	44.2	45.3	-1.1	-2.4
CR-1328	9	--	42.9	43.5	-0.6	-1.3
CR-1339	9	--	34.8	32.1	2.8	8.7
CR-1404	9	--	39.5	35.7	3.8	10.7
CR-1407	9	--	38.2	37.6	0.6	1.7
CR-1410	9	--	36.7	34.1	2.6	7.7
CR-1415	9	--	39.1	36.1	3.0	8.2

Roadway/Segment	Functional Class	Speed Limit (mph)[‡]	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
CR-1422	9	--	37.2	33.1	4.0	12.2
CR-1441	9	--	19.6	32.5	-12.9	-39.7
CR-1451	9	--	39.5	23.2	16.3	70.3
CR-1464	9	--	39.5	38.0	1.5	3.8
CR-1471	9	--	38.0	35.7	2.4	6.7
KY1026	9	55	37.0	51.4	-14.4	-28.0
KY1338	9	--	41.8	42.7	-0.9	-2.1
KY1453	9	--	47.9	43.7	4.1	9.5
KY1663	9	--	48.1	41.0	7.2	17.5
KY1682	9	55	49.7	44.5	5.2	11.8
KY1716	9	--	49.0	46.7	2.3	4.9
KY1801	9	--	40.5	34.5	6.0	17.6
KY1843	9	--	43.9	40.4	3.5	8.7
KY1881	9	--	43.9	42.5	1.5	3.5
KY2636	9	--	30.2	28.7	1.6	5.5
KY2638	9	--	44.0	42.4	1.7	3.9
KY2639	9	--	41.2	33.9	7.3	21.5
KY2640	9	--	25.5	22.8	2.7	12.0
KY2641	9	--	46.7	43.2	3.5	8.2
KY6061	9	--	34.3	33.0	1.4	4.2
KY800	9	--	34.9	38.0	-3.0	-8.0
KY800	9	55	36.0	42.4	-6.5	-15.2
KY813	9	-	39.5	43.7	-4.2	-9.7
KY800	9	--	41.5	40.5	1.1	2.6
I0024 085298	11	65	72.0	74.3	-2.2	-3.0
E9004 007000	12	65	72.8	63.5	9.3	14.6
U0041A002855	14	45/35	35.6	42.3	-6.7	-15.7
U0068B001712	14	55	60.8	55.1	5.8	10.5
U0068B005168	14	55	48.2	52.2	-4.0	-7.7
K1682 001848	14	55	55.8	51.4	4.3	8.4
K0115 001975	16	45/55	39.8	39.1	0.7	1.9
K0380 000000	16	35	25.2	30.8	-5.6	-18.2
K0695 012619	16	55	40.8	25.6	15.1	59.0
U0041 011795	16	35/45/55	34.9	34.0	0.9	2.8
U0041A015290	16	35	29.4	28.8	0.6	1.9
K1682 005418	16	55	21.7	50.1	-28.4	-56.6
KY507	16	35	35.8	31.9	4.0	12.5
K0911 000000	17	35	34.9	36.8	-1.9	-5.1
K1007 000785	17	35/45	27.3	32.2	-4.9	-15.2
map#1(hopk)	19	25/35	27.1	26.0	1.1	4.4
1	19	35	24.6	19.8	4.8	24.3
2	19	25	27.8	17.5	10.4	59.2
3	19	25	28.5	29.1	-0.6	-2.1
3	19	25	25.6	25.7	-0.1	-0.6
4	19	25	30.7	22.5	8.2	36.6
4	19	25	25.6	24.9	0.7	2.6

Roadway/Segment	Functional Class	Speed Limit (mph)‡	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
5	19	25	29.6	24.7	4.9	19.8
6	19	25	19.6	18.8	0.8	4.3
6	19	25	19.6	21.4	-1.8	-8.3
7	19	25	24.5	26.5	-2.0	-7.5
7	19	25	24.6	25.1	-0.5	-2.0
8	19	25	26.3	26.6	-0.3	-1.2
9	19	25	26.1	23.0	3.1	13.5
10	19	25	26.7	27.8	-1.1	-3.8
11	19	25	24.8	26.5	-1.7	-6.4
12	19	25	23.7	23.3	0.4	1.7
13	19	25	27.4	24.6	2.8	11.4
13	19	25	27.6	22.5	5.1	22.9
14	19	25	23.5	27.5	-4.0	-14.5
15	19	25	23.8	19.8	4.1	20.7
16	19	25	15.9	19.6	-3.7	-19.0
18	19	25	13.8	17.1	-3.3	-19.2
19	19	25	30.7	31.1	-0.4	-1.2
20	19	25	30.7	28.9	1.8	6.3
21	19	25	28.7	21.1	7.5	35.5
22	19	25	13.9	13.3	0.6	4.2
22	19	25/35	15.7	15.7	0.0	-0.2
22	19	25/35	16.0	16.5	-0.5	-3.0
22	19	25/35	17.7	14.3	3.4	23.8
23	19	25	14.2	15.3	-1.1	-7.1
24	19	25	23.9	21.5	2.3	10.8
25	19	25	23.1	21.7	1.3	6.1
26	19	25/35	25.3	25.7	-0.4	-1.4
27	19	25/35	24.5	28.4	-3.9	-13.6
28	19	25	17.9	21.7	-3.7	-17.2
29	19	25	25.6	22.1	3.6	16.2
30	19	25/35	15.1	14.2	0.9	6.5
31	19	25/35	21.3	25.0	-3.7	-14.7
33	19	--	31.2	15.9	15.3	96.4
34	19	25/35	26.9	29.5	-2.6	-8.9
35	19	25	24.6	21.2	3.4	15.8
2a	19	25	25.9	24.9	1.0	4.0
2b	19	25	30.7	23.4	7.3	31.4
3A	19	25	25.6	20.3	5.3	25.9
3A	19	25	25.6	23.9	1.7	7.0
3A	19	25	20.8	19.5	1.3	6.5
5A	19	35	32.2	26.7	5.4	20.3
7A	19	35/45/55	34.4	29.7	4.8	16.0
8A	19	25	20.8	24.4	-3.6	-14.6
8A	19	35/25	21.8	24.0	-2.2	-9.4
8A	19	25	21.8	23.6	-1.9	-7.8
8A	19	25	24.5	22.3	2.2	9.8

Roadway/Segment	Functional Class	Speed Limit (mph)‡	Measured Speed (mph)	Estimated Speed (mph)	Difference (mph)	Percentage Difference (%)
8A	19	25	19.1	19.7	-0.6	-3.3
map#1(oak)	19	20	24.5	32.9	-8.4	-25.5
1	19	20	23.2	27.2	-4.0	-14.9
2	19	25/35	27.4	32.6	-5.2	-16.0
3	19	20	19.3	24.6	-5.3	-21.7
4	19	20	18.1	22.8	-4.7	-20.7
5	19	--	25.9	13.2	12.7	95.9
6	19	20	22.5	22.8	-0.3	-1.5
7	19	--	26.2	23.9	2.3	9.7
KY1979	19	--	28.0	24.0	4.0	16.8
KY400	19	35	37.9	32.4	5.5	17.1

APPENDIX B
SOFTWARE TOOL AND INSTRUCTIONS

A software tool was developed based on the Microsoft Excel macro. It needs to be attached to the workbook in which the input data file is stored.

Heavy vehicles need to be classified into one of the four categories defined in Chapter 2. The procedure was outlined in Chapter 4. Prior to executing the program, empty cells (particularly in those fields containing required data items) should be screened out to ensure its proper functioning.

As described in Chapter 4, additional data quality screening may be required to ensure the accuracy of input data.