Indirect Energy Considerations in Transportation Projects

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ABSTRACT

An assessment is made of the appropriate extent of analysis of indirect energy costs and the overall importance of indirect energy considerations for various types of transportation projects. The approach focuses on the analysis of typical alternatives facing the transportation planner for projects ranging from roadway maintenance to construction of a major rail transit facility. Six categories of indirect energy are defined. Indirect energy costs, along with direct and miscellaneous energy costs, are presented for the alternatives in each case study. Among the projects considered in the case studies are highway widening, roadway construction using different types of pavements, bridge repair as opposed to abandonment, a computerized signalization project, a bus route extension, and provision of dial-a-ride services. Criteria for carrying out an energy analysis and for deciding its appropriate extent for a given project type are discussed fully. The major finding is that the importance of indirect energy costs depends in part on the purpose of the analysis. If the primary purpose is to compare the relative energy costs of two or more alternatives, then consideration of indirect energy in addition to construction energy costs is necessary only if the project involves major highway or transit construction or a choice between pavement types. On the other hand, if the primary purpose is to obtain an accurate figure for the overall energy costs of a specific project, then indirect energy costs must be considered. The paper also indicates that cost-based energy factors, which are easy to use, are as acceptable as materials-based factors. The vital importance of the assumptions made in an energy analysis is emphasized.

Analyzing energy used in transportation projects is relatively recent; it grew out of the energy crises of the past decade. Many studies were undertaken that focused on energy savings; however, they often did not include a full accounting of energy costs. There is a tendency to stop after direct energy costs have been addressed, especially when little guidance exists for treating indirect costs. The nature of indirect energy costs contributes to this tendency; at times they appear to be so removed from the project under analysis that there is a question of whether they should be considered at all. This is particularly difficult when the inclusion of certain indirect costs can change the relative energy efficiencies of alternative projects.

The purpose of this paper is to provide guidelines on the extent of energy cost analysis needed for various project types. Results from various case studies are used to illustrate both the formulation of these guidelines and their application. It should be noted at the outset that this study is primarily concerned with energy costs. No new ground is broken concerning energy factors; factors in widespread use in the literature are used and cited here. This paper indicates the types of projects for which indirect energy costs are likely to be significant and highlights which decisions concerning the approach or the depth of an energy analysis would have significant effects on bottom-line energy costs.

Three guiding principles for selecting the approach and depth of an energy analysis are

1. When alternatives are compared, the energy analyses should be carried out in the same depth and detail for both.
2. The criterion for deciding the appropriate content of the analysis for a given project type is that any further considerations of indirect energy would not change the relative energy efficiencies of the alternatives.
3. If the difference in total energy costs between alternatives is less than 10 percent, the second principle is overruled and a full energy analysis is recommended. This principle recognizes that site-specific circumstances have an effect on energy costs and that a typical-project approach has limited applicability if the resulting energy costs are similar.

Although these principles are logical and straightforward, their application is not always simple. In comparing across modes, for example, different types of indirect energy costs are associated with each mode. The question of which costs constitute a comparable extent of analysis does not always have an obvious answer. Also, there may be other circumstances that make it difficult to judge exactly where the line should be drawn to exclude further types of indirect energy. Nonetheless, despite occasional tricky practicalities, these principles provide sound guidelines for assessing indirect energy costs.

KEY ISSUES

Several major issues underlie the assessment of direct and indirect energy costs. One major issue, the extent of the analysis, has been addressed by the three principles stated previously. Included among the general issues are the approach to analyzing energy costs and the methods used. The question of how to account for a certain type of energy will also arise and should be addressed. The types of projects to be analyzed are also important.

Approaches to energy analysis vary between extremes. At one end, a purely incremental approach considers only the energy obviously expended on a project and ignores indirect costs and savings. At the other end, a total approach traces indirect costs back as far as possible and gives full consideration to external costs and opportunity costs associated with energy use. Most examples in the literature choose a middle ground between these extreme approaches. The principles outlined earlier argue for a middle approach that considers indirect energy costs only to the extent that they affect the relative standing of total energy expenditures for alternative projects. Studies involving systemwide energy use tend to take a total approach. Project-level analyses consider important energy effects beyond the scope of the particular project but do not pretend to be all-inclusive.

Along with the issue of what to analyze is the issue of how to analyze. The two methods most commonly used are the cost-based method (often derived from input-output analysis) and the materials-based method (sometimes called process analysis). The cost-based method is preferable when there are time or data limitations; however, the materials-based method is chosen when accuracy is the primary concern. The monetary savings often associated with actions that have lower energy costs are more obvious under the materials-based method. This is because the cost-based method measures energy cost per dollar spent, and the total dollar amount is either an aggregate estimate (for projects to be built) or a total for one alternative (for projects already finished). When the cost-based method is used it is generally not possible to obtain energy cost estimates broken down by energy type or by project component because energy costs have been expressed at an aggregate level. The materials-based method, which uses disaggregate data, calculates the energy cost per quantity of material needed for each project component; thus it provides a finer level of detail as well as a more accurate total for energy costs.

Many energy analyses measure the local or regional impact of a particular project. Certain project-related indirect energy costs may not be incurred in the region, and it is not clear that such energy costs should be charged to the region's energy accounts. For example, in several case studies the energy involved in manufacturing vehicles is included in the calculations, yet those vehicles were manufactured elsewhere. Is it proper to charge that energy to the region? Other examples are the processing energy or potential heat energy of construction materials such as asphalt or concrete. If these materials are produced in another state, are these energy costs relevant to an analysis of regional impacts? In this paper, energy costs for these categories of energy are calculated and included in project energy costs. The analyst should be aware that a case can be made for charging energy costs of this nature to the place where they are actually incurred as opposed to the place where the project is located.

A final important issue for this paper is how to categorize projects. The main purpose is to provide guidelines for the extent of energy analysis by project type; therefore, the choice of categories is important. The three principles are guidelines for analyzing alternatives. For various types of projects, energy costs are considered for typical alternatives and guidelines are presented for the extent of analysis required for each type of project. Case studies that illustrate the calculations of energy costs for each of these typical alternatives are presented and used in conjunction with other projects in the literature to form guidelines on the extent of energy analysis recommended for each project type.

Where possible, the case studies in this paper have been analyzed using the materials-based method, because a breakdown of energy costs is necessary to determine the appropriate extent of the analysis. An incremental approach is generally sufficient, although all relevant indirect energy costs are included. Before analyzing the case studies, precise definitions of the types of energy to be considered, as well as a clarification of the differences between direct and indirect energy, are necessary.

ENERGY TERMINOLOGY

There are many different ways to categorize energy. A study by Apostolos et al., done at the California Department of Transportation and referred to hereafter as the Caltrans study, distinguished between direct and indirect energy and described two types of indirect energy: central energy use and peripheral energy change (1). Erlbaum et al. followed Caltrans in distinguishing between direct and indirect energy; however, they classified three types of indirect energy: guideway, facility, and maintenance (2). The Asphalt Institute (3) and the American Concrete Paving Association (4) use four categories of energy: materials, mix composition, plant operations, and haul and place. Finally, Halstead defines four types of energy: calorific, processing, transport (hauling), and construction (5).

These examples clearly demonstrate that there is no standard categorization of energy types. Generally, the energy categories used here are a combination of Caltrans and Halstead, with some amplification. The distinction between direct and indirect energy is recognized, and (after Caltrans) direct energy is defined as the energy used to propel or operate a vehicle (1). This energy is also known as propulsive energy, and it is the only type of energy classified as direct energy. Often the actual level of propulsive energy is not of as much interest as the energy changes brought about by the specific improvement.

All types of energy other than propulsive are considered indirect. Indirect energy obviously encompasses a wide spectrum of energy uses, which can in turn be classified according to how indirect they are. Closest to direct energy is the energy used in the construction or implementation of the project. Project construction can give rise to maintenance energy requirements or to the energy use associated with necessary ancillary facilities. Also to be considered is the energy embodied in the materials used. Each category of indirect energy is defined in the following paragraphs.

Construction operating energy is the energy needed to operate construction machinery and perform related activities at the construction site. Closely related to construction operating energy is construction hauling energy. This is the energy used in transporting materials from their point of origin to their point of use. All hauling costs are placed in this separate category because proximity to raw materials is thought to affect total energy costs significantly in certain situations. This method of categorization is not always followed in other studies: often, hauling costs include only the energy cost of transporting materials from point of manufacture to point of use. Note also that although construction hauling energy is used to operate and propel vehicles, it is considered an indirect energy cost because this energy use is a by-product of the project itself not an independent use.

Energy costs arise from necessary maintenance to roadways or guideways, to vehicles, and to other necessary facilities. This is maintenance energy. There is also vehicle manufacturing energy, or the energy used in the manufacture of automobiles, buses, or construction equipment. Processing energy is the energy required to convert various raw materials into usable form. this reflects the energy embodied in a given material. There are standard energy factors for the processing energy per given quantity of asphalt, cement, steel, and so forth. Closely related to processing energy is calorific energy. Calorific energy is the potential energy of a material that could be used as fuel; it measures the heat energy released when the material is completely burned.

Other miscellaneous indirect energy costs that do not appear to fit into any of these categories arise from time to time. However, the seven types of energy (one direct, six indirect) defined here are sufficient to categorize the most important energy costs encountered in transportation projects. This method of categorization can clearly show the relative importance of each type of energy cost.

CASE STUDIES

The results of several case studies are discussed so that the appropriate extent of an energy analysis for a given project type can be determined. Although these case studies do not cover every type of project, they are sufficiently varied to provide an excellent idea of the relative impacts of various energy costs for major highway construction projects, major transit projects, and transportation system management (TSM) actions.

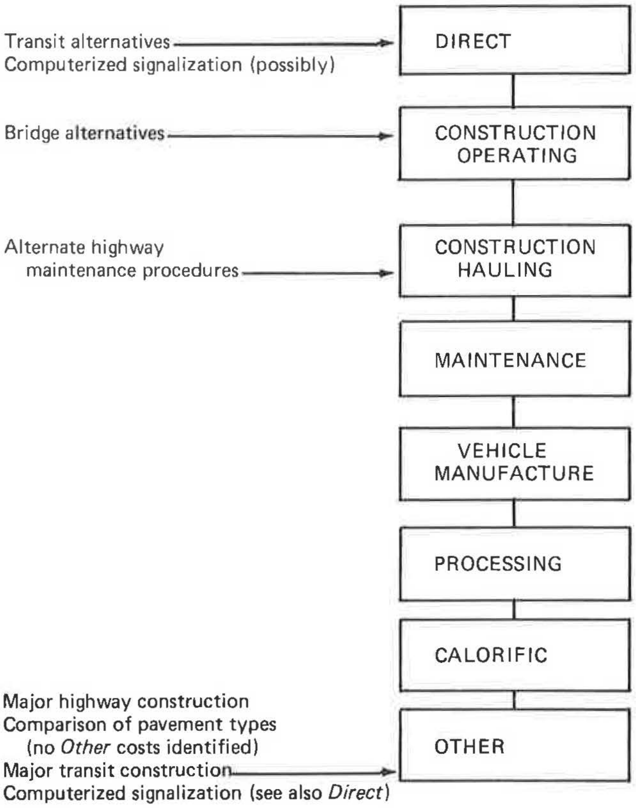
Each case study presents an analysis of alternative projects. The three guiding principles cited earlier are applied to each case study to determine the point at which further consideration of indirect energy does not affect the relative positions of the alternatives in terms of their energy costs. The case studies address the following seven alternatives:

- Highway widening versus "no build,"
- Highway construction: asphalt versus portland cement concrete pavement,
- Rail rapid transit versus freeway equivalent,
- Alternate highway maintenance procedures,
- Bridge repair versus abandonment,
- Highway TSM action: computerized signalization versus null option, and
- Transit service: fixed route versus demand responsive.

For each case study, the alternatives are described briefly, then the results of the energy calculations are discussed. A summary of annualized direct and indirect energy costs for each alternative is presented in Table 1. The relative importance of each energy category is assessed for each alternative, and the appropriate extent to which an analysis should be performed is shown in Figure 1. Consult Boyle (6) for detailed calculations.

TABLE 1 Direct and Indirect Energy Costs for the Seven Case Studies (annual BBtu's)

Case Study	Direct	Indirect	Total	Construction Related, %
Highway widening				
Widen	373.8	259.0	596.8	0.1
No-build	376.1	268.8	644.9	0.0
Highway construction				
Asphalt pavement	–	16.4	16.4	14.8
Cement pavement	–	10.7	10.7	74.2
Transit vs. highway				
BART	1,950	2,943	4,893	42.0
Freeway	2,859	1,667	4,526	3.7
Pavement maintenance				
Recycling	–	0.6	0.6	22.2
Replacement	–	0.8	0.8	20.1
Standard overlay	–	0.3	0.3	15.0
Bridge				
Repair	0	1.6	1.6	100.0
Abandonment	37.3	30.4	67.7	0.0
Traffic flow				
Computerized signalization	127.8	94.2	222.0	0.7
Null option	139.5	92.1	231.6	0.0
Transit service				
Route extension	0.8	1.1	1.9	0.0
Dial-a-ride	1.7	1.6	3.3	0.0



Note: The types of energy listed proceed from the most direct type to the least direct. For a given case study, all energy categories at or above the energy type must be considered.

FIGURE 1 Recommended extent of energy analysis for the seven case studies.

Highway Widening Versus "No Build"

The highway widening case study was taken from the Caltrans manual (1) and involves a proposal to widen a four-lane arterial to six lanes for 5.6 miles. The alternative is to do nothing, which will mean congestion on the road in the future during peak hours. Average daily traffic (ADT) is anticipated to be 25,000 vehicles (both directions). Energy costs associated with construction and materials are much less than direct, maintenance, and vehicle manufacture energy costs. These costs primarily reflect the costs of operating a vehicle (or 25,000 vehicles in this case) and are 8 percent higher for the no-build alternative because of the increased energy costs associated with congestion. Because a difference of this magnitude cannot be considered significant, given the number of assumptions, consideration of all indirect energy costs is recommended. The soundness of this recommendation can be illustrated by examining one of the underlying assumptions more closely. If one were to assume that a 10 percent increase in ADT would result from widening the highway, total energy costs would then be 1.7 percent higher for the widening alternative (6). Similar variations in local conditions can easily cause minor shifts in the relative energy efficiencies of the alternatives under consideration; the third guiding principle is intended to guard against misleading conclusions that do not take local conditions into account.

Asphalt Versus Portland Cement Concrete Pavement

The second case study addresses the use of asphalt or cement pavements in highway construction. Data for this case study are derived from a Connecticut Department of Transportation (ConnDOT) report (7). ConnDOT studied the energy costs of standard and recycled portland cement concrete (PCC) pavements placed on I-84 near Waterbury and the energy costs of standard and recycled asphalt concrete (AC) pavements placed on Route 4 near Burlington. Because the ConnDOT study did not calculate total energy costs but instead used costs per ton or per cubic yard, the results can be adapted to a project of a given size. This case study examines the energy costs of paving a four-lane highway for 10 miles with conventional asphalt concrete and with conventional portland cement concrete.

Roadway maintenance and calorific energy costs are significant for the asphalt alternative; however, the high processing energy requirements of portland cement concrete account for most of the energy costs in the PCC alternative. If the analysis were limited to processing energy, the AC pavement would have a lower energy cost (2.7 percent lower than the energy cost of the PCC pavement). Consideration of the calorific energy in the asphalt, however, makes the total energy cost of the AC pavement 54 percent higher than that of the PCC pavement.

It should be noted that there is considerable debate between the Asphalt Institute and the American Concrete Paving Association (ACPA) over the appropriate treatment of calorific energy costs (3,4). The Asphalt Institute's argument is that when the decision is made to use asphalt as a construction material rather than as a fuel, the energy it contains is no longer available and should not be considered. ACPA emphasizes the fact that calorific energy is available in asphalt and argues that decisions on how to use asphalt do not change that fact.

Many studies concerned with the marginal energy costs associated with a specific project or with localized energy effects do not consider calorific energy costs; the ConnDOT report from which this case study is adapted is among those studies. A complete accounting of indirect energy costs, however, should include calorific energy, particularly when it can change the relative energy costs of two alternatives; therefore, a full energy analysis is recommended.

Rail Rapid Transit Versus Freeway Equivalent

The third case study addresses the energy costs associated with the construction of BART in San Francisco. The alternative to BART is referred to as the freeway alternative, and it takes into account the energy costs of freeway construction and automobile travel presumed to take place in the absence of BART. This case study is based on a study by Lave of the energy impact of BART (8), even though some of Lave's assumptions were found to be untenable and have been changed (6). Because of the difficulty in obtaining accurate totals of quantities of materials used in rapid rail construction as well as energy factors associated with each material, Lave's cost-based methodology is followed. The construction of BART was so energy intensive that it overshadowed savings in propulsive, maintenance, and vehicle manufacture energy. However, the difference in total energy costs between the alternatives is only 8 percent, indicating that local factors are likely to determine the relative energy efficiencies of rail transit versus new freeway construction. A full energy analysis is, therefore, recommended.

Others argue that further energy considerations or different assumptions can actually make transit's energy costs lower than those of the freeway alternative. Usowicz and Hawley argue that the energy required to construct BART was not nearly as great as reported by Lave and was also lower than the figure used here (9). Pushkarev and Zupan claim that BART's energy costs were unusually high because of a reliance on complex technology and that construction of a rail transit system can save energy over the medium term (10).

This wide disparity in estimates of energy used needs to be emphasized. Lave indicates that a rail transit system such as BART is much more energy intensive than a comparable freeway alternative. This analysis indicates that both alternatives are roughly equal in terms of annual energy costs. Usowicz and Hawley show BART to be much more energy efficient than the freeway alternative. Pushkarev and Zupan argue that rail transit is energy efficient, but that BART is not the system to prove it. This disparity reflects the heavy reliance of each analysis on assumptions necessitated by the absence of a good data base.

It is no surprise that Lave reaches a conclusion completely opposite from that of Usowicz and Hawley when one analysis estimates that 74.7 lane kilometers of roadway are necessary in lieu of BART and the other estimates 198.4 lane kilometers of roadway plus a bridge and a tunnel. New rail transit construction in Washington, D.C., Baltimore, Atlanta, and other cities should broaden the data base and lead to a standardization of assumptions.

Alternative Highway Maintenance Procedures

The fourth case study analyzes the energy costs of three alternative maintenance procedures and is drawn from a study carried out in Sherburne, Vermont (11). The first alternative is to recycle the top 4 in. of asphalt pavement surface. The second alternative involves removal, disposal, and replacement of 3 in. of pavement. The third alternative is to use standard maintenance procedure and overlay 1.5 in. of asphalt pavement. These alternatives are applied to a 1.5-mile stretch of US-4, a 40-ft-wide roadway.

The relative energy efficiency of the three alternatives is identical for each category of energy: standard maintenance procedure has the lowest energy cost, followed by recycling and replacement. The total energy cost of replacement is 30 percent higher than that of recycling, which in turn is more than twice the energy cost of the standard maintenance procedure. Consideration of construction operating and hauling energy costs is sufficient to determine relative overall energy costs for maintenance alternatives. The energy costs depend ultimately on the amount of asphalt or AC pavement required. Thus, even through calorific energy costs account for the bulk of overall energy costs, their exclusion would not change the results in terms of overall energy efficiency. As the Vermont report states, in order for the costs (both monetary and energy) of the recycled alternative to be justified, it must reduce future maintenance requirements.

Bridge Repair Versus Abandonment

The fifth case study is drawn from an FHWA report prepared jointly by the New York State Department of Transportation (NYSDOT) and the Genesee Transportation Council (Rochester, New York) (12) and involves a bridge over the New York State Thruway (I-90) in Monroe County. The bridge, originally built in 1953 and repaired several times since, has deteriorated to the point where further maintenance is considered pointless. The first alternative is to repair the bridge; the second is to close the bridge and divert traffic. The detour would result in an additional travel distance of 1.85 miles. Average speed is 45 miles per hour and annual ADT is 13,000 vehicles, 5 percent of which are trucks (4 percent light trucks and 1 percent heavy trucks are assumed). Because details on quantities of materials used on the bridge structure are unavailable and difficult to synthesize, the cost-based method is used in this case study. Energy-per-dollar factors have been developed in a previous NYSDOT report (2). This case study provides an excellent example of how to proceed when reliable estimates of materials and quantities used are not available. In addition, this case study differs from the others in that it focuses principally on marginal energy costs.

Results of the analysis indicate that the propulsive energy costs of the abandonment alternative are much greater than the annualized construction costs of the repair alternative. The relative energy costs become clear when construction operating energy is taken into consideration. It appears that unless the detour is very short and construction costs very high, the additional propulsive energy induced by a bridge closing is likely to outweigh the energy needed to rehabilitate the bridge.

Computerized Signalization Versus Null Option

The sixth case study examines a highway-related TSM action and is drawn from a report prepared by NYSDOT for UMTA (13). An urban radial arterial 3.7 miles long has its noninterconnected pretimed signals replaced by an advanced computer-based control system. There are 10 signals on this length of the arterial. Daily vehicle miles of travel (VMT) is 64,786 and daily vehicle hours traveled (VHT) is 3,714. The improvement will decrease travel time by 25 percent and induce 5 percent additional traffic. The project is proposed for 1983 with a cost in 1980 dollars of $2.5 million. The alternative to the signalization project is to do nothing. Although propulsive, maintenance, and vehicle manufacture energy costs are all slightly higher for the null option, there is only a 4 percent difference in overall energy costs.

The third guiding principle dictates that the results are too close to allow a clear statement of relative energy efficiencies, so a full energy analysis is recommended for projects similar to this case study. However, it is interesting to note that there is only a slight absolute difference [2 billion British thermal units (BBtu's)] in indirect energy costs between the two alternatives. Additionally, both maintenance and vehicle manufacture energy costs are dependent on the same factors that influence propulsive energy. Together these facts imply that the difference in propulsive energy costs is the most significant factor in determining overall relative energy efficiency.

Fixed Route Versus Demand Responsive

The final case study examines alternatives for expansion of transit service to growing suburban developments. The first alternative is to extend an existing transit route for a distance of 2.5 miles. The second alternative is to provide dial-a-ride service, which can act as a feeder to the existing transit line as well as provide intrasuburban mobility. The suburban town has a population of 21,000; 15,000 people are within 0.25 mile of the main arterial along which fixed-route service would operate. Fixed-route services would be offered on a 15-min headway in peak periods, a 30-min headway in the off peak, and a 60-min headway in the evening. The dial-a-ride service would operate several 10-seat vehicles over the course of the day.

Vehicle requirements, anticipated ridership, and additional VMT have been calculated using techniques developed by Alan M. Voorhees and Associates (14). When these have been determined, energy calculations may be carried out. Overall energy costs for the dial-a-ride option are 75 percent greater than energy costs for the route extension alternative. Propulsive energy is the major category of energy costs for both alternatives, and only propulsive energy need be considered in an analysis of alternatives of this type.

SUMMARY

The appropriate extent of analysis of indirect energy costs for various types of transportation projects has been addressed in this paper. An approach was adopted that focused on the analysis of typical alternatives facing the transportation planner for projects ranging from roadway maintenance to construction of a major rail transit facility. Although the difficulty of isolating typical alternatives and projects is recognized, it was believed that providing examples of alternative analyses would be more useful in providing a context for the analysis than simply examining individual projects.

This document is a synthesis of existing work. It has the advantage of applying standardized methods and factors to case studies drawn from a variety of reports, but these methods and factors are not original. Caltrans (1), the Asphalt Institute (3), Halstead (5), and previous NYSDOT studies (2,15,16) are the primary sources for these methods and factors. A complete list of factors may be found in Boyle (6). The point that energy assumptions play a key role in the analysis cannot be overstated; indeed, it deserves to be the first conclusion drawn in this study.

Extent of Energy Analysis

The appropriate extent of energy analysis for each case study is summarized in Figure 1. Indirect energy costs should receive full consideration in the analysis of major highway and major transit construction projects and in cases where the alternatives involve use of different pavement types. In the widening, pavement type, and BART case studies of relative energy efficiencies, consideration of indirect energy costs led to a conclusion different from that indicated by consideration of direct energy costs only.

Consideration of indirect energy costs for minor highway projects is marginal. Although calorific energy was a major component of total energy costs for all three alternatives in the roadway maintenance case study, its exclusion does not change the outcome of the analysis. Therefore, relative energy efficiencies can be clearly established by considering only propulsive and construction energy costs. In the signalization case study, consideration of indirect energy costs beyond construction energy does not influence the results. The results indicate that there is no significant difference between the alternatives in energy terms; direct and construction energy costs are sufficient for determining the relative efficiency of the alternatives.

Indirect energy costs beyond construction energy do not need to be considered in bridge rehabilitation and minor transit projects. For the bridge rehabilitation versus abandonment case study, length of the detour, traffic volume, and construction costs are sufficient to determine relative energy costs. In minor transit projects of a TSM nature that do not involve construction, the change in transit VMT appears to be the determining factor.

Relative Importance of Indirect Energy

Table 1 gives the direct and indirect energy costs associated with the alternatives considered in the seven case studies. In each case study, indirect energy accounts for at least 40 percent of overall energy costs for at least one alternative. This indicates that indirect energy costs account for a significant portion of total energy costs.

This conclusion appears to contradict previous conclusions that view indirect energy as marginal or irrelevant in all except major construction projects and those involving a choice between pavement types. A closer examination of Table 1 reveals that although indirect energy costs are often large, their effect on the relative energy costs of the alternatives in a given project is important less often. This can be seen in Figure 1, which shows the recommended extent of analysis for each case study. In many cases, maintenance and vehicle manufacture energy are the major components of indirect energy costs (6). Energy costs of maintenance and vehicle manufacture are affected by the same factors that affect direct energy costs (principally VMT). Thus, when examining the relative energy costs of alternatives, consideration of maintenance and vehicle manufacture energy tends to reinforce the relative direct energy costs and indirect energy does not appear to be important. However, when examining the absolute energy costs of alternatives, maintenance and vehicle manufacture energy costs account for a significant portion of overall energy costs and appear to be important. This leads to the conclusion that the importance of including indirect energy depends on the purpose of the analysis. In a relative analysis, indirect energy costs are important under the conditions outlined previously. In an absolute analysis of the bottom-line energy cost of a specific project, indirect energy costs are important.

The final column of Table 1 gives the percentage of total energy costs accounted for by construction operating, construction hauling, and processing energy. This column highlights the discussion earlier in this paper of the benefits of the materials-based and cost-based methods of analysis. Recall that under the cost-based method, these three energy categories were combined in a single Btu-per-dollar construction energy factor, whereas the materials-based method treats each separately. The materials-based method is considered more reliable; however, the cost-based method is easier to use.

The final column in Table 1 indicates that construction energy (including the three categories of construction operating, construction hauling, and processing energy) is not generally a significant component in overall energy costs. Construction energy accounts for more than 25 percent of total energy in only three of the fifteen alternate projects considered in the case studies. Moreover, for two of these three projects, the cost-based method was used because of the lack of detailed data on quantities of materials used. Construction energy was a significant portion of total energy costs in only one of the seven alternatives where the materials-based method was used. This suggests that, when construction energy costs are low, the increased accuracy derived from use of the materials-based method may not be worth the additional effort and that, for most purposes, the cost-based method and the materials-based method are equally acceptable for calculating construction-related energy costs. This supports previous studies by Caltrans (1) and Erlbaum (2), both of which used cost-based energy factors exclusively.

CONCLUSIONS

A summary of conclusions follows.

1. The importance of indirect energy costs depends in part on the purpose of the analysis.
2. In an analysis that compares the relative energy costs of two or more alternatives, indirect energy costs are important for major highway and transit construction projects and for projects involving alternative types of pavement. In these situations, a full energy analysis that encompasses all forms of indirect energy is recommended. For other types of projects, consideration of indirect energy beyond construction energy costs is not necessary.
3. In an analysis of overall energy costs of a specific project or projects, indirect energy costs are important and must be considered.
4. The cost-based method and the materials-based method are equally acceptable for calculating construction-related energy costs.
5. Because of the rudimentary nature of an energy analysis, the assumptions made are vitally important. Care must be taken to ensure that the most reasonable assumptions are made.

There is always the question of whether a given case study or a given alternative is indeed typical. Although the range of projects considered here is fairly broad, there are certainly many alternatives that either do not fall neatly into one of the case studies analyzed here or have atypical characteristics. The informed analyst can recognize problems such as these and make the necessary adjustments in the course of the analysis. With the various energy methods and factors provided by Boyle (6), the analyst should be able to perform the necessary energy calculations for those atypical projects and alternatives.

ACKNOWLEDGMENTS

The work reported in this paper was funded by a grant from the Urban Mass Transportation Administration. David T. Hartgen gave valuable advice concerning the overall structure of the paper; Janis M. Gross reviewed it thoroughly and provided helpful comments; and Nathan S. Erlbaum assisted in searching the literature for the energy factors, assumptions, and case studies that were used. The paper was prepared by Sue Carbone, Tedi Toca, and Tammy Zitzman. The author expresses his gratitude to all these people.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.