Estimating the Impacts of Changing Highway Conditions

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A discussion of the Highway Performance Monitoring System (HPMS) is presented. The analytical package is a series of computer models designed to use the annually updated HPMS sample inventory data to estimate needs, determine the relationship between highway investments and highway performance, and assess the benefits and costs associated with various investments. The models express highway performance in terms of sufficiency indexes, vehicle operating costs, fuel consumption, and overall running speed. This system-level planning tool is described and examples of the data output are given. Investment performance curves are presented to illustrate the consequences of different investment levels. Although it is concluded that the current analytical package is useful for assessing the effects of future investments on future system performance, there is a need to bring this package together with economic analyses and econometric forecasting tools to permit economic impact analyses of various sectors of the economy, including highway users and industries. As the predictive ability of the models improves, the ability to estimate the costs and benefits of alternatives will improve.

During the past 8 years, as a part of the Highway Performance Monitoring System (HPMS), FHWA has been developing an analytical package (series of computer models) designed to estimate future highway needs; test the sensitivity of highway needs to repaving and reconstruction policies, the makeup of the vehicle fleet, future travel, and future investment levels; determine the relationship between future highway investment and future highway performance; and assess the benefits and costs associated with various future investments in the functional system. The output from these models is used by the U.S. Department of Transportation and the U.S. Congress in the development of highway programs and policy. Although the models were developed to provide information at the national level, the states have program concerns similar to those of FHWA. For this reason, the models have been modified to provide state highway agencies with the same capability to test their own state highway program options. The purpose of this paper is to describe the operation of these simulation models and to illustrate how they are used to measure the changes in highway conditions and performance resulting from future highway investments.

INPUT

Basic input to the analytical package is inventory data consisting of a limited number of data elements for each section in a statistically designed, small sample of highway sections. These samples (3 percent of statewide mileage) are expanded to represent the arterial and collector highway systems in rural, small urban, and urbanized areas of each state. Specific physical, condition, operational, accident, and capital improvement data for the highway sections sampled are reported annually by the states as a part of the HPMS (1). A list of the data reported annually by the states for the sample sections used by the models is as follows (items followed by an asterisk are rural data; those followed by two asterisks are urban data):

1. Identification
   a. State code
   b. County code
   c. Rural or urban designation
   d. Urbanized area code **
   e. Expansion factor
2. System or jurisdiction: functional class
3. Operation or travel
   a. Type of facility
   b. Section or group length
   c. Current and future average annual daily traffic (AADT)
   d. Number of through lanes
   e. Speed limit
   f. Average highway speed *
   g. K-factor
   h. Directional factor
   i. Capacity
   j. Signal type and timing **
   k. Parking
   l. Percentage of trucks (peak and off-peak)
4. Pavement
   a. Surface or pavement type
   b. Pavement section
   c. Skid number or slab thickness
   d. Pavement condition
5. Geometrics or configuration
   a. Access control
   b. Lane width
   c. Approach width **
   d. Shoulder type and width
   e. Median type and width
   f. Horizontal and vertical alignment
   g. Percentage of sight distance *
6. Supplemental
   a. Drainage adequacy
   b. Type of terrain *
   c. Type of development
   d. Urban location **
   e. Number of intersections

METHODOLOGY

The analytical package is a series of interdependent computer models that use the HPMS sample data as primary input. There are four major models in the analytical process:

1. Needs,
2. Composite index (sufficiency),
3. Investment performance, and
4. Impact assessment.

These models are not designed for independent use. Several options are available to perform specific analyses and to provide output for different times. The needs and investment-performance models are always used in the analysis of future scenarios, whereas the remaining two models may be optionally called for an analysis of the current highway systems or as a part of the analysis of future scenarios or both. Figure 1 illustrates the analytical process and its outputs.

Needs Model

The needs model simulates the improvements necessary to keep the physical and operational conditions of a highway system from falling below prescribed minimum criteria during the analysis period. Basically the model identifies individual highway section deficiencies that occur during the analysis period, determines logical improvement types to correct these deficiencies, estimates the costs of the improvements, and modifies the section record to reflect

performance in the analysis year with and without improvement. The analysis period for this process may be a single time period of up to 20 years (investment-level analysis) or it may be one of up to four separate funding periods (funding-period analysis) within the overall analysis period. In the latter case, each period is analyzed separately.

Deficiency Determination

Each highway section is analyzed independently for each analysis cycle (cycles may be one or more years) starting with the year for which data are reported and continuing until a deficiency has been identified or the last year in the analysis period has been reached. Section deficiencies are identified through comparison of existing or projected conditions with the minimum tolerable conditions (MTCs) established for physical conditions, geometrics, and operational characteristics. These minimum conditions vary by functional class (and rural terrain type and AADT group) and are selected to reflect a general consensus on the lowest level of performance the public would or should tolerate. MTCs represent an adequate or acceptable level of performance for existing or projected traffic, although it is recognized that it is not realistic to identify a section as being deficient if the facility is providing reasonably good service. Table 1 contains one possible set of MTCs. A set of reduced MTCs is also provided for later demonstration of the consequences of such reduction. Design standards

Figure 1. HPMS analytical package, 1982.

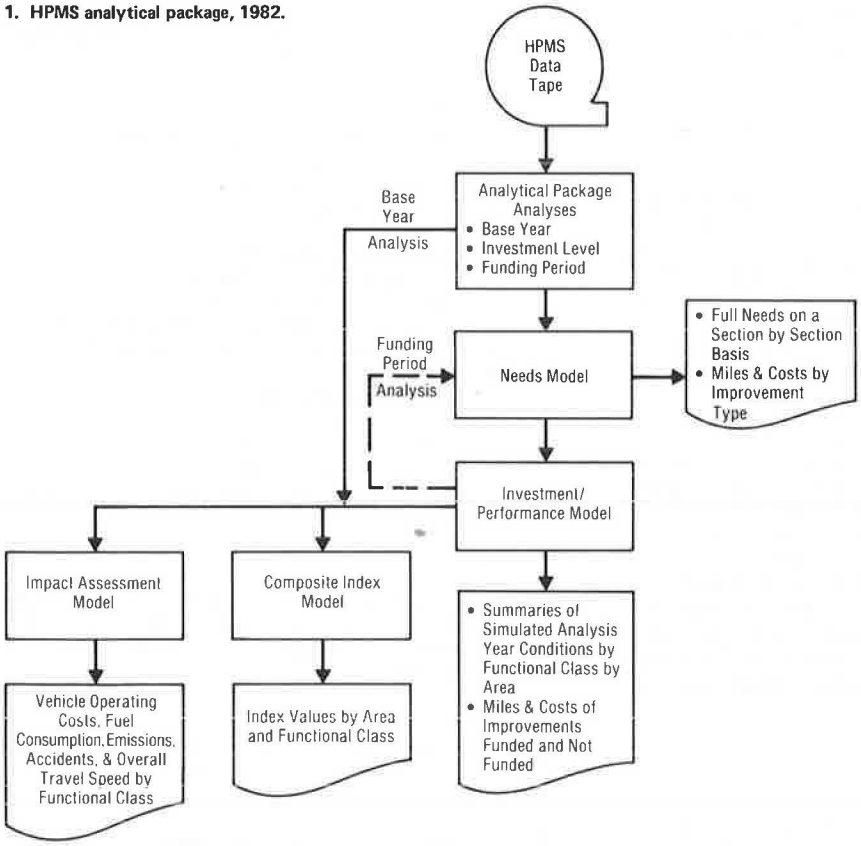


Table 1. MTCs for rural other principal arterials.

	High MTCs by Terrain[a]			Reduced MTCs by Terrain[a]		
Item	F	R	M	F	R	M
Lane width (ft)	11	11	11	10	10	10
Right shoulder width (ft)	8	8	6	6	6	4
Shoulder type[b]	S	S	S	S	S	S
Pavement condition	2.6	2.6	2.6	2.1	2.1	2.1
Operating speed (peak hour) (mph)	55	50	45	20	20	15
Volume-to-capacity ratio	0.70	0.70	0.70	0.99	0.99	0.99
Surface type[c]	High	High	High	High	High	High
Horizontal alignment adequacy[d]	2	2	2	4	4	4
Vertical alignment adequacy[d]	2	2	2	4	4	4

[a] F = flat; R = rolling; M = mountainous.
[b] S = stabilized.
[c] High = high rigid and flexible pavements, pavement-surface codes 60, 70, and 80 as defined in HPMS field manual.
[d] Rating of alignment adequacy of 1 (good) to 4 (poor) as defined in HPMS field manual.

for the rural other principal arterials are as follows (F = flat; R = rolling; M = mountainous):

Item	Terrain F	R	M
Lane width (ft)	12	12	12
Right shoulder width (ft)	12	10	8
Surface type	High	High	High
Median width (ft)	64	64	16
Avg highway speed (weighted design speed) (mph)	70	70	55

The data elements representing the section's conditions and operating characteristics in the first year of the analysis period are compared with the MTCs to determine whether a deficiency already exists. If a section is tolerable in the initial or base year, it is examined for future deficiencies. Future conditions [forecast AADT, deteriorated pavement condition, and operating speed or volume-to-capacity (V/C) ratio or both] are simulated for each analysis cycle and compared with the MTCs. Sections are deficient if any of the following items do not meet the MTCs:

1. Peak-hour operating speed or V/C ratio,
2. Lane width,
3. Pavement condition, or
4. Rural horizontal or vertical alignment adequacy (rural only).

Table 2. Typical rural deficiencies and improvement types.

Deficiency Type and Combination	Resulting Improvement Type
Access control and operating speed[a] (Interstate and high-volume principal arterials only)	Reconstruct to freeway
Operating speed[a]	Major widening
Widening not feasible	No improvement
Operating speed,[a] pavement condition <R,[b] or alignment	Reconstruct with more lanes
Widening not feasible	Reconstruct as is
Lane width	Minor widening
Widening not feasible	No improvement
Lane width, alignment, or pavement condition <R[b]	Reconstruct with wider lanes
Widening not feasible	Reconstruct as is
Pavement condition <R[b]	Pavement reconstruction
Alignment	Isolated reconstruction
Pavement condition <MTC and >R[b] and shoulder type or width	Resurfacing and shoulder improvement
Pavement condition <MTC and >R[b]	Resurfacing

[a] Peak-hour operating speed or V/C ratio.
[b] Present serviceability rating (PSR) below which reconstruction is needed.

Improvement Analysis

The improvement type selected by the needs model depends on the combination of deficiencies identified on the section under analysis. Table 2 gives typical rural deficiencies and the resultant improvement types simulated by this analysis. This table does not contain the complete improvement selection logic.

Improvements sufficient to carry 20-year traffic are made to design standards but may be constrained because of reported widening restrictions. If widening is not feasible, improvements are restricted to maintaining the existing pavement and roadway structure and traffic engineering improvements. Once the improvement types have been selected, the capital improvement (right-of-way plus construction) costs are calculated by using unit improvement-type costs, which vary by functional class, number of lanes after improvement, and terrain in rural regions and by design type, number of lanes after improvement, and type of development in urban regions. Table 3 gives the major output of the needs model, miles and cost by improvement type, for both high and reduced MTCs. By reducing the MTCs, the miles of improvements by type of improvement are greatly changed as are the costs (a 71 percent reduction for the latter). The number of miles improved has been reduced by only 13 percent. The needs model projects the analysis-year conditions with and without improvements and places this information on the section record. This information is the primary input to the investment-performance model in which decisions are made as to what improvements will be made under different investment levels.

Composite-Index (Sufficiency) Model

The composite-index model evaluates highway condition, safety (geometrics), and service (use and operating characteristics) on a section-by-section basis and aggregates these section evaluations by functional system. These evaluations are in the form of composite and component indexes. Section indexes are similar to sufficiency ratings. A rating between 0.0 and 1.00 is given to each data item evaluated and is applied to the total points assigned to the data item. For example, a pavement condition of 2.5 may warrant a factor of 0.4, which, multiplied by 15, yields 6 points out of a possible

Table 3. Rural other principal arterials: miles and cost by improvement type.

Improvement Type	High MTCs Miles	High MTCs Cost ($000,000s)	Reduced MTCs Miles	Reduced MTCs Cost ($000,000s)
Reconstruct to freeway	8,546	18,845	447	1,263
Reconstruct with more lanes	1,221	2,568	24	56
Reconstruct with wider lanes	2,334	2,964	68	77
Reconstruct as is	138	95	0	0
Isolated reconstruction	5,349	2,940	0	0
Major widening	3,953	5,228	57	91
Minor widening	5,437	2,928	881	483
Resurfacing with shoulder improvement	15,009	3,066	20,715	4,131
Resurfacing	19,074	3,447	31,041	4,584
Pavement reconstruction	2,661	2,467	2,146	2,052
Total	63,722	44,548	55,379	12,737

Note: Data are based on 1978 HPMS data for 40 states.

Table 4. Components of composite-index model and point values.

Component	Subcomponent	Point Value
Condition		30
	Pavement type	10
	Pavement condition	15
	Drainage adequacy	5
Safety		30
	Lane width	10
	Shoulder width	5
	Median width	5
	Alignment adequacy	10
Service		40
	Operating speed	20
	V/C ratio	10
	Access control	10

Table 5. Physical features and operating conditions for rural other principal arterials: 1995 conditions with full needs investment.

Item	Percentage of Mileage[a]		
	High MTCs	Reduced MTCs	No Improvement
Surface type high	100	100	90
Pavement condition (PSR)			
<2.0	7	0	82
≥2.0	93	100	18
Lane width, 11 ft	99	93	92
Cross section undivided	61	81	81
V/C ratio			
<0.41	87	74	72
≥0.41	13	26	28
Operating speed (mph)			
<40	4	12	13
≥40	96	88	87

[a]Weighted by mileage.

15 points. The points assigned to each of the three components may vary by functional class. For example, for rural principal arterials, weighting points of 30 for condition, 30 for safety, and 40 for service may be assigned. A composite index of 100 represents a section with no defects and a lesser total represents the degree of deficiency. Each component and its subcomponents and their assigned point values are listed in Table 4. Weighted component and composite indexes by functional system and mileage and travel distributions by component and composite are provided if desired.

Investment-Performance Model

The investment-performance analysis provides the means for relating investment to future highway performance in terms of composite-index values and as summaries of certain physical features and operating conditions--the first significant output of the analytical package. This analysis first determines priority rankings for all proposed improvements by functional system and area (rural, small urban, and urbanized) based on user-specified ranking factors. Potential improvements can be ranked by using one of several methods. The most commonly used method is the cost-effectiveness index calculated by the model as follows:

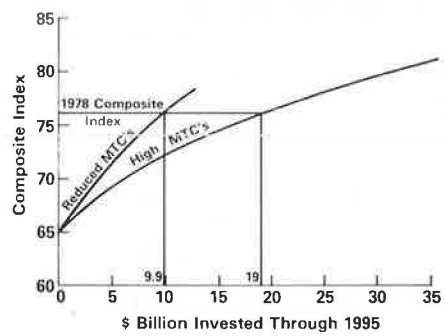
Cost-effectiveness index = [0.5 (100 + target-year composite index) - (smaller of base-year composite indexes or 70)] x 0.5 (target-year AADT + improvement-year AADT) x economic life of improvement type x section length/cost of improvement.

On completion of the ranking process, the improvements are selected and improved analysis-year conditions for the simulated improvement are summarized from the top of the priority list downward until the funds for the given investment level are exhausted. At that point the summarization process is continued by using analysis-year unimproved conditions for the remaining sections because funds are no longer available to support the potential improvements. This process is applied separately for each functional system by area (rural, small urban, and urbanized). The output from this analysis consists of a series of summary tabulations, which are produced for each investment level or funding period. Summaries are provided of composite-index values, pavement types and conditions, lane widths and cross sections, V/C ratios, and peak-hour operating speeds. Also given are the mileage and cost of investment (both funded and unfunded) by functional type and improvement type. Tables 5 and 6

Table 6. Composite-index values for rural other principal arterials: 1995 conditions with full needs investment.

Functional System	High MTCs	Reduced MTCs	No Improvement
Condition	26.4	27.4	15.7
Safety	27.9	26.0	24.9
Service	29.3	24.9	24.3
Total	83.7	78.3	64.9

Figure 2. Rural other principal arterials: 1995 composite index versus dollars invested.



show the output of this analysis in terms of 1995 conditions for investments equal to full needs for the high and reduced MTCs. (Reduced MTCs concentrate investments on pavement problems, thus producing much higher system pavement conditions for much less money at the expense of increased congestion.) The 1995 conditions with no improvement are also shown. Figure 2 shows one method for presenting investment-performance information--the investment curve. By plotting the systemwide composite index versus various investment levels, a curve is produced that enables one to assess the investment necessary to achieve certain conditions (e.g., to maintain the 1978 composite index in 1995, $9.9 billion will be necessary under reduced MTCs and $19 billion with high MTCs).

Impact-Assessment Model

The purpose of this section of the modeling process is to convert existing and future highway physical and operating conditions into user cost factors. Because a primary reason for highway investment is to reduce user costs, this impact-assessment method-

ology was developed to supply the benefit portion of the cost/benefit ratio.

The calculated user cost factors are expressed in terms of rates. The factors include fuel consumption, vehicle emissions (carbon monoxide, hydrocarbons, and nitrogen oxide), vehicle operating costs, average overall travel speeds, and three types of accidents--property damage only, nonfatal injury, and fatal. With these factors comparisons can be made between today's highway performance and future performance levels achieved with various investment levels and investment strategies. The comparisons can then be used to determine the relationships that exist among investment, travel, user costs, and improvement types.

Input

The primary input to the impact-assessment model is sample inventory data. Analyses of base- or inventory-year physical and operating conditions use these data as reported. Analyses of future target- or analysis-year user cost factors use the inventory data modified by the needs and investment-performance analysis models described earlier to reflect analysis-year conditions. Individual sections will have analysis-year conditions reflecting improvements simulated, if any, as a result of investments made.

Analysis Process

The impact-assessment model analyzes physical and operational conditions in the inventory year or a future analysis year and produces user cost factors indicative of either the conditions that exist in the inventory year or the conditions that are expected to exist in the analysis year as a result of the assumptions made in the needs and investment-performance analyses. Each sample, expanded to represent its portion of the universe, is individually analyzed, and individual section user cost factors are weighted together to produce functional system user cost factors or performance measures.

The logic of the analytical process is built around a series of tables, curves, and equations developed by FHWA through in-house or contract research efforts. These components of the process can be changed when updated or improved data or relationships are available. The major components are as follows:

1. Daily distributions of traffic by functional class and design type (2);
2. Speed-estimating relationships by design type and congestion level (2);
3. Adjustment relationships for pavement condition and alignment speed (3);
4. Estimating relationships for speed-change cycle, stop cycle, and speed-change magnitude by vehicle type (2);
5. Idling-time relationships (2);
6. Tables for fuel consumption, travel time, and vehicle operating cost by vehicle type for pavements in good condition (PSR = 4.5) (2,3);
7. Pavement condition adjustment factors for vehicle operating costs and fuel consumption (2);
8. Vehicle classification data by area and functional class (3,4);
9. Emission rates for carbon monoxide, hydrocarbons, and nitrogen oxide by vehicle type and calendar year (5); and
10. Total, fatal, and injury accident rates by design type and AADT carried (2).

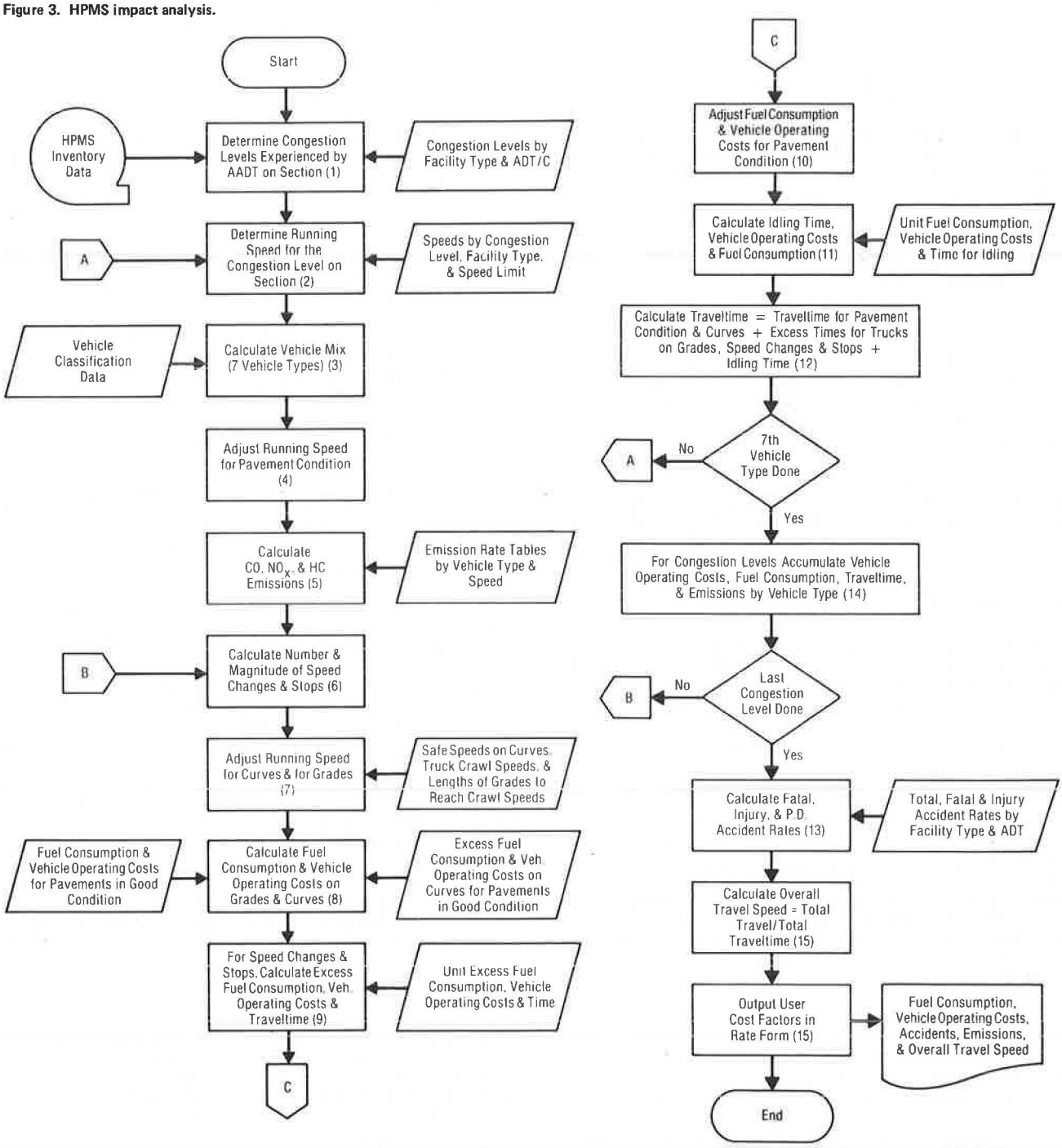
Specifically each section is analyzed as follows (see Figure 3 for flowchart of analytical process; numbers on flowchart refer to steps in process):

1. The AADT is stratified into 3 to 12 daily increments of relatively uniform congestion to more accurately represent daily vehicle operations and the required user cost factors. Each congestion period is analyzed independently and the resulting user cost factors are weighted together to develop factors for each vehicle type representative of the overall average day.
2. For each congestion period an initial unadjusted running speed free from the effects of pavement condition, speed changes, curves and grades, and idling time for specific design types is established.
3. Within a congestion level the AADT is stratified into seven vehicle types, as follows:
   a. Small automobiles (<3,000 lb);
   b. Large automobiles (>3,000 lb);
   c. Pickups and vans;
   d. Two-axle, six-tire, single-unit trucks;
   e. Single-unit trucks with three or more axles;
   f. Multiunit trucks with three or four axles; and
   g. Multiunit trucks with five or more axles.

The number of each type of vehicle on the average day is determined as a function of the reported percentage of trucks and vehicle classification data for each rural and urban functional class. Each vehicle type is independently processed for a given congestion period.

4. The initial running speed for a given congestion period is adjusted to reflect the pavement condition of the section being analyzed.
5. The emission measures (CO, HC, and NO_x) are calculated as a function of the year being analyzed, vehicle type, and the running speed adjusted for pavement condition.
6. The running speed adjusted for pavement condition is then used to calculate the number and magnitude of speed-change cycles for automobiles, single-unit trucks, and multiunit trucks. Likewise, the number of stop cycles is calculated.
7. The running speed, which has already been adjusted for pavement condition, is then adjusted for curvature by using the safe speed for each curve class. If the running speed exceeds the safe speed of a curve, the safe speed becomes the running speed for that part of the section. The calculated running speed is used as the entry speed in the table for vehicle operating cost and fuel consumption for automobiles, panel trucks, and pickups. This same running speed is then used to determine the table entry speeds for trucks for the reported grades as a function of the running speed, the length of grade, and the crawl speed.
8. By using the table entry speeds calculated for each grade class, the unit vehicle operating cost and fuel consumption rates are interpolated from the appropriate grade tables and used to calculate the fuel consumption and vehicle operating costs for grades for the section. A similar procedure is used to determine the excess fuel consumption and vehicle operating costs for curves by using table entry speeds adjusted for curvature. The excess operating costs and fuel consumption rates for curves are added to values for grades to get the vehicle operating costs for curves and grades.
9. By using the running speed adjusted for pavement condition as an initial table entry speed and the magnitude of the speed-change cycle, the excess vehicle operating costs, fuel consumption rates, and travel times for a speed-change cycle and

Figure 3. HPMS impact analysis.



stop are determined by interpolating from the appropriate tables. By multiplying the appropriate unit values by the numbers of speed-change cycles and stops, the excess operating costs, fuel consumption, and travel times associated with speed-change cycles and stop cycles for the section and congestion level are determined. The excess costs and fuel consumption are added to the like values for curves and grades.

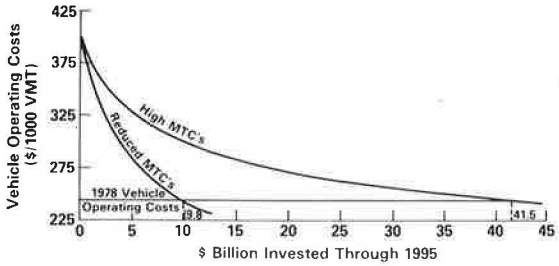
10. The vehicle operating costs and fuel consumption rates for curves, grades, speed-change cycles, and stops are modified to reflect pavement conditions other than 4.5.

11. The amount of time spent idling is calculated. Then the vehicle operating cost and fuel consumption associated with idle time are calculated and added to similar values for curves, grades, speed-change cycles, and stops to get the section totals for these items.

12. The total travel time is based on the initial running speed adjusted for pavement condition, curves, grades (trucks), speed-change cycles, and stops plus the idling time. The overall travel speed is calculated as the vehicle miles of travel (VMT) divided by the travel time.

13. The accident measures (fatal accidents, in-

Figure 4. Rural other principal arterials: 1995 vehicle operating costs versus dollars invested (all vehicles).



jury accidents, and property-damage accidents) are calculated as a function of traffic volume, design type, and VMT on the section.

14. This process is repeated until all vehicle types and congestion period traffic volumes are complete. Vehicle type values are accumulated for all congestion levels.

15. Final user cost factors are calculated and output.

Output

An example of the all-vehicle output (vehicle operating costs) for the rural other principal arterial system is illustrated as an investment performance curve in Figure 4. This figure shows that user cost factors may be used as a tool for assessing the consequences of different investment levels under different assumptions.

CONCLUSION

The analytical process described here has been developed to provide a tool for predicting the economic and environmental effects of current and future highway investment options. It is essential that decision makers be aware of the interactions among several dynamic factors, including highway user costs, changing highway performance, capital investment in highways, and highway travel demand.

Investments for capital improvements on U.S. highways have been at the $15 billion level in recent years. Investments of this magnitude, approaching 1 percent of the gross national product, have a substantial impact on the labor force and many industries and have a ripple effect throughout the economy. The effect of investments of this magnitude and the resulting changes in system performance must be understood and should be analyzed. The HPMS analytical process has been in use only a short time. Over the next few years the process will be fine tuned, providing the U.S. highway system with a better current and projected condition inventory than most, if not all, public-owned property in the United States.

Bringing these products together with currently available economic analysis and econometric forecasting tools will permit economic impact analyses on various sectors of the economy, including highway users, the construction industry, and related industries. Cost-benefit analyses of alternatives will improve as the predictive ability improves.

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