Energy Impacts of Transportation System Improvements

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A quick-response methodology for estimating the energy impacts of transportation system capital and operational improvements is presented. The method considers both energy consumed by vehicles and energy consumed in the construction and maintenance of facilities. Unlike many earlier energy impact estimation procedures, this methodology explicitly considers induced and diverted travel resulting from a transportation improvement and the effect of this travel on the level of service of transportation facilities. Application of the manual methodology takes less than 4 h and uses readily available data. The results are very sensitive to baseline operating conditions on the facilities that are affected by an improvement. The methodology was applied to 20 sample projects and produced results that were frequently counterintuitive. Highway expansion and new construction sometimes result in increased energy consumption both because vehicle fuel economy generally decreases at speeds above 35 mph and because of the energy consumed by induced travel. However, because the fuel consumption of congested travel is extremely high, projects that eliminate stop-and-go conditions frequently reduce energy consumption in spite of induced travel and in spite of the energy consumed in constructing and maintaining the expanded facility. Ramp metering and traffic signal improvements are generally effective in reducing energy consumption.

This paper describes quick-response methods for evaluating the energy impacts of transportation projects. The procedures were developed for the California Energy Commission (CEC) to evaluate projects considered for inclusion in the California State Transportation Improvement Program (STIP). The STIP is a five-year programming document that sets priorities for the allocation of state transportation funds among candidate projects. The STIP is reviewed and updated on an annual basis by the California Transportation Commission (CTC). The annual update is based on recommendations provided by the state and regional offices of the California Department of Transportation (Caltrans) and by regional planning agencies. Project rankings are based on a wide variety of technical and nontechnical factors, including project cost, expected benefits (e.g., reduced delay or congestion, reduced travel time, improved facility use, and improved safety), and equity (frequently based on the distribution of highly ranked projects by political jurisdiction and/or geographic location).

One benefit that is frequently stressed by project proponents is the potential reduction in energy consumption that will result from a proposed project. For the most part, these benefits are not rigorously justified. The energy impact assessment method described in this paper consists of an incremental, elasticity-based set of models that enables a technician or transportation planner to determine the net change in energy consumption that will occur as a result of a candidate STIP project.

The development of the energy impact estimation procedures was the product of a joint agreement between Caltrans and the CEC. This cooperative venture is intended to increase the ability of Caltrans and the CEC to respond to the energy concerns represented by the CEC. The estimation procedures were developed to conform to several important specifications:

1. The method is quick response so that a large number of projects can be evaluated; a typical project analysis takes from 2 to 4 h to complete.
2. The procedures make extensive use of standard existing project data sources. This ensures that projects can be analyzed quickly and facilitates comparisons between projects because the variability that might result from incompatible data sources is eliminated.
3. The procedures handle a wide range of project types, from extensive new freeway construction to TSM pricing or marketing strategies. Both transit and highway projects can be analyzed. The procedures can also be used to estimate the impacts of various combinations of project types [e.g., express bus service on a new reserved high-occupancy-vehicle (HOV) lane]. This is critical because only rarely is a project implemented in total isolation from other transportation system changes.

SOURCES OF ENERGY CONSUMPTION

The energy impact assessment procedures calculate the effect of a proposed project on the following three broad areas of energy consumption:

1. Energy consumed by moving vehicles;
2. Energy consumed in the construction or implementation of a facility or project; and
3. Additional energy consumed in the yearly maintenance of an improved or expanded facility.

Simplified procedures for estimating the second and third areas of energy impacts have been developed by Apostolos, Shoemaker, and Shirley (1). However, quick-response procedures for calculating the first category of energy consumption (vehicle energy impacts) have been inadequate for the reasons described below.

When a project is implemented, there are three sources of change in vehicle energy consumption:

1. Vehicles currently traveling on the facility or facilities to be improved may experience changes in their speed and traffic-flow characteristics. Usually, travel speeds will be increased, delays and idling time will be reduced, and/or congested stop-and-go traffic will be relieved. These changes will affect the energy consumption characteristics of the vehicles themselves.
2. An improvement on one facility may divert traffic from other facilities of the same mode. A new highway bypass will attract vehicles from an existing arterial; a new transit route may draw patronage away from other routes that have similar service areas. Because the level-of-service characteristics (e.g., travel speed) of the competing routes may be different, this diverted travel can result in a change in energy consumption.
3. A transportation improvement may induce new travel. These new trips represent entirely new travel generated as a result of increased accessibility between points served by the improved facility. These new trips consume additional energy and therefore affect total energy consumption.

Several earlier procedures for estimating energy impacts (1,2) deal with the first of these three sources of change in vehicle energy consumption. These other methods do not, however, consider the level of induced and diverted travel and the impact of this travel on the level of service of affected facilities. The procedures described here explicitly calculate these impacts. Trips diverted away from a particular facility or mode result in a net energy savings for this facility or mode; trips induced on or diverted to a facility incur energy costs on that facility. Equilibration is performed on all affected facilities to account for supply and demand interaction to ensure the accuracy of the results.

OVERVIEW OF METHOD

A simplified view of the structure of the method is shown schematically in Figure 1. The first step is to identify those trips that will be affected by a given improvement. These trips may be on one or more highway facilities and on one or several transit routes. In this critical step of the process, the analyst must exercise careful judgment to identify facilities that may be in competition with the facility that is being improved.

Current-year affected travel is then factored to the future planning year to account for long-term changes in population and vehicle operating cost. Then, the future baseline level of service, travel time, and energy consumption are calculated for the affected trips on the network without the given improvement (the STIP project).

At this point in the process, the impact of the STIP project on the level of service that is provided to affected trips is calculated. By comparing the baseline and "build" travel times and applying the appropriate diversion factors and elasticities, diverted travel and induced travel are computed. However, the change in traffic volume may significantly affect travel time; if so, iteration takes place until travel time and traffic volume reach equilibrium.

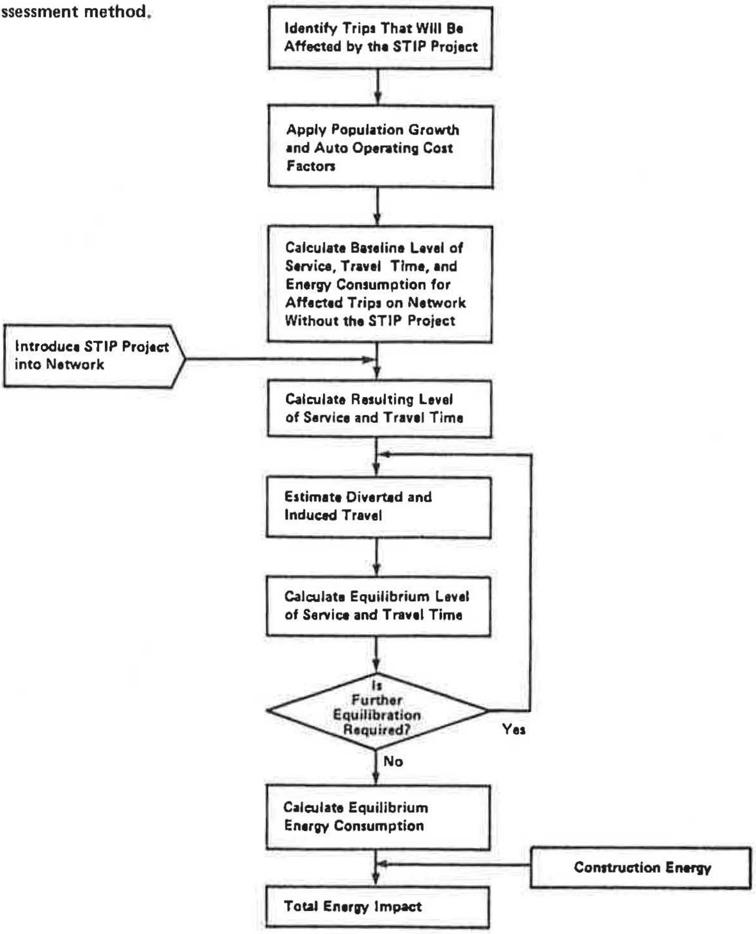
The energy consumed by moving vehicles is then estimated (based on the new traffic volumes, vehicle speeds, and flow characteristics) and combined with construction energy estimates to yield the total energy impact for the project. One early finding of this study was that the energy consumed in the maintenance of a new or improved facility is negligible compared with vehicle and construction energy. For this reason, it has been omitted from the analyses reported here.

MODEL OUTPUT

The new impact estimation procedure forecasts the change in energy consumption in a given target year that results from the construction or implementation of the STIP project. The target year may be any year desired by the analyst (e.g., the year of project construction or 20 years after construction). Two sets of energy estimates are produced. The first is a baseline or no-build forecast of the energy consumed in the target year on the "affected" facilities in the existing network (this is not usually the same as the current-year energy consumption due to changes in population and automobile technology over time). The second is a "build" forecast of energy consumed in the same target year with the added improvement in the transportation infrastructure. Therefore, the two estimates are not before-and-after estimates but rather with-and-without estimates.

Life-cycle energy impacts can also be calculated by using the impact procedures and simply calculating the energy impacts at several time periods in the life span of the project and interpolating for intermediate years. Though the change in energy consumption may be somewhat nonlinear over time, by selecting several time points the total change in energy consumption can be calculated quite accu-

Figure 1. Overview of energy impact assessment method.



rately. Note that, when calculating life-cycle energy impacts, the analyst may want to discount energy flows over time (just as an economist discounts future costs and revenues in evaluating major investments). Discounting of energy flows is appropriate in considering the "value" or economic worth of energy consumed rather than simply the amount of energy used.

Note that, because the model treats individual trips as the behavioral unit of travel, it estimates the total energy consumed by these trips, including those portions of trips that take place both on and off the affected facilities. It does not produce estimates of total energy consumed on the new or improved facility (or facilities) or on specific segments of facilities.

The construction energy impact estimates apply to the complete STIP project. These cannot be directly compared with the vehicle energy impacts because vehicle impacts are calculated for a given year. By dividing total construction energy by the project life, an undiscounted estimate of annual construction energy can be developed and compared with vehicle energy impacts.

VARIABLES ENTERING INTO IMPACT ASSESSMENT PROCEDURES

The impact assessment procedures are sensitive to a wide variety of variables. This section of the paper briefly describes these variables and how they are accounted for in the models. A full discussion of the structure of the models and detailed descriptions of the model equations are given elsewhere (9).

Estimates of fuel consumption are based heavily on previous work by Apostolos, Shoemaker, and Shirley (1); Tardiff, Benham, and Greene (3); and Claffey (4). These estimates are sensitive to the following variables:

1. The vehicle mix on the facility (automobiles, buses, and trucks);
2. Long-term changes in automobile and truck fleet fuel economy;
3. Average vehicle operating speed under both congested and uncongested conditions, both on and off the facility;
4. The incidence and effect of stop-and-go traffic conditions; and
5. Energy consumed during delays at signals and metered ramps.

Estimates of highway capacity and speed are based on methods outlined in the 1965 Highway Capacity Manual (5) and updated in Transportation Research Circular 212 (6). These methods are used heavily by Caltrans in the calculation of various performance indexes (7,8). Highway capacity and speed are a function of the following variables:

1. Facility size and type;
2. Design speed;
3. Grades, geometrics, and sight-distance restrictions (for two-lane roads);
4. Vehicle mix (automobiles versus trucks); and
5. Effects of traffic signals.

The fuel efficiency of vehicles declines dramatically as volume exceeds capacity (i.e., congestion occurs) and average speeds decline precipitously. Fuel efficiency also declines rapidly as vehicle speeds exceed 30 mph for automobiles and diesel trucks and 35 mph for gasoline trucks (see Figure 2). Congestion, however, occurs only during certain times of the day. The impact estimation procedures, using empirical data from the Los Angeles area, calculate the percentage of traffic that experiences congestion on the basis of the relation shown in Figure 3. This allows the separate calculations of travel speeds and fuel economy and consumption during the "congested" and "uncongested" portions of the day, ensuring sensitivity to the markedly different vehicle performance and energy consumption characteristics of these two periods.

Long-term changes in population are accounted for by factoring current-year travel to the baseline year by using county or smaller-area population forecasts. County-by-county data on average trip length are also used. Similarly, the effects of long-term changes in automobile operating cost are included by applying the appropriate direct and cross elasticities of automobile and transit travel with respect to automobile operating cost. (Elasticities used in the initial application of the method in California are given in Table 1, which was developed by Charles River Associates.)

As discussed earlier, the impact estimation procedure incorporates induced and diverted travel. Induced travel is calculated by using travel-time direct and cross elasticities (Table 1), whereas diverted travel is calculated by using travel-time-based proportional assignment. The level of induced travel is, of course, based on the change in total trip travel time rather than on the travel time on some segment of a trip. Trips are divided into on- and off-facility portions. Off-facility speeds are based on existing speeds for urban and rural local traffic. Default values can be used for these speeds with minimal loss of accuracy in the typical case when detailed speed data are not available. Differences between urban and rural areas are also accounted for through the use of larger rural operating-cost and travel-time elasticities (Table 1) and the longer average trip lengths generally observed for rural areas.

Changes in transit travel are sensitive to a variety of variables, including changes in automobile operating cost and travel time. Induced transit travel results from project-related changes in transit travel time and wait time. The energy consumption of the automobile leg of park-and-ride trips is included explicitly (including cold-start factors for automobile fuel economy). In addition, when modal shifts occur between automobile and transit, average automobile occupancy factors are used to equate transit average daily passengers with automobile ADT.

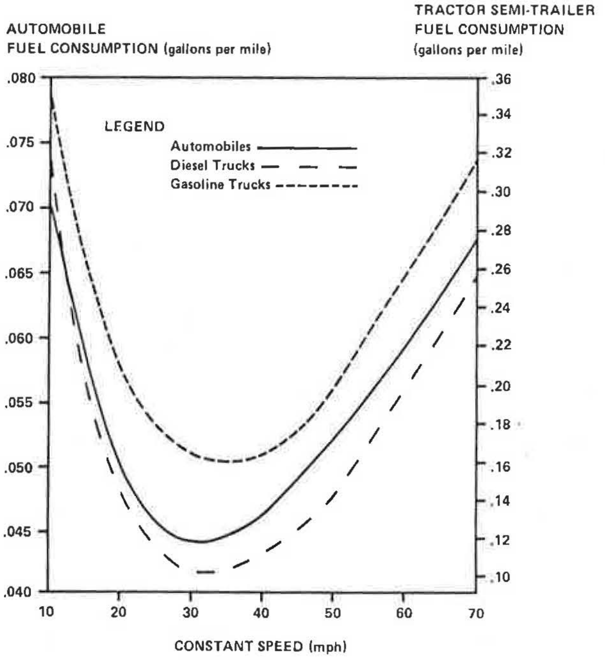
IMPACT ESTIMATION WORKSHEETS

Fifteen different worksheets are available for use in the manual impact estimation procedure. Some of these worksheets (input data, travel time estimation, and project summary sheets) are filled out, at least in part, for all types of projects. Others are used only for specific types of projects. The complete set of available worksheets is described in detail elsewhere (9). The worksheets guide the technician or analyst step by step through the impact estimation process. Intermediate calculations and results are accessible, so that the sources of changes in energy consumption can be identified and discussed. Therefore, the methodology is highly transparent and user oriented. The analyst can also input special knowledge he or she may have concerning the project or its impact area by entering travel speeds, traffic volumes, or other known variables. In addition, the analyst can repeat the impact estimation procedure by using different estimates of selected input parameters to measure the sensitivity of the results.

RESULTS: ENERGY IMPACTS OF SELECTED PROJECTS

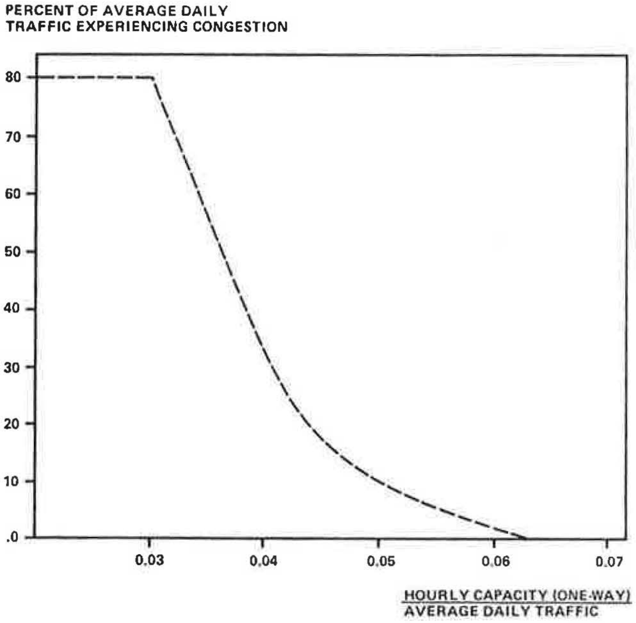
The energy impacts of 20 proposed STIP projects were calculated for the target year of 1999. They included a wide range of project types, including major and minor highway improvements, transit service changes, bicycle zone construction, new freeways, HOV lanes, and ramp metering. This section presents and discusses the results of four representative project analyses.

Figure 2. Fuel consumed at constant speeds by automobiles and tractor-semitrailer trucks.



NOTE: Base Year = 1974

Figure 3. Percentage of ADT experiencing congestion.



US-101, Ventura County

Alternative 1

US-101 in Ventura County is currently a congested four-lane freeway. Under alternative 1, an 18.9-mile segment of the facility is expanded to six lanes, all of which are open to general traffic at all times of the day.

The data given in Table 2 show that a significant decrease (9.2 percent) in vehicle energy consumption results from the proposed project. Because the project reduces congestion, the average trip travel time of affected trips is reduced by 2.2 min (this is the travel time both on and off the freeway for those trips using the improved section). This results in an induced travel of 5.8 percent of the private-vehicle vehicle miles of travel (VMT) in the target year (1999). However, because the travel speed on the currently congested facility is increased to free-flow conditions, average fuel economy improves (Figure 2). Therefore, in spite of significant induced travel, total vehicle energy consumption decreases as a result of this particular project. The construction energy impacts of the project are insignificant compared with the energy consumption of private vehicles.

Alternative 2

Alternative 2 involves the same basic construction as the preceding project, but the six-lane facility will be operated with a reserved with-flow HOV lane and ramp metering during congested periods in both directions. Meters are located at all entrance ramps, and ramp bypasses are provided for HOVs.

The results of the energy impact analysis indicate that a smaller reduction in vehicle energy consumption results from this project alternative (see Table 3). Energy consumed by moving vehicles is reduced by 4.0 percent, and 10.0 percent of the absolute amount of this savings is offset by the energy consumed by vehicles idling at the metered ramps.

The reduction in vehicle fuel consumption results once again from the improved fuel economy of formerly congested traffic that now operates under less congested conditions as a result of ramp metering. Average trip travel times decrease slightly; the increased freeway speed in this case is partly offset by the delays experienced at the metered ramps. Induced travel of 3.3 percent results from this

Table 1. Travel demand elasticities.

Type	Elasticity Urban Site	 Rural Site
ADT direct elasticity with respect to		
Automobile operating cost	-0.35	-0.50
Automobile travel time	-0.40	-0.68
Daily transit passengers direct elasticity with respect to		
Bus travel time	-0.25	NA
Bus wait time[a]		NA
<5 min	-0.13	
≥5 min	-0.20	
Daily transit passengers cross elasticity with respect to		
Automobile operating cost	+0.15	NA
Automobile travel time	+0.08	NA

Note: ADT = average daily traffic.

[a] It is assumed that average wait time is equal to half the headway for transit headways of <10 min. For longer headways, the elasticity value provided here was derived from a bus frequency elasticity of +0.20. It is expressed as a wait-time elasticity only to facilitate the use of the standardized worksheets for all ranges of bus headways.

Table 2. Energy impact summary results: US-101, Ventura County, alternative 1.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000 000s)	2.74	2.90	+5.8
Private-vehicle fuel economy (miles/gal)	22.6	26.3	+16.4
Average trip time (min)	16.65	14.45	-13.2
Energy consumed (10^{12}Btu)			
Moving vehicles	5.54	5.03	-9.2
Idling vehicles	0	0	

Note: Total project construction energy = 1.00×10^{12} Btu; annualized project construction energy (undiscounted) = 0.04×10^{12} Btu.

Table 3. Energy impact summary results: US-101, Ventura County, alternative 2.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000 000s)	2.74	2.83	+3.3
Private-vehicle fuel economy (miles/gal)	22.6	25.2	+11.5
Average trip time (min)	16.65	15.86	-4.7
Energy consumed (10^{12} Btu)			
Moving vehicles	5.54	5.32	-4.0
Idling vehicles	0	0.02	∞

Note: Total project construction energy = 1.00×10^{12} Btu; annualized project construction energy (undiscounted) = 0.04×10^{12} Btu.

Table 4. Energy impact summary results: CA-39, Los Angeles County.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000s)	144.3	147.7	+2.3
Private-vehicle fuel economy (miles/gal)	22.9	30.7	+34.1
Average trip time (min)	21.83	21.05	-3.6
Energy consumed (10^9 Btu)			
Moving vehicles	245.7	213.9	-12.9
Idling vehicles	46.6	6.0	-87.1

Note: Total project construction energy = 5.5×10^9 Btu; annualized project construction energy (undiscounted) = 1.1×10^9 Btu.

project. The new HOV lane by itself increases capacity and results in a small amount of induced VMT. Thus, in this case the effect of the HOV lane is to increase, rather than decrease, energy consumption.

The construction energy impact is essentially identical to alternative 1 of the project. Under the second alternative, the annualized construction energy increase (which in the former project was dominated by the vehicle energy savings) offsets about one-fifth of the vehicle energy savings.

CA-39, Los Angeles County

CA-39 in Los Angeles is a 3.4-mile highway segment that contains 13 signalized intersections. These signals were designed to be interconnected, but the existing control equipment is unreliable. The proposed project is the replacement of existing equipment with new signals and controllers.

In the baseline case, it was assumed that the 13 signals (each with 50 percent green time) functioned essentially independently--i.e., with no interconnection. Therefore, every vehicle had roughly a 50 percent chance of having to stop at each signal. In the "build" case, the signals are assumed to be perfectly interconnected. Therefore, no vehicle stops more than once except under congested conditions when interconnection breaks down and the signals are again conservatively assumed to operate independently.

Significant energy savings result from the project (see Table 4). Idling is reduced substantially so that energy consumed by idling is reduced by more than 85 percent. Equivalent absolute energy savings (though smaller in percentage terms) result from a return to continuous-flow conditions for nearly all uncongested travel, and there is a resulting improvement in fuel economy. These energy savings occur in spite of induced travel of 2.3 percent that results from a 3.6 percent reduction in average trip travel time.

The total construction energy is less than 10 percent of the annual energy savings resulting from this project. This is clearly a project that offers significant energy savings, as well as many other travel-related benefits such as reduced delay.

CA-99, Merced County

CA-99 in Merced County is a four-lane rural expressway running through the city of Livingston, California. Within the 6.1-mile project limits, there are one signalized intersection, five other at-grade intersections, and numerous "T-intersections". Several sections have no shoulders. The existing facility has a very high proportion of heavy truck traffic. The proposed project involves the construction of a four-lane, limited-access bypass near the existing alignment. The existing facility would remain to serve local traffic.

This project was analyzed by treating the existing CA-99 and the new bypass as competing facilities. Traffic was allocated between the two facilities on the basis of relative travel times on the two routes. It was assumed that all heavy-truck traffic would use the bypass (a negligible amount of this traffic is local traffic). Signal delays and idling time were calculated in a manner similar to that used for the CA-39 project in Los Angeles, except that the effects of the signal on cross-street traffic were also considered.

The results of the energy impact analysis given in Table 5 indicate that the combined vehicle energy consumption of affected vehicles on the old and new facilities increases by almost 40 percent as a result of the proposed project. This large increase stems primarily from two sources:

1. High speeds on the bypass result in a net decrease of 7.5 percent in average trip travel time, which in turn generates induced travel of 4.7 percent.
2. For the traffic using the bypass, the average on-facility speed increased from 32.5 mph to nearly 65.0 mph, which results in markedly increased fuel consumption (Figure 2). This effect is even more pronounced because of the high percentage of heavy-truck traffic, whose fuel economy declines even more rapidly at high speeds than that of automobiles.

In addition to the increases in vehicle energy, the construction energy for the new facility is substantial--equivalent, in this case, to the total energy consumed in three years by all vehicles on the existing facility. This is clearly a project that has negative energy impacts associated with the benefits of reduced travel time, increased capacity, and improved safety conditions.

DISCUSSION OF RESULTS

The energy impact estimation techniques presented in this paper were used to analyze a total of 20 California STIP projects and project variations. From

Table 5. Energy impact summary results: CA-99, Merced County.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day^a (000s)	151.0	158.1	+4.7
Private-vehicle fuel economy^a (miles/gal)	29.9	22.1	-26.0
Average trip time^a (min)	19.69	18.22	-7.5
Energy consumed^a (10^9 Btu)			
Moving vehicles	230.3	326.1	+41.6
Idling vehicles	4.2	1.6	-61.9

Note: Total project construction energy = 917.5×10^9 Btu; annualized project construction energy (undiscounted) = 36.7×10^9 Btu.

[a] Data are based on affected trips made by vehicles on both old and new facilities.

these sample projects, a number of interesting conclusions can be drawn about the typical energy impacts of various classifications of projects. Some of these results are counterintuitive and contrary to commonly accepted conclusions concerning the energy impacts of projects. These results are summarized below:

1. Highway widening or bypass projects can either increase or decrease vehicle energy consumption. Energy is generally saved as long as the improvement is on a congested facility and is small enough just to allow stable traffic conditions. As the capacity improvement allows speeds to exceed about 35 mph, vehicle fuel economy decreases and additional traffic is induced. Both of these factors increase overall energy consumption.
2. STIP projects that are primarily safety related, such as two-way left-turn lanes and shoulder improvements, have negligible energy impacts.
3. Ramp-metering projects yield energy savings when implemented under congested conditions. Above baseline speeds of about 35 mph, ramp metering tends to increase energy consumption. In most cases, ramp delays reduce the amount of induced new travel.
4. Traffic-signal improvements along corridors are effective energy savers, as are all projects that relieve stop-and-go traffic conditions. The effectiveness of signal improvements decreases, however, as the existing level of congestion increases. This is because signal interconnection has decreasing benefits under saturated conditions.

RECOMMENDATIONS FOR FURTHER DEVELOPMENT

With relatively simple modifications, the impact estimation procedures described here could be automated for application on a hand-held calculator or a small minicomputer. This would reduce the length of time needed to evaluate a project from 2-4 h down to less than 15 min. Automating the procedures has five primary benefits:

1. Equilibration of induced and diverted travel could be performed to much stricter tolerances.
2. Faster turnaround time would allow the analyst to make more estimates while varying project and input parameters as a check for sensitivity.
3. The fuel consumption characteristics of a greater number of vehicle types (e.g., small and medium trucks) could be considered.
4. Estimation of life-cycle energy impact would become available without imposing a great time burden on the analyst.
5. The likelihood of human error would be reduced.

As described earlier, most of the components of the quick-response method of assessing energy impacts have been derived from existing complex models or modeling systems. However, the method for deriving the VMT impact of HOV lanes is based on a very limited number of empirical observations. Ongoing work on HOV lane impacts (10,11) is significantly improving the state of the art in modeling these impacts and should be incorporated into the existing set of impact estimation procedures.

Energy consumption data are based on a 1971 report (4) that used road tests of vehicles from model years 1960 through 1968. Overall fuel economy levels have, of course, been factored up so that fleetwide average fuel economy matches current and projected levels. However, the effect of average speed on fuel economy may have changed somewhat in recent years as automobile engines and bodies have been redesigned to be more fuel efficient. This raises the possibility that the curve shown in Figure 2 may not be appropriate for the current vehicle fleet. On the other hand, there is some recent evidence that the basic shape of the curve in Figure 2, including the speed of minimum fuel consumption, is in fact appropriate for newer cars (12). This problem is not specific to the project. Inadequate attention has been paid to this problem in the recent literature, and significant new research in this area is critically needed.

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