FINAL REPORT

ESTIMATING USER COSTS AS A BASIS FOR INCENTIVE / DISINCENTIVE AMOUNTS IN HIGHWAY CONSTRUCTION CONTRACTS

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ABSTRACT

The Virginia Department of Transportation (VDOT) occasionally includes an incentive/disincentive for early completion (I/D) in its construction contracts. This report presents the results of a project to identify procedures that would (1) enhance the effectiveness and enforceability of the I/D provision and (2) reduce the staff time and effort necessary to determine the need for an I/D and to calculate an appropriate per-day dollar amount. The researcher first reviewed the relevant literature pertaining to construction contracts and to road user cost calculation, and then evaluated the available user cost methodologies, especially computer software. Next, the researcher surveyed the current use of I/D provisions in Virginia and other states, and described VDOT's current project development process, with special emphasis on the user cost data that are typically generated during that process.

The report makes five conclusions. First, various forms of I/D, though known by a variety of names, are fundamentally similar. Second, use of an incentive rather than a disincentive alone enhances the enforceability of the disincentive clause, though it *may* increase the final cost of the contract. Third, cost-plus-time bidding enhances the effectiveness of the incentive clause and the enforceability of the disincentive clause. Fourth, the end of the design public hearing is a logical point for VDOT to judge the need for an I/D. Fifth, road user cost savings calculated from the output of the Highway Capacity Software already in common use in VDOT forms a legally sound justification for a per-day dollar I/D amount.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) routinely includes a liquidated damages clause in its construction contracts to recover the engineering and administrative costs incurred when a contractor fails to complete a highway project on time. The department currently uses a "Schedule of Liquidated Damages," published in its *Road and Bridge Specifications*, [1] to calculate the appropriate amount of liquidated damages per day for each contract. This schedule is based on VDOT's historical experience with project delays. VDOT only rarely adds an incentive/disincentive (I/D) clause to motivate contractors to stay on or ahead of schedule. VDOT personnel base the per-day value of the I/D on road user cost savings or on other variables. On those occasions where the amount is based on road user cost savings, VDOT personnel consult the relevant traffic engineering literature and calculate an appropriate per-day I/D amount.

Making VDOT's current case-by-case approach to incentive/disincentive provisions more systematic would yield two advantages: it would make VDOT contracts less vulnerable to legal challenge, and would reduce the personnel hours required to calculate road user cost.

U.S. contract law states that I/D amounts must be based on reasonable estimates of the costs attributable to delayed completion of a contract. FHWA *Technical Advisory T5080.10* requires that I/D amounts be "based upon estimates of such items as traffic safety, traffic maintenance, and road user delay costs." [2] In a decision described in the September 27, 1990, edition of *The Engineering News Record*, the Alabama Supreme Court invalidated the disincentive assessments in two contracts in part because the state failed to demonstrate that the disincentive amounts were related to road user costs. [3] By following no standard procedure in calculating I/D amounts, VDOT may run the risk of seeing a tardy contractor challenge and invalidate the I/D clause in one of its contracts in court. Derivation of a per-day I/D amount from user cost estimates, according to a method based on accepted engineering standards, would guarantee that every I/D clause in a VDOT contract meets the criteria that the FHWA and the courts currently require.

Under current procedures, VDOT engineers construct a new cost estimation method each time an incentive/disincentive clause is required. This practice devours skilled employees' time and leads to inconsistent results. The introduction to the Highway User Cost Accounting (HUCA) software user's manual describes a similar situation in New York State: "...many of the calculations in the programs are performed very infrequently by any one analyst, with the result that most analysts are not knowledgeable in the theoretical basis for the calculations. [Furthermore], when managers have given the same...analysis assignment to a number of analysts, each analyst would develop results based on ad hoc calculation parameters, with the result that the...answers managers received were dependent on the analyst selected to accomplish the calculations." [4] A standardized method would enable personnel of varying skill levels to calculate appropriate I/D amounts quickly and consistently, saving the state both time and money.

PURPOSE AND SCOPE

An initial study of the I/D problem for VDOT by J.C. Huckabee included a discussion of the legal status of I/D provisions, a detailed examination of the methodological basis for user cost analysis, a survey of the use of liquidated damages and I/Ds in the 50 states, and a review of the user cost software available as of mid-1991.[3] This report proceeds from the Huckabee study, producing guidelines that the Construction Division may follow when including an I/D clause in a highway construction contract. In particular, the report describes how road user costs may be calculated to justify a per-day (or per-hour) I/D amount.

This report does not develop criteria to help VDOT managers decide whether or not to employ an I/D provision. The cost-effectiveness of an I/D depends on the alternative uses of a dollar from the Transportation Trust Fund (a subject beyond the scope of this report), and on the contractors' expected behavior with and without the I/D, a subject treated below only in qualitative terms. The project engineer should carefully assess these two factors when determining whether an I/D clause is appropriate.

RESEARCH METHOD

This project proceeded in two phases. The first phase built upon the findings of the previous Huckabee study in several increments. First, the researcher reviewed some of the relevant literature pertaining to construction contracts and surveyed the principal varieties of I/D provision. Second, he examined the theoretical principles that govern the application of any user cost method to the calculation of incentives for early completion. Third, he surveyed road user cost literature and software, especially products that have become available since 1991. Fourth, he described the current use of I/D provisions in Virginia and in some other states.

The second phase involved an evaluation of the available user cost methodologies, with reference to those activities in VDOT's current project development process that generate data useful to road user cost analysis and those that indicate public interest in the impact of the proposed construction. The results of this evaluation appear below. They recommend policy and procedure changes to incorporate decisions about I/D use seamlessly into the pre-construction process and to make the I/D more effective. They also describe a road user cost-based method that VDOT can use to calculate incentive/ disincentive amounts. Finally, promising methods for future consideration are recommended.

RESULTS AND FINDINGS

Highway capacity changes during an improvement project: capacity is “normal” before road work begins, it is lower while road work is in progress, and it is higher after the project is completed. One of the goals of any state department of transportation (DOT) is to shorten the intermediate low-capacity state as much as possible, and to hasten the arrival of the final high-capacity phase. The term incentive/disincentive (I/D) in this report refers most broadly to language in the construction contract that links the total value of the contract to the road builder’s success in achieving these goals.

Forms of I/D

Several types of incentive/disincentive clauses exist. The categories and the terms used to denote them vary from state to state. Two chief distinctions are (1) whether a disincentive for late completion is provided alone or in combination with an incentive for early completion, and (2) whether or not an incentive/disincentive is combined with cost-plus-time (A+B) bidding. Although the details influence the effectiveness of every I/D clause, there is no fundamental difference among the various types of I/D provision. An incentive clause that assumed, or allowed for, repeated closing and opening of lanes during the construction period would probably be denoted a “lane rental” in most parts of the country, while one that assumed a single reopening date would probably be denoted an “incentive for early completion.”

Impacts of I/D

An I/D clause of any type tends to increase the expected cost of a construction project, for a variety of reasons. An I/D clause, especially one that includes an incentive, almost invariably reduces the duration of work under the contract. Recent surveys show that contractors working for an incentive almost always made or beat the target date. Essentially, when a DOT uses an I/D clause, it usually trades time for money. Incentives may be expected to raise the total payout on a given construction contract, other things being equal. Careful calculation of the contract completion time, or recourse to A+B bidding, may help to minimize the cost impact

Use of an incentive for early completion, rather than a disincentive alone, also appears to have an impact on contract enforceability. Legal research indicates that a disincentive provision combined with an incentive is less likely to be construed as an arbitrary penalty than a simple disincentive provision, and therefore is less vulnerable to legal challenge.

A+B bidding appears to improve the average road builder response to an I/D provision and also to improve its enforceability. A+B bidding in combination with an I/D reportedly elicits more innovative bids than an I/D provision does alone (although there is no financial reason why this should be so). A+B bidding also removes the legal possibility that a contract claim, based on the contention that the contract time was unreasonably short, will void a disincentive assessment. Other contract alternatives that place even more responsibility on the contractor, such as design-and-build, would also provide protection against a claim based on unreasonably short contract time.

The State of the Art and the Practice in Calculating Road User Costs

None of the models currently available perfectly identify road user costs. However, a user cost calculation based on the1985 *Highway Capacity Manual* (*HCM*) is accurate enough to form a sound basis for a per-day or per-hour incentive/disincentive. Standard HCM methods calculate travel time savings using simple linear relationships between operating costs, miles travelled, and mean speed. The model can use a number of authoritative estimates of accident costs to calculate this portion of user cost. Appendix A describes how to use portions of this model for the purpose of determining an I/D amount.

Both state-of-the-art and standard practice for estimating the value of time savings to road users are based in large part on two sources. These are the 1985 *Highway Capacity Manual* (*HCM*), sometimes incorporating the 1992 and 1994 revisions, and the 1977 AASHTO *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements* (the *"Red Book"*), whose methods were updated and built into the MicroBENCOST software package in 1993. The 1982 and 1992 editions of the ITE *Transportation and Traffic Engineering Handbook* are cited less frequently. Although some variation in opinion and practice exists on some components, substantial agreement about how to treat speed-flow relationships and intersection delay patterns makes the calculation of time cost savings straightforward. [22, 31, 32]

The state of the art in calculating vehicle operating cost is ill-defined. The developers of the MicroBENCOST package in 1993 relied heavily on the results of a 1982 study by Zaniewski et al. [40] while acknowledging that these results did not suit their needs ideally. A recent journal review asserted that all of the current VOC models are inadequate.[42] Samples of recent user cost calculations from a few state DOTs indicate that a simple approach prevails, tying the components of operating cost to miles travelled, mean speed, and vehicle type. [4, 64]

The state of the art in estimating accident costs is undergoing rapid change. Agreement is growing that the formerly numerous and popular accident models implicitly based on random normal distributions (i.e., linear or loglinear least-squares regressions) do not provide a good fit. Models based on Poisson, Logistic, or other distributions are superceding these. Several different authorities publish accident cost statistics, using two or three different systems of classification. Some state DOTs forecast accident rates from regression equations like those mentioned above. Other states, skeptical about the value of accident models estimated on national or even statewide accident statistics, forecast the impact of highway improvements on accident rates incrementally using accident reduction factors (ARFs). Among the fifty state DOTs, the estimated costs of fatalities, injuries, and property-damage-only (PDO) accidents are based on at least ten different authorities whose estimates differ from one another by as much as a factor of four.[21, 45]

Both the state of the art and the state of the practice in calculating the quantity and dollar value of pollutant emissions, be they runoff, particulates, or greenhouse gases, is admitted by practitioners to be fairly primitive. The Vermont Agency of Transportation has used a formula to value the change in air quality resulting from a highway improvement, but most DOTs and most discussions of user cost in the literature decline to attach a money value to auto emissions.

Current Use of I/D

Among state DOTs, use of the disincentive for late completion alone appears to be rather more common than one combined with an incentive for early completion. A large majority of the contracts in which some type of I/D clause is included involve work on a bridge or other "bottleneck" where a high-capacity detour is infeasible.

The concerns that lie behind the demand for an I/D clause are sometimes not related to the road user cost impacts of the construction project. However, road user cost may justify an incentive/disincentive big enough to gain the contractor's attention even in cases where other, less quantifiable issues dominate.

The literature suggests that state DOTs prefer opening a road on schedule to reducing payments to the contractor. State DOTs' use of the I/D clause suggests that they seek to set the I/D/ amount at a level sufficient to motivate the contractor—even if a particular user cost calculation supports a different dollar amount. An explicit acknowledgement of this goal appears among MDOT's criteria for use of special liquidated damages (i.e., use of a disincentive alone): the amount must be "substantive enough to cause the contractor to follow the schedule."[10] The amount of the disincentive cannot appear to be arbitrary, however, as the courts will not uphold it.

Some state DOTs appear to use discretion in determining how many cost elements to include when calculating an I/D amount. For example, during 1994-1995 the Vermont AOT went to the effort to calculate fuel consumption and air quality costs for just one of four I/D clauses.[64] The Colorado DOT explicitly recognized the existence of operating and accident cost components but chose to ignore them when setting the dollar amount in a lane rental clause.[18] These experiences suggest that sometimes the travel time cost, usually the largest and simplest cost to calculate, justified an incentive amount that the project engineer believed was sufficient to induce good contract performance, obviating the need for further cost calculations. The VDOT user cost worksheet (Figure 5) explicitly allows the calculated amount to be reduced to a "reasonable" level.

For the last several years, VDOT has awarded 8-9 contracts that use an I/D provision. In none of these did the disincentive have to be assessed. In general, the decision to use an I/D came late in the planning process, usually after public concerns were raised about the disruption the project would cause. The process did not always allow sufficient time for calculating road user costs to justify the decision.

The design public hearing is a logical point to judge the need for an I/D clause. During the development of the typical large (one- or two-hearing) VDOT construction project, sufficient information to determine whether the project is a likely candidate for an I/D clause becomes available at the conclusion of the design public hearing stage. This occurs 3-24 months before the Construction Division receives the "first submission" package from the Location and Design Division (L&D). The "first submission" package will often include a traffic analysis based on the methods of the *Highway Capacity Manual* (*HCM*). It will seldom contain any other data for a user cost calculation.

Desirable Properties of a Standard Method

A standard method for calculating I/D amounts must balance several goals simultaneously:

- It must be rigorous and accurate, as the state of the art permits.
- It must be easy for the users to understand and apply.
- It must be convenient; to the extent possible it should “piggyback” on existing project activities, using data already available, so that it requires little additional effort.
- It must be applicable to a high proportion of the cases where an I/D clause is wanted.

No one method can be applicable in all cases where an I/D clause is desired, because the public interest that the clause is to reflect varies from one highway project to another. Furthermore, because the amount of new data collection and analysis that can be justified will vary for projects of different sizes, the availability of data at the time the contract is written may constrain the choice of methods. However, the HCM output can be tailored to fit a variety of situations, as can MicroBENCOST. Appendices A and B describe how these models may be applied to determine road user costs on which to base an I/D amount.

DISCUSSION

Contract Literature

A small but useful body of contract literature discusses the legal and engineering issues that I/Ds raise, and includes surveys and case studies of I/D use.

Forms of Incentive/Disincentive

A single principle lies behind every type of I/D clause. The simplest construction contract specifies the work to be performed and the price to be paid for it, leaving claims attributed to variations from the unique specified outcome to be settled through administrative or legal processes. I/D clauses contractually make payment amount contingent on variations in the outcome.

The most common types of time-based I/D are liquidated damages, disincentives for late completion and incentives for early completion, and lane rentals. However, a contract provision that is called a “disincentive” in one state might be called “liquidated damages” in another, as the terminology by which I/D clauses are described varies somewhat from state to state. The taxonomy below identifies the various forms by their most widely-used names.

Liquidated Damages

The liquidated damages clause dictates a payment reduction, typically assessed on a per-day basis, for a schedule overrun. Liquidated damages normally represent the administrative, engineering, supervisory, and inspection costs, and other expenses that the state highway agency incurs when a construction project runs late. The cost impact on the motoring public is generally not considered. The clause never provides a reward for early completion. [1, 3, 8]

Disincentive for Late Completion / Incentive for Early Completion

The disincentive clause dictates a payment reduction, typically assessed on a per-day basis, for the tardy completion of construction or of some intermediate milestone, such as the (re)opening of the road to traffic. The incentive/ disincentive clause dictates a reduction as above or a bonus, also typically assessed on a per-day basis, for the early completion of construction or of some intermediate milestone. The clause often sets a cap on the size of the incentive payout (but not the disincentive). The section of this report, "Current Practice in Virginia" describes a variety of deviations from the typical case.

I/Ds have been acceptable in federal aid highway projects since 1984.[5] The FHWA currently prescribes that I/D amounts be "based upon estimates of such items as traffic safety, traffic maintenance, and road user delay costs." [2] This definition would appear to include money valuations of user cost impacts; it does not clearly encompass redistributional impacts. In practice, incentive/disincentives represent a variety of impacts, among which road user cost savings are usually included. [3]

Lane Rentals

The lane rental concept was first developed and implemented by the British Department of Transport in 1983. [9] The lane rental clause assesses a rental fee against the contractor, typically on a per-lane per-hour basis, for the length(s) of time that a contractor closes one or more lanes of an existing road. A fee based on the estimated hours of closure is incorporated into the contract specifications, so that if the work is completed on time the contractor will be paid the bid price. The user cost and/or redistributional impacts that result from the disruption of traffic form the basis for the lane rental fee. [9, 10]

The terminology to describe these alternative special contract provisions is far from uniform among the states. In actual usage, some state DOTs have employed "liquidated damages" or "special liquidated damages" to account for impacts on the motoring public, and others have used "incentive/discincentives" that ignore user cost.[3,11] As far as function is concerned, whether the penalties for late completion are justified by agency costs, road user costs, or other considerations matters nothing to a contractor. Likewise, a provision for early reopening of traffic does not differ qualitatively from a lane rental provision.

Court rulings and FHWA policy do appear to draw distinctions among these provisions. Liquidated damages should represent costs to the government, and I/Ds or lane rentals should represent costs to the public. Neither type of incentive may be calculated without reference to one of these costs. Further, although assessment of damages for harm that the facility owner (in this case, the DOT) suffers as a result of late completion has a long history in contract law, and FHWA accepts routine liquidated damages clauses, FHWA guidelines imply that I/Ds are to be used only for critical projects—or phases of projects—where delays must be minimized.[12,2] FWHA Technical Advisory 5080.10 also recommends that a Critical Path Method Schedule be approved prior to the state of work on "federal-aid project[s] whose completion date is reinforced by an I/D clause." Having noted these distinctions, in this report, the term "incentive/ disincentive" generally denotes any payment adjustment contingent upon the completion date.

Impact on Contractor Bidding and Performance

An I/D clause allows the state highway agency to "buy" additional benefits for the motoring public by spending additional public funds on the construction contract, and possibly by investing additional staff time. Calculating the correct size of the incentive/ disincentive ensures an economical trade-off between road user benefits and DOT costs: that is, a reduction in road user costs that exceeds in dollar value the additional contract payouts and DOT staff hours that it entails.

Impact on Construction Bids

Use of the I/D clause probably causes construction bids to rise. It transfers some risk from the state to the contractor. Many builders will perceive that they must adjust their project management practices in order to bring under their control all of the factors for which the I/D clause holds them newly responsible. If contractors feel that the I/D clause has imposed too much additional risk on them, they will not bid on the project. Those who do submit bids will quote a slightly higher price to assure a higher return in exchange for the higher risk. Furthermore, contractors bidding on contracts with an I/D clause often build in higher labor rates to pay for overtime and night work in order to meet the completion date.[14]

Use of the incentive provision (as opposed to use of the disincentive alone) has drawn the criticism that it raises the final cost of highway construction projects too much. [15,] Some of the criticism originates in discomfort at the resulting unavoidable cost uncertainty. Often, it originates in suspicion that the contracts specify unnecessarily generous completion dates. A 1991 survey of I/D use by the Iowa DOT found that a contractor working under an incentive almost always beat the target completion date, and that 40 percent of the time the contractor earned the maximum incentive payment allowed under the contract provision. NCHRP Synthesis 215 observes, "accurate estimates of contract time are a key to success when using the I/D method." Combining the I/D contracting method with the A+B bidding method is suggested as a way to reduce the likelihood of setting contract time at too high a level."[14]

Impact on Agency Costs and Quality of Work

A contractor working with a "ticking clock" will not want to wait for hours or days to resolve questions that arise unexpectedly. The time pressure that attends an incentive/ disincentive for early completion can also magnify the importance of quality issues, particularly if some night work is expected or permitted.[17] Both the time pressure and the consequent pressure on quality make close agency supervision of the construction site critical. As a consequence, the state or local highway authority can expect to incur higher agency costs per day in overseeing work on a contract that contains an I/D, although the number of days' duration might be considerably less.

The Colorado DOT field report on the nation's first lane rental contract work observed, "Trying to fine grade roadway at night is very difficult even with large flood lights [but] the contractor is not going to stop and wait for daylight when he is being penalized." The report noted that during this four-day project, *two* unforeseen developments arose that could only resolved by an on-site CDOT engineer knowedgeable about the project.[18] The evidence on this point is especially strong in the case of lane rentals. The British Department of Transport's ten-plus years of experience show that the agency staff workload was much higher on lane rental projects, but the quality of work was successfully maintained.[14]

Impact on Duration of Road or Lane Closures

In most cases, use of the I/D clause reduces costs to motorists. The I/D clause incorporates the daily impact on motorists into the road builder's bottom line: in order to maximize his/her own profit, the contractor must weigh these road user costs, embodied in the monetary incentive, against the other costs that the construction project entails.[9]

A simple disincentive clause merely encourages the contractor to meet the target date; the prospect of reward that an incentive/ disincentive clause offers spur him/her to find innovative ways to reduce construction time. [12] In dollars and cents, I/D provides all the stimulus a bidder should need. However, some experience suggests that cost-plus-time bidding can do more than an incentive provision alone to shake bidders loose from industry norms. The Michigan LTAP journal *The Bridge* cites an instance in which a cost-plus-time advertisement elicited an unorthodox, astonishingly low time bid that was questioned heatedly by the losing bidders but which proved to be more than feasible. The journal argues that conventional bidding, even on a contract that contained an I/D, would not be likely to elicit such an innovative proposal.[13]

Enforceability

American law honors contractually-specified disincentives for late completion even in situations where the actual cost of the delay is difficult to measure. However, these disincentives must be tailored to reflect real damages and not merely to punish tardiness.[3] Furthermore, whereas properly-calculated disincentives or damages normally are sustained when a delay results from the contractor’s fault or from risks that the contractor has assumed under the contract, if the government agency is jointly responsible for the delay the damages will generally not be upheld.[12]

The literature suggests that an incentive/disincentive clause has some legal advantages over a disincentive alone. A legal study prepared as part of NCHRP Project 20-6 says that when coupled with an incentive, “the disincentive provision will be more enforceable in any court action because the disincentive is less likely to be considered a forfeiture” – in other words, the owner’s willingness to pay an incentive shows that the disincentive is not an arbitrary penalty. [12]

Cost-plus-time bidding adds strength to an I/D clause because it makes the contractor responsible for justifying the completion date. [13] In contrast, use of the I/D clause alone makes the DOT responsible for setting a reasonable completion date. [19] NCHRP Synthesis 215 reports that courts have found an implied warranty of design in conventional contracts. It states: “Contractors’ claims based on unreasonable contract times are compensable if the time is found to be significantly at odds with conventional practice. Contract time must represent the time in which an average, competent contractor will be able to complete the project.”[14]

The Theoretical Case for I/D

A conventional construction contract gives the road builder plenty of reason to control the labor and materials costs of the work, but little reason to control its impact on the public. Even when the value of the project’s impact on motorists and nearby residents is potentially quite large in relation to the cost of labor, materials, equipment, and overhead, the builder’s profit responds positively to innovations that shrink construction costs, but not to those– such as accelerated work schedules – that reduce costs to the public.

Cost Impacts Before, During, and After Construction

This section describes the impact of highway construction on the public. The terms “costs” and “benefits” are used almost interchangeably throughout, since a transportation-related benefit is usually a reduction of some element of cost.

Cost (or Benefit) Impacts of a Highway Improvement

The value of a highway improvement is measured in terms of its benefits – changes in factors such as travel volume, travel time, gas consumption, property values, income, employment, sales, and tax revenue. [20-22] One of the most straightforward, fundamental ways to assess the project’s value is to measure its impact on motor vehicle travel cost. [23] Travel cost is comprised of three parts: travel time cost, vehicle operating cost (VOC), and accident cost.

Travel time cost is an opportunity cost -- the difference between the value of the time that a vehicle’s passengers spend en route and the value of the best alternative use of that time. The cost per hour of travel time depends on the opportunities for recreation or work that are available to passengers in the vehicle (the presence of cellular phones, car radios and even scenery will affect these possibilities) and on the opportunities available elsewhere. The travel time cost for cargo depends in a similar fashion on the inventory or carrying cost of the goods in transit, which depends on the relevant interest rate, and on the cargo's rate of deterioration or spoilage. A highway improvement normally expands capacity so that travel time is reduced.

Vehicle operating costs are those incurred by driving a vehicle: gasoline, oil and most wear-related maintenance expenses. A highway project affects the gasoline consumption component of VOC the most due to its impact on traffic movement: idling time, cruising speed, and the frequency of speed changes. Factors such as pavement roughness also have an impact on operating costs.

Accident costs are the actual or imputed value of lives lost, work time lost, medical expenses and property damage attributable to highway collisions. Accidents can also cause a temporary reduction in highway capacity due to lane closure or rubbernecking, with consequent time delay and vehicle operating costs. A typical improvement makes a highway safer at any given speed and traffic volume, but as both average speed and volume rise, the net impact on accident costs is not invariably downward.

Most discussions of highway impacts recognize that road user costs include some real costs to parties who are not using the highway. Pollutant emissions and vehicle noise are the most common of these "externalities". Some applied user cost methods attempt to repair this acknowledged deficiency by appending an estimate of some pollutant emissions to their user cost calculations.

Cost and Redistribution Impacts of Construction Activity

The initial construction and subsequent maintenance of a highway involve costs in addition to the relatively easily and accurately measured payouts to the road builder. First, construction work will often temporarily constrict the capacity of an existing highway facility, with a resulting impact on road user costs. The construction work may also entail utility service interruptions or pollution emissions, especially runoff (erosion) and noise that affect those who reside near the worksite. Lastly, the state highway agency incurs costs to inspect and oversee work at the construction site. [17, 24]

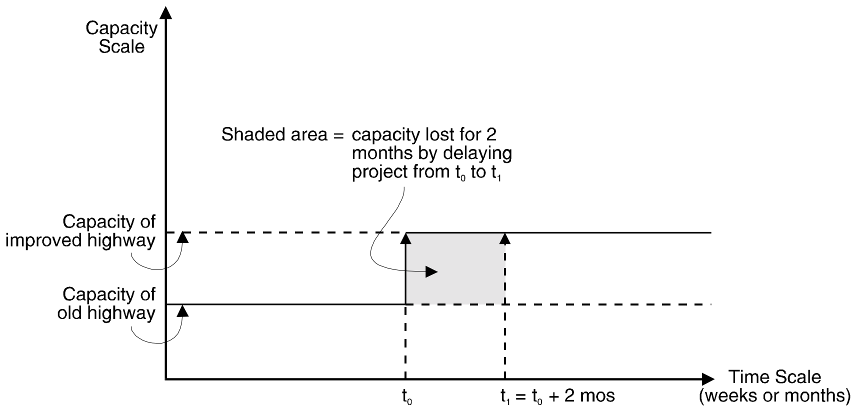
When estimating the cost impacts of construction, it is important to forecast as accurately as possible the actual volume of traffic that will continue to use the constricted facility during the construction work. Just as traffic volume typically expands when the improvement is complete, the converse is true during the construction period.

In addition to the impact on road user benefits/costs, the temporary constrictions to capacity that highway work zones cause may have a noticeable temporary impact on the travel and shopping patterns of consumers. These shifts in patronage could have a noticeable impact on the sales at individual commercial establishments even in cases where the construction work's net impact on road user costs is rather small. [25-27] The science of how to predict the redistributional impact of a highway improvement is outside the scope of this report. It is important to recognize, however, that feared redistributional impacts to business are often the principal motivation for introducing an I/D clause into a highway construction contract.

The Evolution of Capacity and User Costs Over Time

Figure 1 is a graph of highway capacity at different points in time, viewed over a time frame of many weeks or months. It shows how capacity is expected to change as the result of a construction project that is carried out in a negligibly short period of time and completed at the date t_0. Presumably the motorist benefits, like the capacity, will rise above their old level when the work concludes.

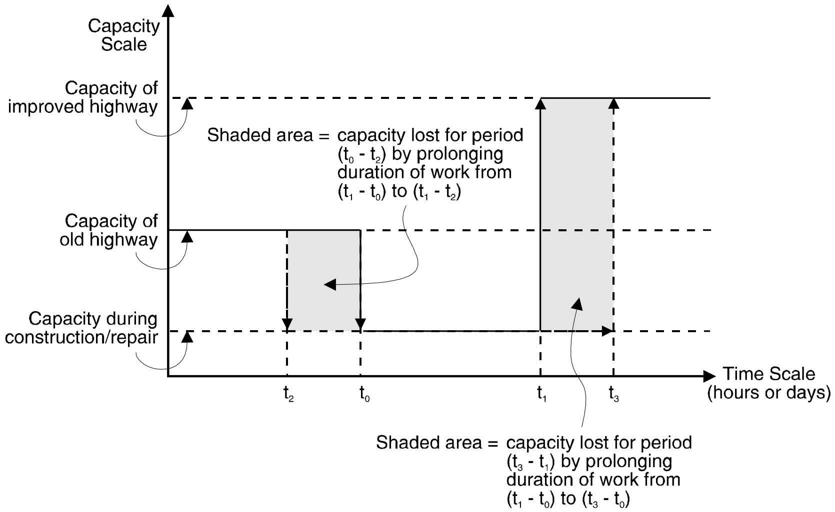
Figure 1. Highway Capacity Over Time



The difference between the actual capacity beyond date t_0 (the solid line) and the capacity that would have existed if the construction project were not undertaken (the lower dashed line) indicates a flow of road user benefits resulting from the project. If the project takes place two months late (say, at time t_1 instead of t_0 in the figure) then the public incurs an unexpected loss of benefits (i.e., additional travel costs) for the two-month duration of the delay, because of the difference between the capacity before and after construction.

Figure 2 depicts highway capacity at different points in time, viewed over a time frame of only days or even hours. It shows how capacity is expected to evolve before, during, and after a construction project whose duration occupies most of the relevant time frame. The capacity drops at time t_0 when the work site is set up, and rises again at time t_1 when the work is completed. Benefits to the motorist also will sink below their original level while the work is underway, and will surpass their original level when the work concludes. If the construction begins two days earlier than planned (say, at time t_2 instead of t_0 in the figure) and ends on the originally scheduled completion date, the public incurs an unexpected loss of benefits (i.e., additional travel costs) for the added two-day duration of the project, because of the difference in capacity before and during construction. The same kind of loss occurs if the construction begins on the appointed day but ends two days later than planned (say, at time t_3 instead of t_1 in the figure. It should be noted that the costs in the two cases are slightly different. The section, “Function of the I/D Clause” demonstrates that the difference between travel costs during and after construction, illustrated in the last example, is *usually* but not always the one that matters when calculating an I/D amount.

Figure 2. Highway Capacity During A Construction Project

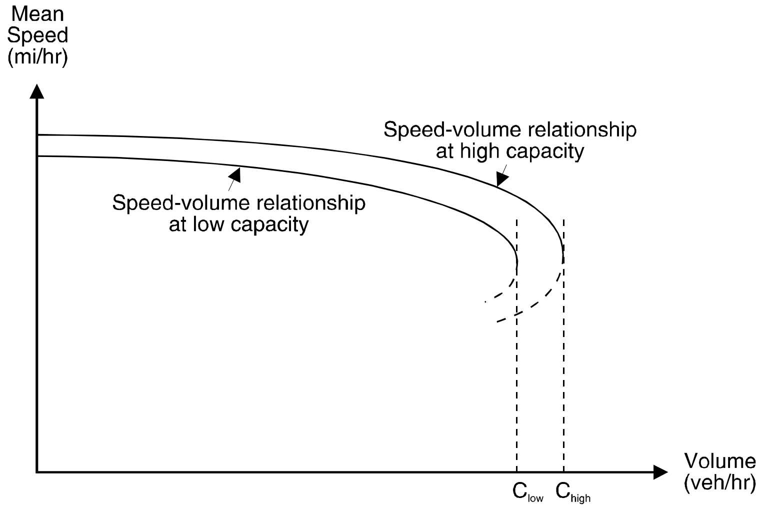


User Cost Impacts and Latent Demand

Sound user cost analysis should take into account the response of travel volume to capacity changes, or other changes. [28] The volume of traffic on a road will depend on the road’s capacity, safety, and other features. If the “latent” travel demand is large, then the cost savings that accrue to new users will be a significant portion of the total benefits that a highway improvement provides. Conversely, if a work zone or some other problem drives a large volume of traffic off of a highway, the departing travellers must be presumed to avoid a portion of the additional travel costs they would have incurred had they remained on that highway.

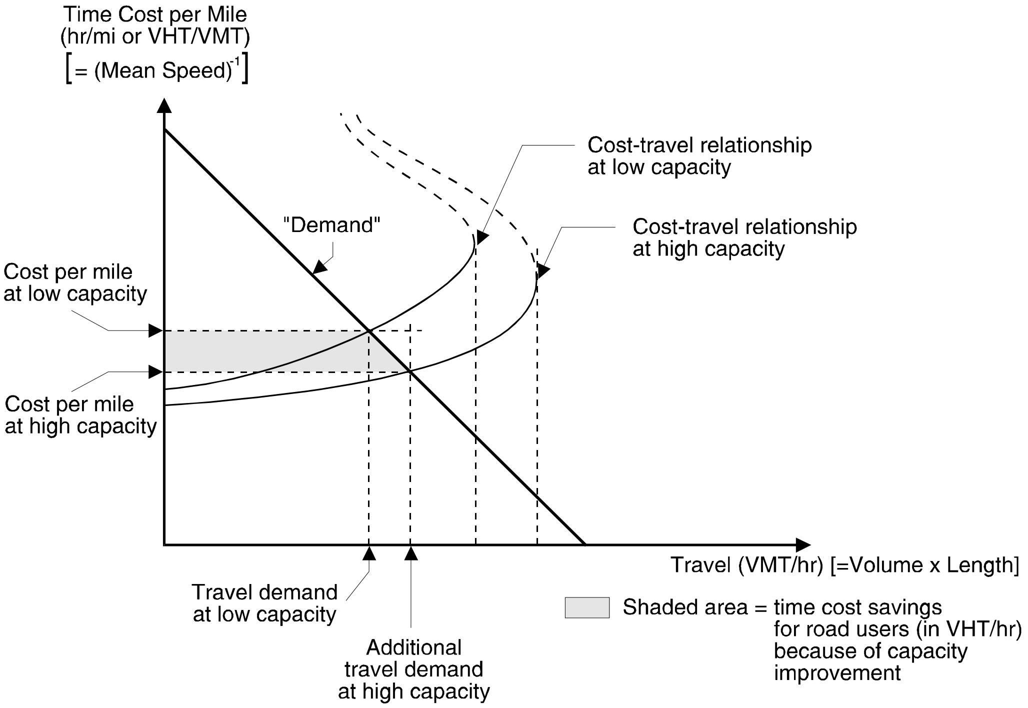
Figure 3 shows two standard speed-volume curves that illustrate the low-capacity and high-capacity situations on a hypothetical highway during and after an improvement project.

Figure 3. Speed/Volume Relationships During and After Highway Improvement



Relying on the fact that, other things being equal, travel times – and travel time costs – are inversely proportional to mean speed, Figure 4 illustrates the relationship between travel (VMT per hour) and time cost per mile (VHT per VMT) for the same two situations on the same hypothetical highway. Figure 4 also features a downward-sloping "demand" curve that shows how much use the motoring public would actually choose to make of the highway at any given time cost per mile.

Figure 4. Vehicle Miles Travelled and Travel Time Cost During and After Highway Improvement



The area between the “demand” curve and a horizontal line at the higher time cost mark (the triangular area *above* the shaded trapezoid in Figure 4) depicts the net value the low-capacity highway adds to the road users’ lives. That is, it shows the travel time that the motorists as a group would have been willing to spend on the road if they had to do so, minus the time they actually spend. (This simple measure of value as time savings neglects the possible savings in operating costs, accident costs and pollution costs.) A highway improvement’s value in time savings to road users is measured by how much it adds to the area between the “demand” curve and the time cost mark as it lowers the time cost per mile. The shaded area in Figure 4 shows the time cost savings that motorists gain by the capacity expansion. This area consists of two parts: a rectangular portion showing the added time savings for the travellers who were using the highway before, and a triangular portion showing the time savings for the travellers who begin to use the highway as a result of the capacity expansion. If the new travellers raise traffic volume on the highway by 10 percent after the improvement, this means a pre-project user benefits calculation that excluded latent demand from consideration would underestimate user benefits by about 5 percent.

Calculation of the other components of user cost should follow the same principles. This logic also applies to the calculation of pollution costs; a valid assessment of the changes in daily pollution emissions before and after (or during) a capacity expansion should take account of the induced changes in volume.

Readers familiar with economics will recognize that the above account glosses over some subtleties involved in the calculation of consumers’ surplus (CS). Those who want to understand why neglect of these subtleties usually introduces little error into the calculation of CS may wish to consult Willig.[29] Those who want to make exact CS calculations should consult Hausman. [30]

The Function of the I/D Clause

The primary purpose of an I/D for early completion is to introduce the impact of construction on road users and other third parties into a road builder’s cost calculations. The basis for calculation of the incentive or disincentive amount is a comparison of the estimated benefits and costs per unit time that affected motorists bear at different points in the life of the construction work. In principle, the I/D clause has two separate objectives: an early completion date and a short construction period. In practice these denote the same thing.

The state DOT’s decision to undertake a given project implies that the value of the daily user benefits that the highway improvement will yield exceed the value of the daily benefits (interest) that the construction funds earn in the bank. All other things being equal, there is an advantage in completing the project as soon as possible, regardless of the project’s start date. A per-day incentive for early completion relative to a fixed date – any fixed date – builds this consideration into the contractor’s cost calculations.

As ongoing construction typically reduces a road’s capacity below the pre-construction level, states want to minimize this period. A per-day incentive for early completion relative to the actual start date builds consideration of the impact of slower vs. faster work schedules into the contractor's cost calculations. In cases where a project requires the builder to develop a schedule for daily lane closures and re-openings, a per-hour lane rental fee accomplishes a similar purpose.

Therefore, in general cases, a justification exists for including two separate incentives in a construction contract: one based on the completion date and one based on the duration of the work. In practice, however, the start date is virtually a fixed date, so there is little difference between an early completion incentive defined relative to a fixed date and a duration incentive defined relative to the start date. A single incentive will therefore probably achieve both objectives. (This might not be the case if a construction firm's resources were very fully employed and the firm were to bid successfully on more than one contract that contained an I/D clause. However, mechanisms other than incentives deter such "overbooking.")

Road User Cost Methodology and Applications

Two documents, TRB's 1985 *Highway Capacity Manual* (*HCM*) and AASHTO's 1977 *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements* (the *"Red Book"*), dominate the field of user cost analysis. [22, 31] Most user cost models and applications rely heavily on one of these; some (e.g., HUCA) draw from both and from other fundamental texts such as ITE's 1982 *Transportation and Traffic Engineering Handbook*. [32] As of the early 1990s, few analytical models explicitly claimed to be updated to reflect the 1992 and 1994 revisions to the *HCM*, or the revisions in the 1992 edition of the ITE *Handbook*.

Selected User Cost Literature

Latent Demand

In order to assess the cost impact on motorists who choose to join (or abandon) the traffic stream because of a capacity change, it is necessary to predict the latent demand for additional travel on the highway in question. There are several ways to analyze this problem. Appendix C provides an explanation of how to apply elasticities to forecast the change in demand following a road improvement.

Harvey (1994) [33] surveyed the published findings from eight studies that measured the travelling public's reaction to particular transportation pricing schemes. The schemes included two bridge toll increases, a road toll increase, a fuel tax increase, a transit fare increase, and three parking price increases. The measured elasticities of travel demand (percentage change in travel volume divided by the percentage change in price) varied. They ranged from –0.05 for a toll hike on the San Francisco Bay Bridge, to –0.1 for a toll increase on the Everett Turnpike in New Hampshire, to –0.2 to –0.25 for fuel tax increases around in various countries around the world, to –2.0 for a fee increase at the long-term (8+ days) parking lot at Boston's Logan Airport. All of these estimates must be considered lower bounds on the absolute value of the elasticities with respect to total cost, as the toll, fare, fee, or tax increases are measured only as percentages of the money cost. The money cost does not include ↵ and, with the exception of fuel costs, is not strongly correlated with ↵ travel time costs, another significant component of travel cost. (The percentage increases in total travel cost resulting from the pricing schemes studied above would be smaller than the percentage increases in money cost alone. Thus, the elasticities of travel demand with respect to *total cost* implied by the observed changes in travel must be larger in absolute value.)

Harvey also described the structure of the San Francisco Bay Area Model and some of its applications to travel problems in the Bay Area and other parts of California. In one case, the model provided forecasts of the impact of a per-mile user fee on daily VMT in Southern California. By positing an initial cost per mile, for instance $0.33/mi (time cost) + $0.27/mi (operating cost) = $0.60/mi, one can calculate the elasticities (percent change in VMT divided by the percentage change in cost per mile) implied by these forecasts. The Bay Area Model divided the travelling population into income quintiles, and posited progressively lower demand elasticities for progressively higher income quintiles. For the motoring population in aggregate, the elasticity ranged from –1.22 at the highest fee (+$0.20/mi), to –1.45 at the lowest (–$0.09/mi.).

Cohen (1995) [34] surveyed recent studies of induced traffic (the latent demand that manifests itself after a capacity expansion). Much of the research modelled traffic volume or VMT as a function of capacity in a specific facility or corridor. A study of the Zeeburger Tunnel in the Netherlands found that the tunnel expanded capacity by 25% in the corridor where it was constructed but that auto traffic, other than that due to route diversion, rose by only 2%. This finding indicated a demand elasticity with respect to capacity of 0.08. Two studies in California suggested that while capacity expansion of an existing facility induced an increase in VMT with an elasticity of about 0.44, construction of a new freeway that allowed shorter trips between many points in the study area actually reduced VMT. A report that looked at 18 capacity additions to existing highways found short-run (10-year) elasticities with respect to lane-miles in the range of 0.3 to 0.4, and long-run (20-year) elasticities in the range of 0.4 to 0.7.

Some of the research modeled area-wide VMT as a function of an area-wide quantity. Studies of several metropolitan areas, comparing VMT against various measures of capacity such as total lane-miles, freeway lane-miles, and the percentage of driving surface represented by freeways, produced elasticity estimates in the range of 0.0056 to 0.16. Two reports estimated the elasticity of VMT with respect to average highway speed at 0.58 and 1.76, respectively. These imply elasticities with respect to travel time of –0.58 and –1.76. Three studies estimated the elasticity of VMT with respect to some measure of transit capacity, obtaining values in the range –0.0098 to –0.09.

A few of the reports modeled the number of trips or the VMT as a function of travel time. A study in Louisville estimated the elasticity with respect to travel time at –0.4 for auto work trips. A study in Sydney, Australia, found an elasticity of –0.17. A 1984 work estimated that when the traffic caused by induced changes in land use was excluded, the elasticity was –0.27; with the traffic caused by land use changes included, the elasticity was –0.51. One study in

Boston found elasticity of auto work trips with respect to in-vehicle travel time to be –0.82 and the elasticity of auto shopping trips to be –1.02. The fact that this effort did not distinguish between new trips and trips due to changes in destination may explain the higher estimates. The author concludes that the elasticity of travel with respect to travel time cost appears to be greater than –1.0 (i.e., less than 1.0 in absolute value) in the long run, and greater than –0.5 in the short run.

Cohen argues that the most appropriate research models the number of trips or VMT as a function of travel time cost. He points out that the divergent results in the above studies can be explained by the fact that while capacity expansions have a significant impact on average travel time during peak periods, they may have a negligible impact on travel time during off-peak periods.

Travel Time Costs

When a road user cost impact is calculated, travel time cost savings typically emerge as the largest single component. The literature on travel time costs addresses two primary issues: the relationship between highway capacity, traffic volume, and travel time; and the valuation of travel time.

Travel Time and Flow Volume. The *HCM* [31] describes empirically validated relationships between (space-) mean speed and traffic volume for the several categories of highway facilities, allowing for differences in geometrics. The *HCM* also describes empirically validated relationships between average delay time and volume for the different types of intersections, subject to signal timing (if any), cross-traffic, and so on.

Shepard and Cottrell (1984) [17] developed methods to assess the impact that night work zones have on measures of capacity (vehicles per hour), measures of congestion (volume/ capacity ratio, queue length), measures of delay (vehicle-hours), measures of cost (both time cost and operating cost), and measures of safety (accident rates). The cost assessment methods relied on values of time estimated in an earlier work by Abrams & Wang (1981), [35] and on operating costs provided in the 1977 AASHTO *"Red Book"*. The authors provided limited information about the impact on agency costs, but did not attempt to put the cost of accidents in money terms. Noise (a pollution impact on third parties) was noted but not subjected to rigorous analysis.

The authors also discussed at length the special demands that night work makes on an agency's relations with employees, contractors, the police, and the public, and the special needs that it creates for traffic control, lighting, clothing, and other equipment. Most of the method developed in the report would also be applicable to day work zones.

The Value of Time. Chui and McFarland (1986) [36] used a "speed choice" model in which each driver is assumed to choose a travel speed that minimizes the monetary sum of travel time costs, vehicle operating costs, and accident costs. Given specified relationships between travel speed on the one hand and travel time, vehicle operating expenses, and accident rates on the other, plus estimates of accident costs, the model allowed the researchers to infer the average value of travel time from responses to a travel-speed survey. They estimated that the average value for passenger vehicles on four-lane divided highways was $10.40/hour in 1985. Their survey sample contained too few responses from truck drivers to permit an estimate of the average value of travel time for trucks; to fulfill their immediate purpose, the authors produced a revised estimate for trucks, $19.00/hour, simply by adjusting an older estimate for subsequent inflation.

If the “speed choice” method can be said to have a weakness, it is that the value of time is calculated as a function of other user cost components. The quality of Chui and McFarland’s estimates is only as good as the quality of the estimated speed-flow, operating cost, accident rate, and accident cost relationships on which they relied.

Vehicle Operating Costs

NCHRP Report 133 [37] reported findings based on trial runs of passenger cars under a variety of traffic conditions. The results of this study supplied the basis for the vehicle operating cost relationships used in the AASHTO *“Red Book”*, [38, 39] which was developed by largely the same group at the Stanford Research Institute, for NCHRP Project 2-12/1.

Zaniewski et al. (1982) [40] measured fuel consumption, oil consumption, tire wear, depreciation, maintenance and repair costs at various uniform speeds and various grade levels for four passenger vehicle and four truck types. The authors also calculated *excess* fuel consumption, tire wear, and maintenance and repair costs, for each speed, grade, and vehicle type, when a horizontal curvature from one degree to 30 degrees (per 100 ft) was added.

The Final Report for NCHRP 7-12, *Microcomputer Evaluation of Highway User Benefits* (1993), [41] lamented the fact the absence of an updated comprehensive operating cost model; the Zaniewski et al. study was the most recent one that the NCHRP 7-12 research team was able to obtain. The authors programmed a voluminous set of look-up tables with equations, closely approximating the Zaniewski et al. relationships, into MicroBENCOST. The team considered an attempt to incorporate some of the fuel consumption estimates from the ARFCOM model into MB, but rejected the idea because the vehicle types modeled by ARFCOM did not match those modeled by Zaniewski et al. The authors adapted the NCHRP Report 133 findings from the *“Red Book”* to model the effect that speed change cycling has on operating costs. Again, they admitted that they were settling for less than what they might have liked, as the Report 133 results were reported in 1970 dollars, and were not reduced to sub-categories such as gallons of fuel, dollars of maintenance, and so forth.

Bein (1993) [42] reviewed the more recent models of VOC and drew fairly pessimistic conclusions about their general utility. The author concluded, for instance, “Modelling of either cold-start fuel consumption, rolling resistance, maintenance, or vehicle capital cost, or a number of these relationships, need improvement in all of the models....Most affected by the limitations of the VOC models are the appraisals of urban transportation projects, which will likely dominate infrastructure budgets in the foreseeable future.” Bein judged the Zaniewski et al. results and their application in MicroBENCOST “not suitable for use in North American road asset management.” Mechanistic models, such as the ARFCOM model developed in Australia and the VETO model developed in Sweden, which explain variations in fuel consumption only as a function of climatic variables and the technical specifications of the vehicle, received more positive reviews. Unfortunately, the ARFCOM program models fuel consumption only, and the VETO program is not available in a personal computer version.

Accident Costs

The accident cost literature also addresses two primary issues: the relationship between accident rates and highway and traffic characteristics; and cost per accident. Some studies have telescoped these issues and estimated directly the relationship between accident costs and road and traffic characteristics.[43]

Accident Rates. The ITE *Transportation and Traffic Engineering Handbook* (1982, second edition)[32] contains a section on transportation safety. Though superceded by the two-volume fourth edition in 1992, this volume is cited in a number of still-used user cost formulae that were developed in the late 1980s and early 1990s. The Handbook contains a table of accident reduction factors (ARFs) that is the inspiration, if not the source, for many sets of ARFs in current use.

Miao & Lum (1993)[44] investigated the statistical properties of four regression models — two conventional linear (i.e., least-squares) models based on a normal probability distribution and two models based on the Poisson probability distribution — in terms of their ability to simulate vehicle accident rates and design safety relationships. They found that the linear models provide a poor fit for the true accident data. These models sometimes imply that a design upgrade will lead to a negative accident rate. The estimation of the parameters in these models is very sensitive to the inclusion of accident data from very short highway segments. The authors find that the Poisson regression models perform much better, although they sometimes tend to underestimate the dispersion of accident data relative to the mean accident rate.

Forkenbrock et al. (1994)[45] performed a statistical analysis of three years of accident data on rural primary roads in Iowa. They estimated both accidents per million VMT and accident costs per million VMT as linear functions of road features such as the pavement serviceability rating, the sharpest horizontal curve, the shoulder width, and the ADT per lane. The authors also surveyed recent literature and current state DOT practices pertaining to the estimation of accident costs. They found that some state DOTs forecast accident rates from regression equations, while others, agnostic about the value of accident models estimated on national or even statewide accident statistics, forecast the impact of highway improvements on accident rates incrementally using accident reduction factors (ARFs).

Lum & Reagan (1995)[46] discussed the gap between the research into safety relationships and the incorporation of these relationships in the design process. The authors cited the FHWA publications *Safety Effectiveness of Highway Design Features, Vols. I-VI* (1992) as a classic example of why many safety relationships have not been included in design manuals: (1) the reports focus on separate, specific design-safety relationships rather than on a comprehensive design procedure; (2) they do not describe geometric features in the format used by engineers; and (3) the low R-square statistics , typically 0.25 to 0.35, inspire distrust among design engineers. [47] Relying on the work of Rumar concerning the causes of road accidents in the United States, the authors noted that a perfect model would attribute about 34 percent of R^2 to roadway variables, with driver and vehicle characteristics alone accounting for the remaining 66 percent.

Costs per Accident. Forkenbrock et al.[45] (1994) surveyed recent literature and current state practices, and made recommendations to the Iowa DOT (IDOT) on how to update its calculation of accident costs. The authors found that "best" estimates of the costs per accident have moved upward over time in real terms, as the willingness-to-pay approach to valuing accidents has gained in favor at the expense of narrower cost measures. The current average valuation of fatal, non-fatal, and property-damage-only accidents among the fifty states is $1.2 million, $41,700 and $3,000 respectively. These values are substantially higher than those IDOT was using in 1994 ($650,000, $32,500, and $3,200 respectively), but substantially lower than the most recent estimates published by the FHWA ($2.7 million, $69,600, and $4,500). The high and low ends of the range of costs-per-accident used for cost/benefit analysis in the fifty states differed by a factor of four.

A report by Blincoe [48] (1996) presented the results of an analysis of motor vehicle crash costs in 1994. The report included a 1994 update of the "comprehensive" (i.e., economic plus intangible) costs calculated in Miller et al., *The Cost of Highway Crashes* (1991). The economic cost alone (measurable losses due to medical care, administrative and legal expenses, and lost time at work) ranged from $7,243 for a moderate injury (MAIS 2) accident to $831,919 for a fatal accident; the comprehensive cost ranged from $10,840 for MAIS 2 to $2,854,500 for a fatal accident.

Rollins & McFarland (1985) [49] studied the relationship between accident costs and traffic and roadway variables. Texas accident statistics and roadway data for the years 1981-1982 were aggregated and averaged across a number of different cross-classifications to produce a series of tables. These included cost tables for various accident types, tables of average cost per accident for a variety of highway types (classified by the HEEM system) and speed limits, and many others. The authors argue that since their results were derived from Texas data, their analysis is particularly relevant to the Texas DOT – an implicit recommendation that other states should also rely on their own accident and roadway data.

Pollution Costs

Lindberg (1995) [50] reported that "Emissions of nitrogen oxide, hydrocarbons, sulfur and carbon dioxide as well as noise disturbances have been given a monetary value in Swedish infrastructure planning. The values are mainly based on imposed fees within the transport and other sectors....the political process has assumed these values to be reasonable to charge for the emissions and thus hopefully close to the marginal cost and benefit."

In 1995 the transport sector in Sweden was charged the equivalent of US$0.045 per kilogram of estimated carbon dioxide emissions. The portion caused by private motor vehicles is collected via a fuel tax. The fees for sulfur, nitrogen oxides, and hydrocarbons were $4.10, $5.50, and $2.75 per kilogram respectively.

Noise emissions, for which no fees were collected, were assigned a value based on research into their impact on real estate prices. One percent of affected persons were presumed to be "disturbed" by railway or roadway noise in the range of 60-65 decibels (dBA); five percent were assumed to be "disturbed" at 65-70 dBA, 13 percent at 70-75 dBA, and 25 percent above 75 dBA. In 1995 noise pollution was valued at US$960 per person disturbed per year.

Other Issues

Sterling (1994) [24] catalogued exhaustively the direct and indirect costs that attend utility work, including the costs that utility placement and repair impose on travelers. Sterling posited that local governments historically have allocated space underneath public streets in a manner that does not reflect the growing value of the increasingly scarce space. Sterling is one of few who have explicitly considered the impact of construction work on local trade but, citing the AASHTO *"Red Book"* in which "[i]t was recommended in the manual that business loss not be considered unless specific data is [*sic*] available upon which to base a conclusion", he does not attempt to model that impact.

Litman (1994) [23] has assembled the best available dollar estimates of a wide variety of cost impacts that highway construction is known to impose. In addition to the user costs to motorists and pollution costs to third parties discussed above, the author has addressed the negative "barrier effects" that vehicular traffic creates for non-motorized travel modes, and the influence that highway improvements can exert over the patterns of land use and economic development. Many of the less-frequently studied impacts, however, resemble interest costs in that they compound with the passage of time. While these costs can be sensitive to the decision to undertake a major highway construction project, they are not sensitive to a few days' or weeks' delay in the completion of the project.

Data Requirements

The estimation of changes in road user cost requires an established groundwork of both traffic engineering and economic data collection and analysis. A typical user cost calculation depends on the value of motorists' time, on the price (or social cost) of the fuel they burn, and on those costs of automotive maintenance that are sensitive to vehicle use. Data on the composition of traffic (percentage of heavy trucks, percentage of buses, etc.) are of great value in estimating the value of travel time. Information on the local costs of fuel and maintenance is necessary to estimate vehicle operating costs. A user cost calculation also requires knowledge of the relationships between roadway features, traffic speed and volume, and accident rates and costs. Typically, a statistical database of statewide accident statistics provides a means to estimate these relationships.

The estimation of user cost changes for a particular project also requires additional project-specific traffic engineering data collection and analysis. A road user cost calculation depends on the total amount of time required to traverse the road section in question and on the volume of traffic that flows through it. Therefore a traffic engineering analysis that measures stop/delay time, running time or speed, and either flow volume or density, provides information crucial to a user cost calculation.

Traffic Analysis Software

Numerous pieces of traffic analysis software are available to evaluate the performance of a highway facility scheduled for improvement, and to predict the performance of the facility during construction and afterward. A few of the most familiar software packages are described below.

TRANSYT-7F

TRANSYT-7F, [51] a macroscopic simulation model, simulates the movement of platoons of vehicles through each of the intersections in a network (NETSIM, by contrast, simulates the movement of individual vehicles). The program can run in either of two modes. First, it can simply simulate and assess the quality of traffic movement through a network whose intersection signals operate according to a specified plan. Second, it can iteratively adjust the initial signal timing plan to minimize a "performance index" defined by the user. This performance index equals either the total user (or operating) cost (estimated as a function of VMT, stops, delay time, fuel consumption, and average occupancy), or a weighted linear combination of delay time and vehicle stops. Performance quality is derived from the following factors: the flow through each link of each intersection (veh/hr); the total VMT/hr per link and for the network; the total VHT/hr per link and for the network; the number of vehicle stops (both absolute and as a percentage of all vehicle approaches); total fuel consumption (estimated as a function of VMT, delay time, and stops); and the chosen "performance index." The program can also generate optimized signal timing tables, flow profile plots, time-space diagrams, and platoon progression diagram plots.

The TRANSYT-7F documentation stresses that calculation of some of the performance criteria, especially fuel consumption and total operating cost, is relatively simple. "No explicit consideration [is] given to factors such as vehicle mix, geometrics, or environmental considerations." The calculations are also based on limited empirical data, so that while these performance criteria provide a useful basis for comparing the relative costs of alternative signal timing plans, they do not provide a valid basis for comparing the absolute costs of travel under a signal timing plan with other cost quantities measured outside of TRANSYT-7F. Furthermore, survey of current practice (provided below) reveals that, historically, contracts for improvements to intersections rarely utilize I/D clauses. These two facts limit TRANSYT-7F's applicability for calculating per-day incentives.

NETSIM

NETSIM, [52] a microscopic simulation model, defines the relevant piece of the highway grid as a network, or a set of sub-networks, made up of links (highway segments) and nodes (intersections and other points where the traffic flow or road geometry change). NETSIM is one part of the TSIS package. TSIS also includes FRESIM, a program designed to analyze freeway traffic, and CORSIM, a module that couples the NETSIM and FRESIM programs to permit analysis of more complex highway systems, as well as other tools for macroscopic analysis.

NETSIM requires data on volumes and turning movements for all approaches to all intersections in the road grid under simulation, as well as data on the signal timing or other traffic controls at all intersections. A new NETSIM simulation requires a fairly large amount of detailed data input, and sometimes a bit of creative abstraction on the programmer's part, to represent the peculiarities of an actual road network in NETSIM code. At the conclusion of a simulation, the package generates statistics describing the performance of each link and node in the network — delay per vehicle, average running speed, lane occupancy, etc. — as well as cumulative statistics describing the performance of the system as a whole. The cumulative output includes total vehicle-miles, total vehicle-minutes, moving time and delay time as fractions of total trip time, fuel consumption and pollutant emissions.

The fuel consumption program module in NETSIM reads the second-by-second record of speed and acceleration for each simulated vehicle, and looks up fuel consumption and emissions in a set of imbedded tables containing over 16,000 entries. It then calculates cumulative fuel consumption and emissions for all simulated vehicles for the duration of the run. [53, 54] The imbedded tables, developed in 1977, can be modified by the program user. The user should do so, if the CORSIM fuel consumption statistics are to be compared with figures calculated by other means.

Highway Capacity Software

The Highway Capacity Software (HCS) [55] automates, chapter for chapter, all of the most common analytical calculations in the *HCM*. HCS contains modules to treat freeway segments, weaving areas, ramps and ramp junctions, multilane rural and suburban highways, two-lane highways, signalized intersections, unsignalized intersections, urban and suburban arterials, plus a module to calculate the equivalent single-grade equivalent for a segment of mixed grades. Appendix A describes a procedure for introducing portions of the HCS output into travel time cost and vehicle operating cost calculations.

Cost/ Benefit Analysis Software

A few software packages calculate traffic engineering performance measures in a manner similar to those generated by traffic analysis software, and then proceed automatically to derive road user costs from these measures.

Queue Work Zone Model

The Queue Work Zone Model (QUEWZ) [56] has been used in Texas since 1982 to calculate the road user costs resulting from lane closures. The model requires the following data inputs: 1) choice of one of two lane closure strategies (simple closure of 1+ lanes in one direction, or complete closure of one side while the other carries two-way traffic); 2) the total number of lanes and the number open through the work zone; 3) the length of the closure in days and the hours of closure (work zone activity) on each of those days; and 4) hourly traffic volumes. It will accept as optional inputs the percentage of truck traffic and specific points on the speed-volume curve, although the model provides default values for these. The model generates the following outputs: 1) hourly and daily user cost (an aggregate of the dollar values of vehicle running cost, speed-change cycling cost, and time delay); and 2) road capacity, average speed through the work zone, and length of queue (if any), by hour. QUEWZ relies on vehicle operating costs provided in the 1977 AASHTO *"Red Book"* and on values of time taken from the HEEM III model. MicroBENCOST (MB), which was developed to replace the *"Red Book"*, appears to supercede QUEWZ and HEEM III. In analyzing freeway lane closures as well as several other types of highway projects, MB adapts the QUEWZ calculations to its more general framework.

Highway Economic Requirements System

The Highway Economic Requirements System (HERS) [57-59] is designed to perform highway needs analyses for a highway system. The model is based on, and intended to be compatible with, the FHWA's HPMS paradigm; in fact, the model parameters were estimated on a stratified random sample from the HPMS database. HERS requires the user to enter as inputs the number of miles of each of several types of road, the pavement condition and other characteristics for each of these facilities, and selected parameters to guide the evaluation of the available improvement/investment alternatives. The model's benefit/cost criterion compares an improvement feasible in the current "funding period" (e.g., five years) with a base case in which improvement is deferred to the next "funding period. Although the HERS method is detailed and thorough and could certainly be adapted to the purpose of calculating a per-day incentive, its current system-level output is not what I/D calculation requires.

Highway User Cost Accounting Package

The Highway User Cost Accounting (HUCA) micro-computer package is a battery of seven Lotus 1-2-3 spreadsheet templates, including several "macros" designed to estimate the user benefits associated with a specified highway capacity improvement, and to compare these benefits with the construction and maintenance costs. [4] The program is a micro-computer version of the upstate urban traffic simulation package that the New York State Department of Transportation (NYSDOT) has been running for years on a mainframe computer. It makes use of information from Chapters 3,7,8,9, and 11 of the 1985 *HCM*, the 1982 ITE *Handbook*, and the 1977 AASHTO *"Red Book."* As of April 1996, NYSDOT was updating the HUCA package, converting it from Lotus 1-2-3 format to Quattro Pro format.

The first HUCA template generates output related to the impact of lane closures on freeways (e.g., duration of closure, number of lanes closed). The second concerns time and operating costs (e.g., percentage of truck traffic and truck types, average vehicle occupancy, and the money value of time). If desired, this intermediate output can replace some of the default values in the four main templates.

The four main templates enable the user to calculate fairly detailed hourly and annual user costs for existing expressways, arterials, two- and multi-lane rural highways before and after improvement. Each template requires (with slight variations) information on link length, AADT, percentage of truck traffic, terrain type, peak hour factor, and projected accident rates. They also need additional traffic and geometric data such as directional split (rural two-lanes only) and cycle lengths (arterials only) that vary with the type of facility. Each completed spreadsheet provides volume, volume per lane, adjusted volume (volume divided by peak hour), capacity, a volume to capacity (V/C) ratio, average speed, vehicle-hours traveled (VHT), vehicle-miles traveled (VMT), three categories of user cost (travel time, operating, and accident costs), and level of service, all calculated separately for each hour of a “typical” day. The arterial spreadsheet generates additional output of arterial green time, demand volume, running time, and total approach delay.

The seventh template takes the user cost output provided by one of the previous spreadsheets, plus data on the proposed project's design life, estimated cost, obligation and completion dates, and the discount and inflation rates, and calculates the present discounted value of the user benefits (i.e., user cost savings). It also generates the present value project costs to use in comparison. A HUCA user who is calculating road user costs for inclusion in an I/D clause could skip this seventh template, as the software does not proceed automatically to benefit-cost analysis, and the user cost analysis already would have generated the results that are needed for the I/D – hourly user costs.

The HUCA software requires the user in some cases to look up numbers in tables in the user's manual (typically, tables taken from or based on the *HCM*) and then enter them into the spreadsheet. For instance, a user of the Rural Two-Lane template does not enter the conventional terrain type (flat, rolling, mountainous) directly into the spreadsheet. Instead, the user must consult two tables: one that cross-indexes terrain type and percentage of truck traffic, and another that cross-indexes terrain type and percentage of road designated as no passing zones. He or she then enters the appropriate values into the spreadsheet. Default values for the accident rates with and without the proposed improvement must be looked up and entered in the same fashion.

The HUCA analysis also assumes that the pattern of AADT through time is independent of whether the improvement project is accepted or rejected: in other words, the spreadsheets do not deal with traffic (re)assignment. This means that the program invariably underestimates user benefits. For the same reason, HUCA cannot be used to assess the impact of a completely new facility.

MicroBENCOST

MicroBENCOST (MB) [41, 60, 61] is the product of a research effort to update the user cost methodologies in the AASHTO *"Red Book,"* and to render them into a microcomputer software package. Developed in 1993 and widely distributed in 1995, MB has been adopted for use in a few states and in several Canadian provinces.

MB eschews the detailed procedures that *HCM* prescribes for calculating intersection delay on the grounds that the procedures require more information about signal timing, phasing, approach volumes, and such than is usually available at the time of an *ex ante* cost-benefit analysis. MB relies instead on a simpler procedure, using *simulated parameters* based on the behavior of the TRANSYT 7-F model, to calculate intersection and interchange delays.

The MB user benefits calculation takes into account the impact that latent demand has on user benefits, provided that the program user inputs the increase in traffic volume ("induced traffic") that is expected to result from a planned highway improvement. [41] MB will automatically calculate the full cost savings per unit volume for traffic that uses the corridor under study both before and after the improvement ("continuing traffic"), and attribute one-half of these cost savings per unit volume to the traffic that begins to use the corridor after the improvement.

The package's Update Program makes it possible to modify almost any part of the cost calculation. The user can customize the default parameters in most of the traffic engineering relationships, such as the speed-flow curves, the hourly directional volume distribution, the percentage of truck traffic, etc., to reflect local conditions. The user can also adjust or update the default unit costs that go into the time and operating cost calculations. Modifying the regression equations for fuel consumption, tire wear, etc., which underlie the VOC cost calculation is not recommended.

Use of I/D: Current Practice

Recent Surveys of I/D Use in the United States

The TRB Task Force A2T51, "Innovative Contracting Practices", designed a questionnaire on state-of-the-art contracting practices, which was sent to the chief construction engineer in each of the 50 state highway agencies, and to Task Force members in early 1989. Among the 38 states that responded to the questionnaire, 28 reported that they were using time-based I/Ds; three reported that they were currently considering their use. Only ten of the respondents specified that they provided for incentive amounts, rather than disincentives alone, on construction contracts. [62]

The Iowa DOT conducted a survey in 1991 on the use of I/Ds by various state DOTs. Among the 39 states that took part in this survey, 35 reported that they were using I/Ds in contracts. "Most states used a combination of scheduling methods when determining contract time, and set the I/D rates in the range of $1,000 to $5,000 per day. In nearly 80% of these states, the incentive and disincentive rates were set at the same amount". [14, 63]

Huckabee [3] conducted a state survey of practice in August 1991. Among the 43 state DOTs responding, all reported using liquidated damages. Fourteen of these reported including user costs in the assessment of liquidated damages. Thirty-three of the respondents indicated that they were employing some type of I/D provisions; of these, 28 indicated that they included user costs in the determination of I/D amounts.

Some Applications of I/Ds in States Other than Virginia

The following section examines recent experience in the use of I/D clauses in four other states. Each case illustrates lessons that are relevant in Virginia and elsewhere.

Colorado

The Colorado Department of Transportation (CDOT)'s 1993 Project BRF-CYBRF-CX285-4(43) was the first in the U.S. to include a lane rental provision in a construction contract. The project entailed rebuilding a graded interchange and replacing two structurally deficient bridges. The project field report states, "Lane Rental was used on this project because there was no detour suitable to handle the volume of traffic for any sustained period of time".[18]

CDOT staff employed the Highway Capacity Software (HCS) to calculate the increase in average delay time per vehicle at two points along the affected road: at a signalized intersection and at the signalized entrance to a shopping center. The values of this delay were calculated separately for the main-line truck and passenger car volumes, and then added together to yield an estimate of the user cost impact at each signal. For the sake of conservatism, CDOT set the per-day lane rental fee equal to the cost at the less severely affected intersection. No attempt was made to calculate the impact on vehicle operating costs, accident costs (probably negligible at a signalized intersection) or pollution emissions, though construction noise was recognized to be a problem.

The field report on the project showed the importance of investing extra staff hours to oversee the work. During this four-day project *two* unforeseen developments arose that could only resolved by a CDOT engineer knowedgeable about the project. Because the project engineer was on-site, the contractor's questions in each case received immediate answers and the work was able to proceed with minimal delay.

Vermont

The Vermont Agency of Transportation employed an I/D for early completion three times, and a lane rental provision once, during 1994 and 1995. The user cost calculations that supported the I/D amounts or lane rental fee always included travel time costs or delay costs; one I/D calculation also included fuel consumption costs and air quality costs. The calculations were performed using the Highway Capacity Software, whose output underwent further treatment in a prepared spreadsheet program. Three of the four projects involved bridge rehabilitation or replacement and one involved work on a signalized intersection that governed the entrance to a newly-constructed high school. [64]

Michigan

The Michigan Department of Transportation (MDOT) often combines the use of the I/D clauses with the use of the cost-plus-time (A+B) bidding procedure. *The Bridge*, a Michigan LTAP publication, says that “Since the contractor must specify his own time to completion, this involves him in up-front careful planning, as opposed to I/D clauses which may only allow the contractor to react to the owner’s idea of time to completion”. [13] Apart from the legal implications mentioned earlier, if an advertisement already contains an I/D clause, the addition of A+B bidding does not change the contractor’s financial incentives at all. *The Bridge,* however, implies that the unusual bidding rules somehow command the contractor’s attention.

MDOT defines the “I/D” clause as a provision that specifies both an incentive and a disincentive. It calls a provision that contains solely a disincentive a “special liquidated damages” (SLD) clause.[11] MDOT prescribes the following possible conditions for an I/D clause:

1. Substantial user cost savings can be realized
2. Total additional user costs are expected to be at least 5% of the project cost, with $5000 considered the daily minimum for major projects
3. An expedited construction schedule can compress the duration of traffic restriction by at least 15 days
4. Traffic capacity will be reduced below an acceptable LOS and no detour is available
5. The detour route has an unacceptable LOS.

MDOT prescribes the following possible conditions for an SLD clause:

1. The state would incur additional costs in the form of maintenance on temporary roads, or traffic control costs, even though user costs are not substantial
2. Substantial user costs could be justified, but the construction time is too short to allow a meaningful incentive for early completion
3. The amount of the SLD is substantive enough to cause the contractor to follow the schedule. This last reason, which seems to regard the SLD as an arbitrary penalty, might not be enough by itself to justify the SLD before a court challenge. [3, 12]

California

One can scarcely discuss incentive/ disincentive clauses without mentioning the experience of the California Department of Transportation (Caltrans) both before and after the Northridge earthquake. Prior to 1994, California used the I/D in the $100 million Ventura Improvement Project (VIP), which was comprised of three separate but overlapping projects to widen and rehabilitate the Ventura Freeway (US 101). The project included three bridge reconstructions. The construction contracts divided the VIP into 120-day-long "designated portions." The lead contractor for each portion was entitled to receive a $6,000/day incentive for completion in 120 days or less, and bound to pay a $6,000/day disincentive if the work lasted longer than 120 days. In addition to the incentives for early completion, the contracts specified that all lane closures be carried out during off-peak or evening hours, and that all ramp closures be carried out on weekends.[65]

In order to bring the damaged pieces of Los Angeles' highway network back into service as quickly as possible following the earthquake on 17 January 1994, Caltrans and local agencies in the area employed an exhaustive set of expedients to accelerate the rebuilding. These expedients included federal emergency funding, a fast-track design approval process, and emergency contracting procedures under which a contract could be bid, awarded, approved, and executed in as little as one day. Enormous financial incentives for early completion, based on analyses of the daily cost of delay in each damaged corridor, were also employed. A report on the reconstruction effort notes that one contractor hired to work on I-10 in Los Angeles conpleted work 66 days ahead of schedule and earned a $200,000 *per day* incentive payment.[66]

Caltrans used the results of routine travel time (floating car) runs conducted before and after the earthquake to estimate the travel time delay in each affected corridor. The agency also obtained estimates of traffic volume in each affected corridor before and after the earthquake. Applying value-of-time and fuel-consumption methodologies developed for the state of California to these data, Caltrans estimated the travel time costs and fuel consumption costs that motorists would incur on each day that the highway facilities remained in their damaged state. The agency then compared these with the costs that motorists would incur on each day once the facilities were rebuilt.

Application of I/Ds in Virginia

A look at the practice in VDOT illuminates some of the issues in using estimated user cost savings as a basis for the I/D amount. The I/D clause is often requested at a point in the pre-construction process when little time is left for numerical analysis. Furthermore, the I/D clause is applied occasionally in cases where road user cost is irrelevant.

Origination of the Request for an I/D

The initial request for an I/D clause typically comes from the VDOT district or residency responsible for the project in question, and typically late in the project development process, a few months before the scheduled advertisement date. Anecdotally, a large fraction of the requests arise from concerns expressed by motorists affected by the planned construction, and by those businesses that serve or employ them. An I/D clause is very seldom sought for a project whose impact, however large, is not a subject of public concern.[67, 68]

Between January 1992 and mid-1995, VDOT included I/D clauses in 30 contracts. A few of the I/D clauses dealt with unusual circumstances. One highway contract covered drainage improvements that happened to affect a rail line; the extraordinary $21,000/hour disincentive was based on the value of the access that the rail line provided rather than on the benefits that the highway provided. Another contract covered construction that temporarily took a large commuter parking lot out of service; calculation of the $500/day disincentive was based principally on the cost to VDOT of providing an alternative parking facility. A third contract covered improvements to a bridge approach on a scenic highway; the disincentive depended on the number of trees removed, not on the date of completion. The great majority of the incentives and disincentives, however, were justified by the expected impact on motor vehicle traffic.[68]

Extent of Use

In 1988, Mr. Claude Garver, then administrator of the Northern Virginia construction district, prepared for Mr. J.S. Hodge, the chief engineer, a memorandum in which he reviewed VDOT’s experience with I/D clauses from the rescission of 23 CFR Part 635 in March 1984 up to 4 March 1988. Mr. Garver reported that during this period, 32 of the contracts that VDOT awarded contained an I/D clause. [69] A search of the VDOT Construction Division’s contract files for the calendar years 1992-1995 discovered 30 contracts that contained some type of I/D clause. It would appear therefore, that in a typical year VDOT awards eight or nine contracts containing I/D clauses.

Of the 30 contracts in the period 1992-5, 20 involved a bridge. Twelve called for both an incentive and a disincentive, while 18 provided only a disincentive. Almost all of the I/D clauses depended upon completion, or achievement of some milestone (e.g., lanes open to traffic), by a certain date. The size of the disincentives ranged from $500 to $15,000 per day (with the one exception noted above), while the size of the incentives ranged from $700 to $10,000 per day. In some contracts, the per-day disincentive amount exceeded the incentive amount. In all contracts where an incentive was provided, a cap was set on the maximum payment.

Table 1 provides a location/type breakdown of the 30 I/D contracts. The upper part of Table 1 shows that eight contracts were in “rural” counties with relatively small, slowly-growing populations, and another ten were in “urban” counties with large or rapidly-growing populations. Ten were in cities or towns (O’Leary (1997) [70]), and two straddled jurisdictions that fall into two of these categories. This part of the table also shows that an incentive/disincentive clause was included in at least one contract in every VDOT construction district during this period. It is noteworthy that the three most urbanized districts, Northern Virginia, Richmond and Suffolk, made the most use of I/Ds. The lower part of Table 1 reveals an apparent trend toward more frequent inclusion of an incentive for early completion in addition to a disincentive.

Table 1. Incentive/ Disincentive Clauses in VDOT Contracts, 1992-5

A. Use of I/D Provisions, by Construction District and by Type of Jurisdiction

Construction District	"Rural" County	"Urban" County	Town or City	All Types of Jurisdictions
Bristol	3	–	1	4
Culpeper	–	–	1	1
Fredericksburg	1½	–	–	1½
Lynchburg	1	–	–	1
Northern Virginia	–	4	1	5
Richmond	–	4½	–	4½
Salem	1½	–	1½	3
Staunton	2	–	1	3
Suffolk	–	2	5	7
All Districts	9	10½	10½	30

B. Use of Disincentive Provisions with and without Incentive Provisions, by Year

Special Provision	1992	1993	1994	1995	All Years
Incentive / Disincentive	0	2	4	6	12
Disincentive Alone	4	7	4	3	18
Total	4	9	8	9	30

Note: One contract in VDOT's Salem Construction District covered work that overlapped the boundary between the city of Salem and the county of Roanoke. Another overlapped the boundary between Caroline County, in VDOT's Fredericksburg District, and Hanover County, in the Richmond District.

Outcomes with I/Ds and One Experiment with Cost-plus-time Bidding

In none of the Virginia examples during 1992-1995 did the disincentive for late completion have to be assessed. The number of cases in which the contractor earned the full incentive payment, up to the cap, was not determined. In addition to the noted uses of time-based incentives and disincentives, VDOT experimented with cost-plus-time bidding on a single project in 1993. Unfortunately, certain design defects were discovered only when work under the contract began. These problems necessitated considerable revision of the schedule of work and consequently, re-negotiation of large portions of the contract. These extraordinary complications made it difficult to draw any conclusions from the experiment. [71, 72]

Traffic Analysis in the VDOT Project Development Process

In order to identify the earliest point at which the need for an I/D clause can be determined and when estimation of road user cost savings becomes feasible, it is necessary to look at how and when the VDOT project development process generates certain information. Further, in order to identify the best basis for a standardized user cost calculation, it is necessary to determine what data analysis is expected to occur during the project development process.

The Project Development Timetable & Data Availability

The duration and complexity of the project development process depends on the size and significance of the project. VDOT in practice divides the infinite variety of possible projects into four classes. The “no-plan” project proceeds on a very compressed timetable; neither environmental study nor right-of-way acquisition is required, and preparation of the roadway plans takes place in a single phase. The “minimum-plan” project, developed on a compressed timetable, requires no environmental study, but a preliminary design stage and approval of the right-of-way plans precede the completion of the roadway plans. The “one-hearing” project typically requires a combined location & design public hearing, and an environmental study. The “two-hearing” project requires both a location public hearing and a design public hearing, as well as an environmental study.

VDOT employs a Program/Project Management System (PPMS) to guide the scheduling of pre-construction activities for most projects. For each project, PPMS identifies necessary activities, estimates the amount of time that each activity will require, and constructs a suggested schedule. Three key steps in the project development process involve the collection or analysis of traffic engineering data: 1) plan design and field inspection (PPMS Activity 36); 2) publication of the “willingness” notice and/or conduct of the (location and) design public hearing (PPMS Activities 47 and 48); and 3) the first submission of complete roadway plans by the Location and Design Division (L&D) to the Construction Divison (PPMS Activity 65). [73]

All projects except for those designated “no-plans” entail a “Plan Design and Field Inspection” phase. During this phase, L&D produces preliminary plans that include horizontal and vertical geometrics, typical sections, design features, and traffic control devices. A plan-in-hand field inspection, at which representatives of other VDOT divisions have the opportunity to make recommendations, refines these plans. L&D will have assembled, at a minimum, available traffic data and geometrics in sufficient detail to establish right-of-way requirements by this time.[74] For a minimum-plan project, this phase would typically take place at least three to six months before L&D submits the right-of-way plans to the Right-of-Way Division. In the development of both the one-hearing and the two-hearing project, it precedes the location and design public hearing (Activity 48, for which PPMS allows four months), the formal Commonwealth Transportation Board approval of the design (Activity 49, two months), and submission of the right-of-way plans by L&D to the Right-of-Way Division (Activity 51, one month). [73, 75]

The design public hearing (in the case of a one-hearing project, the combined location and design public hearing) involves preparing exhibits for public review and preparing a transcript of the comments received. PPMS allows four months for this process. Unless lack of response to the initial public notice leads the responsible State Engineer (Urban, Secondary

Roads, or L&D) to waive the hearing, public concerns about the impact of the project will be heard at this stage. The hearing immediately precedes formal Commonwealth Transportation Board approval of the design (Activity 49, for which PPMS allows two months), and submission of the right-of-way plans by L&D to the Right-of-Way Division (Activity 51, one month), so that public comment on the design comes in a minimum of three months before the acquisition of right of way begins. From 3 to 24 months could pass between the beginning of right of way acquisition and L&D↥s first submission to the Construction Division. [73]

L&D makes the first submission of final roadway plans to the Construction Division after making any changes arising from the public comments; incorporating bridge, landscaping, and traffic control device plans; and updating its quantity summaries and cost estimates. At this point the Construction Division will begin preparing the contract for advertisement, while working with L&D to eliminate any flaws in the first submission.

It should be possible to identify I/D candidates at the completion of the plan-in-hand field inspection (PPMS Activity 36) and the design public hearing (Activity 48). Traffic counts and forecasts are at hand; a preliminary road design, including a traffic maintenance plan for the construction period, will have been drawn up; and public concerns about the impact of the project will have been heard. If an environmental document has been prepared, it too will be available. As noted, for one-hearing and two-hearing projects the last of these steps, Activity 48, immediately precedes the preparation of final roadway plans, so this would be a logical point for the District Construction Engineer and the Location and Design Division to make a judgment of the need for an I/D clause.

Information relevant to a user-cost analysis can be collected at the same time that the final plans are being assembled. Precise information about roadway geometrics and traffic controls becomes available upon L&D’s first submission of plans (Activity 65), immediately prior to preparation for advertisement (PPMS Activities 71 and 72). This information affords the most accurate picture of the work zone geometrics. Using this data, it should therefore be possible to calculate an I/D amount per day during this stage of the planning process.

Data Analysis

The Highway Capacity Software (HCS) is widely used. As traffic volumes control certain aspects of the design for most facility types, [74] L&D often performs a traffic capacity analysis to demonstrate the better service that the designed highway improvement will produce. Many of VDOT’s design engineers, and a number of its transportation planners, have employed HCS for this purpose. On most projects using an I/D clause, no traffic analysis other than HCS analysis is carried out. Figure 5 provides the method VDOT has used to calculate the user cost impacts of a predetermined detour length and speed, or of a predetermined delay time, using only basic traffic analysis measures.

FIGURE 5. VDOT Worksheet for Computing a User Cost-Based Incentive / Disincentive

JUSTIFICATION
(Retain Copy in Project File)

FORMULA FOR COMPUTING INCENTIVES\DISINCENTIVES

CITIZEN COST

$$\text{VPD} \times \text{est. No. Passengers per vehicle} \times \frac{\text{Detour length \{Mi.\}} \times \text{Min. Hr. Wage}}{\text{Vehicle speed through detour}}$$

or

(VPD × est. No. Passenger per vehicle) × (Delay Time* × Min. Hr. Wage)

$$\text{*Delay Time} = \frac{\text{Length of Work Zone}}{\text{Normal Speed}} - \frac{\text{Length of Work Zone}}{\text{Speed thru Work Zone}}$$

VEHICLE COST

VPD × Detour length {Mi.} × Fuel cost per mile {Adv. vehicle}

Citizen Cost + Vehicle Cost = I\D amount per day**

**This figure may be quite high and unreasonable for bidding purposes, therefore, I\D amount should then be discounted to be reasonable. Historically, discounts have been 50 to 75 percent range where VPD counts have been high.

Highway capacity analysis is known to be inadequate to model the flow of traffic through a network of roads where a bottleneck at one intersection may affect flow at neighboring intersections. VDOT staff therefore uses NETSIM or other components of the TSIS simulation package during the design phase of some improvement projects in densely developed areas, principally in the Northern Virginia construction district. NETSIM output could also be the basis for a user cost calculation although it have never yet served this purpose.

The environmental impact statement (EIS) or environmental assessment (EA) occasionally includes a traffic engineering analysis to assess the proposed highway improvement's impact on traffic volumes and average speeds, which in turn affect pollutant emissions. The ideal flow charts in the *PPMS Manual* indicate that preparation of environmental documents and acquisition of permits do not normally lie on the “critical path” for any of the four project types. In VDOT experience, environmental permits have only rarely delayed advertisement on large, controversial projects.[79] The ideal flow chart for the one-hearing project suggests that environmental documents are drafted (PPMS Activity 25) at about the same time as the preliminary designs are prepared. Both are finalized (Activity 33) at about the same time as the right-of-way plans are approved, just before preparation of the final plans begins. For the two-hearing project, which requires a location public hearing prior to the design public hearing, the ideal flow chart indicates that environmental documents are completed much earlier, before preliminary plan design begins. [73] A chart of the "Typical VDOT Design Process", prepared in 1993, indicated that in the development of a large federal-aid (two-hearing) VDOT project, the preliminary draft EIS will be completed for review 42 to 60 months before the projected construction advertisement date, and the final EIS will be approved at the federal level 36 to 48 months before the advertisement date.[70] Therefore, any traffic or user cost analysis done for the environmental document will be complete before the point at which the need for an I/D clause would become evident, and well before the calculation of the I/D amount would be necessary.

Though few VDOT engineers put other analytical software to work, consultants under contract to VDOT do so in exceptional cases. Where signal timing is a critical part of traffic maintenance, design may proceed in a nested sequence. An engineer first uses a software package such as PASSER II or MAXBAND to optimize the progression ("bandwidth") along a critical corridor, or uses a package such as TRANSYT-7F or the Signal Operations Analysis Package (SOAP) to optimize signal timing within a network. Second, he or she employs NETSIM to evaluate the interactions (if any) between adjacent intersections, and to assess the impact of additional traffic control system modifications. [76] Early in the development of an expensive, high-profile project (for example, the improvements to U.S. 58 through southern Virginia [77]) VDOT may ask a consultant to carry out an explicit analysis of road user benefits to inform the Commonwealth Transportation Board and/or the public.

RECOMMENDATIONS

The procedures for determining I/D vary depending on the size and importance of each construction project and on the amount of traffic engineering or benefit/cost analysis that it is to receive. For this reason the policy, procedures, and methods recommended below are intended to afford the project engineer and the Construction Division some flexibility in determining the need for an I/D clause and in calculating the amount once the need is determined.

Policy and Procedures

1. VDOT should consider including an incentive for early completion as well as a disincentive for late completion whenever the expected duration of a project is long enough to make early completion a valuable outcome. The evidence indicates that an incentive will induce earlier completion.

2. VDOT should consider the possibility of a cost-plus-time advertisement on every project for which an I/D clause is deemed appropriate. Cost-plus-time bidding is believed to have a positive impact on the effectiveness of an I/D clause, by attracting more innovative bids. This type of bidding also improves the enforceability of an I/D clause by making

the contractor responsible for justifying the completion date.

3. The conclusion of the design public hearing (PPMS Activity 48) is the time for the Location and Design Division to judge the need for an I/D clause, or to ask the responsible district office to judge the need. Little additional information about the impact (or perceived impact) of the highway project will become available between the design public hearing and the advertisement. Traffic counts and forecasts are at hand, the preliminary road design, including a traffic maintenance plan for the construction period, will have been drawn up, and public concerns about the impact of the project will have been heard. If an environmental document has been prepared, it too will be available. A determination at this point will leave the Construction Division at least two months, while L&D is preparing its “first submission”, to identify and fill any deficiencies in the data that will be needed to perform a user cost analysis.

4. An informed opinion of the contractor’s behavior with and without an I/D is crucial in deciding whether to employ an I/D at all; this informed opinion is likewise crucial in judging what amount is sufficient. If a contractor is able and willing to shorten duration by one day by incurring an extra $1,000 in overtime costs, then a $1200/day provision will make it profitable for the contractor to do so. There is not much point in incorporating additional elements of road user cost if a calculation of travel time savings alone – usually the largest element – justifies an incentive amount big enough, in the project engineer’s judgment, to motivate the contractor to discover almost all possible means to hasten the construction work.

Proposed Methods

5. The Construction Division should, when possible, base I/D amounts on road user cost savings derived from Highway Capacity Software output. Appendix A of this report describes calculations to “translate” HCS performance measures into per-day travel time costs and operating costs. While the output of any of several software packages can provide a basis for valid calculation of user-cost-based incentive amounts, only HCS output currently fulfills this function in VDOT. For those projects where more elaborate data collection and analysis are not justified on other grounds, the relatively simple data that the Highway Capacity Software (HCS) generates provide a sound basis for a travel cost calculation that is difficult to question and extremely difficult to refute.

   Even when redistributional impacts (e.g., impacts on local merchants) or other unusual issues lie behind the desire for an I/D clause, the road user cost impacts alone may justify an I/D amount large enough to satisfy the public’s concern and to motivate the contractor.

6. The incentive/ disincentive calculation should be based on comparison of the relevant capacity phases. The most likely case is a project that entails creation of a work zone, especially a lane closure, that will remain in place until near the completion of the project. In this case, the incentive for early completion (or early reopening) ought to be based on the difference between the user costs during construction and those after completion.

However, other situations are possible. If a project entails establishment of a work zone in which two lanes will be open to traffic when a crew is at work and four lanes open to traffic and four lanes open to traffic when the crew is gone, then a lane rental fee or other incentive based on the difference between user costs in the two states of the work zone might be more appropriate.

7. While a thorough road user cost methodology must address all of the components of cost, calculation of the cost components can be separated to some extent. Calculation of incentive/ disincentive amounts can and should proceed in a sequence of steps – time cost calculation, then operating cost, then accident cost, for instance – after any of which the responsible decision-maker may decide to stop. VDOT will never lose a suit by using an I/D amount that is *smaller* than what the total user cost savings could justify.

Further Research

8. Output of the TRAF-NETSIM products merits consideration as a basis for calculation of travel time cost and vehicle operating cost savings. This package analyzes networks that are beyond the scope of HCS; it should be considered in projects for which analysis with TRAF-NETSIM is to be performed anyway.

9. The HUCA package and the MicroBENCOST package, which produce travel cost as a direct output, merit consideration in the future. For projects whose exceptional significance justifies a considerable investment in data collection and analysis on other grounds, MB may be a convenient alternative. MicroBENCOST uses a simpler procedure than HCS or NETSIM to model the behavior of traffic at intersections and interchanges (see Appendix B for how to apply this model). However, if intersection geometry and signal timing are known *and* are a crucial part of the project, then either HCS or NETSIM would be more appropriate than MB. Furthermore, MB is not used for traffic analysis alone, so VDOT engineers may not be familiar with it.

10. Sample calculations using HUCA, MicroBENCOST, and possibly NETSIM should be worked up using data available from several recent VDOT contracts that included I/D clauses. Case studies drawn from the 30 recent instances where VDOT used an I/D, with emphasis on the timing of the request and the motivation of the request, could provide a basis for evaluating the untried methods such as HUCA and MicroBENCOST. The default values within these packages could be edited to achieve congruence with the standards by which traffic engineers and transportation planners currently model conditions in Virginia. Case studies of a few projects where an I/D was not used might also be instructive.

11. It is recommended that the Virginia Transportation Research Council explore these alternatives via technical assistance to VDOT. It is likely that VTRC could create a

spreadsheet modelled after the HUCA package to “automate” the calculation of per-day (or per-hour) road user costs from the HCS performance measures as described in Appendix A, minimizing the computational burden on the VDOT engineering staff. It is possible that a similar spreadsheet to make use of NETSIM output could also be developed.

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APPENDIX A

Deriving Road User Costs from Highway Capacity Software

To derive road user costs on which to base an I/D, it is necessary to compare a road's performance before and after it is interrupted by construction. Depending on the situation, any two of the following three states of completion can be used for comparison: (1) before construction begins, a state for which accurate traffic engineering information will typically be available; (2) during construction, a state – or possibly two states – for which the traffic engineering data must be predicted; (3) after construction is complete.

Step One

Characterize the geometry and traffic controls of the affected highway before, during, and after construction. Estimate the highway's capacity in each of these states.

1. Describe the current facility geometry and traffic controls that the construction will affect. Estimate the current traffic-carrying capacity of the affected facility(s).

2. Describe as precisely as possible the geometry and traffic controls that will exist in the work zone during the construction work (there may be two separate work zone scenarios if the zone opens partially during peak traffic hours or weekends), and estimate the capacity of the affected facility during construction.

3. Describe as precisely as possible the geometry and traffic controls that will exist at the completion of construction. Estimate the capacity of the affected facility.

Step Two

State the criterion that will determine how large an incentive or disincentive the contractor receives – for instance, the number of days between the completion date and ninety days after the start date – and choose the relevant capacity phases for comparison. In the typical case where the size of the incentive/ disincentive payment depends on the numbers of days from start to completion or to (re)opening to traffic, the relevant phases would be the capacity during and the after construction.

Step Three

Quantify the volume and composition of traffic during the two relevant phases. For instance, if the phases are during and after construction:

1. Forecast the volume and composition of traffic that will use the facility during construction. (See Appendix B.)

2. Forecast the volume and composition of traffic that will use the facility after construction. (See Appendix C)

If the capacity before construction begins were chosen as one of the relevant phases, one of the above sub-steps would be: “1. Measure the volume and composition of traffic using the affected facility prior to construction.”

Step Four

Analyze the performance of the affected facility during the relevant phases. Given traffic volume and geometrics, HCS calculates the mean speed, among other statistics, for freeways, multilane highways, and two-lane rural highways. For signalized and unsignalized intersections, HCS calculates the total delay per vehicle. For arterials HCS calculates both the mean speed between intersections and the average delay per vehicle at each intersection.

It is important to remember that traffic volume normally varies from one time of day to another, and that performance may have to be calculated for several representative hours – for instance, one rush-hour peak hour, one off-peak hour, and one evening/holiday hour – in order to evaluate the performance over a 24-hour period.

Step Five

Translate the traffic analysis measures of performance into road user costs per hour. The analyst using HCS must calculate each cost component manually or by spreadsheet from the performance statistics. It is suggested that travel time cost be calculated first, as this component is normally the largest. Any or all of these cost components may be included, at the discretion of the project engineer.

1. *Travel Time Cost*

The essential statistics for a time cost calculation are the traffic volume, the space mean speed (if applicable; or its inverse, travel time per mile), the delay per vehicle (if applicable), and the value of time. The cost may be calculated separately for the portions of total traffic that represent passenger cars, buses and trucks.

Time Cost ($/hr) = (Moving Time + Delay Time) ⇇ Time Value ($/veh-hr)
Moving Time = Volume ⇇ Length of Segment ⇤ Mean Speed
Delay Time = Volume ⇇ Mean Delay per Vehicle
Time Value ($/veh-hr) = Avg Occupancy (pers/veh) ⇇ Time Value ($/pers-hr)

HCS [55] (or any traffic analysis software) provides the mean speed and mean delay needed for the standard travel time calculation.

Chui & McFarland, [36] as noted above, calculated time values of $10.40/veh-hr for passenger cars and $19.00/veh-hr for trucks in Texas in 1985 (note that these estimates already take occupancy rates into account). If these values are inflated to 1996 dollars, they would equal about $14.80 and $27.10 respectively.

The MicroBENCOST default settings value time in 1990 dollars for vehicles (or, for cars and buses, occupants) as follows: [41]

Passenger Car/Pickup/Van $9.75/person-hr
Bus $10.64/person-hr ($28.84/hr for the driver)
2-Axle Single Unit Truck $13.64/hr
3-Axle Single Unit Truck $16.28/hr
2-S2 Semi Truck $20.30/hr
3-S2 Semi or Larger Truck $22.53/hr

VDOT may prefer, however, to use time values based on Virginia statistics.

2. *Vehicle Operating Cost*

To match the calculations in MicroBENCOST (MB), the designated successor to the AASHTO *“Red Book”*, would be desirable. Unfortunately the VOC calculations in MB, comprehensive but far from elegant, rely on a set of regression equations embodied in 42 imbedded ‘look-up’ tables. To apply these manually, or via a computerized spreadsheet, to HCS output would be more laborious than simply using MB in the first place. Three alternative methods of calculating VOC from HCS output are offered.

a. Although the battery of equations that MB uses to calculate VOC for moving vehicles is too unwieldy to use without computer automation, the relationships between VOC and each 1,000 hours of idling time are quite simple: [41]

Vehicle Type	*Fuel Cons’n*	*Oil Cons’n*	*Deprec’n*	*Price*	*Maint & Rep (avg cost per 1000 mi)*	*Cost*
Small Car	271.0 gal	5.80 qt	0.81% (of	$8710	57%	$54.74
Med/Lge Car	563.0	5.80	0.81 price)	11980	58%	71.53
Pickup/Van	756.0	3.50	0.50	9080	60%	84.28
2-Axle S.U. Truck	198.0	3.20	1.10	13530	23%	158.00
Bus/SU-3A Truck	398.0	3.46	1.10	70750	26%	223.44
2-S2/3-S2 Semi	470.0	3.46	0.38	≥ 85000	24%	231.42

Operating Cost while Standing ($/hr) = Volume (veh/hr) × Percentage of Vehicle Type × Mean Delay per Vehicle (veh-hr/veh) × {(Fuel Cons’n Rate × Fuel Price) + (Oil Cons’n Rate × Oil Price) + Depreciation Rate + Maint. & Repairs Rate}.

b. A 1981 report from the Federal Highway Administration [78] described a method to estimate fuel consumption and emissions on urban arterials and networks. For each vehicle type, the fuel consumption component of operating costs is as follows:

Fuel Consumption Cost ($/hr) = Volume (veh/hr) × Length of Segment (mi) × Fuel Consumption Rate (gal/veh-mi) × Price ($/gal).

The fuel consumption rate equations in the FHWA method are as follows:

For Passenger Cars and Light Trucks

Fuel Consumption Rate (gal/mi) = 0.0362 + (0.746 / Average Transient Speed)

Average Transient Speed (mi/hr) = Length of Segment / (Moving Time + Delay Time)

For Single-Unit Trucks of GVW between 19,500 and 26,000 lbs.

Fuel Consumption Rate (gal/mi) = $1 / (0.48 + 1.12\,(\text{Average Transient Speed})^{1/2})$

For Tractor-Trailers

Fuel Consumption Rate (gal/mi) = 0.17 + (2.43 / Average Transient Speed)

For buses the report supplies only a nomograph.

c. The AASHTO *"Red Book"* itself described a method to estimate total operating costs. [21, 37] The calculations in the method (updated to 1981 dollars by Memmott & Dudek [56] for the QUEWZ software package) are as follows:

For Segments

1. Operating Cost (\$/hr) = Volume (veh/hr) × Length of Segment (mi) × ((VOC_{pc} × Percent Cars) + (VOC_{tr} × Percent Trucks));

2a. VOC_{pc} (\$/veh-mi) = $395.6898 \times e^{(0.01537 \times \text{Mean Speed})} \times (\text{Mean Speed})^{-0.45525} \div 1000$;

2b. VOC_{tr} (\$/veh-mi) = $(179.1466 \times e^{(0.02203 \times \text{Mean Speed})} \times (\text{Mean Speed})^{-0.35902} + 1201.8847 \times e^{(0.0322 \times \text{Mean Speed})} \times (\text{Mean Speed})^{-0.79202}) \div 1000$

For Queues at Intersections

1. Operating Cost (\$/hr) = Cycle Rate (cyc/hr) × Approach Volume (veh/hr) × Max. Length of Queue (mi) × ((ΔVOC_{pc} × Percent Cars) + (ΔVOC_{tr} × Percent Trucks)) × Flow Capacity ÷ (Flow Capacity – Approach Volume);

2a. ΔVOC_{pc} (\$/veh-mi) = $\{395.6898 \times e^{(0.01537 \times \text{Mean Speed thru Q})} \times (\text{Mean Speed thru Q})^{-0.45525} \div 1000\} - \{395.6898 \times e^{(0.01537 \times \text{Mean Approach Speed})} \times (\text{Mean Approach Speed})^{-0.45525} \div 1000\}$;

2b. ΔVOC_{tr} (\$/veh-mi) = $\{179.1466 \times e^{(0.02203 \times 0.9 \times \text{Mean Speed thru Q})} \times (0.9 \times \text{Mean Speed thru Q})^{-0.35902} + 1201.8847 \times e^{(0.0322 \times 0.9 \times \text{Mean Speed thru Q})} \times (0.9 \times \text{Mean Speed thru Q})^{-0.79202}) \div 1000\} - \{179.1466 \times e^{(0.02203 \times 0.9 \times \text{Mean Appr Speed})} \times (0.9 \times \text{Mean Appr Speed})^{-0.35902} + 1201.8847 \times e^{(0.0322 \times 0.9 \times \text{Mean Appr Speed})} \times (0.9 \times \text{Mean Appr Speed})^{-0.79202}) \div 1000\}$;

3. Mean Speed through Queue (mi/hr) = (Max. Length of Queue (mi) × 60 min/hr)/(2 × Length of Red (min));

4. Max. Length of Queue (mi) = (40 ft/veh × Approach Volume (veh/hr) × Duration of Red (min)) ÷ (2 × 60 min/hr × 5280 ft/mi × Number of Lanes).

3. *Accident Cost*

The accident rate tables in MB's Appendix A (tables A37-A48), [41] automated in that package, can be applied manually to HCS output. The accident calculations, which are borrowed from the HERS package, [57] depend only on traffic volume and on a limited number of geometric variables: the area type (urban or rural), the number of lanes, the type of access control, the presence or absence of a median, the type of intersection or interchange, or the type of warning device. These calculations will not capture the impact of many common safety improvements, such as straightening or super-elevating a horizontal curve, adding a guardrail, or increasing sight distance.

4. *Pollution Emissions*

Huckabee, citing Curry & Anderson, [37] concluded, "A standard method for determining the user costs associated with increased emissions is not readily available. While at least one proposal has been identified, it may be safely assumed that the effects of emissions are negligible in determining the total user cost". [3] The equation used to calculate carbon dioxide emissions for MB could be applied manually to HCS output, but the problem of valuing the emissions would remain unresolved.

$\log(\text{CO (gm/mi)}) = 148.66542 - (0.8063745)*\log(\text{Mean Speed (mi/hr)}) - (0.0122428)*\text{Ambient Temperature (degrees Fahrenheit)} - (0.1937841)*\text{Altitude (= 1 for low, 0 for high)} - (0.0714954)*\text{Year (1987 to 2005)} + (0.0147989)*\text{Percent Cold-Start VMT}.$

Step Six

HCS calculations typically use an hour as the unit of time. Aggregation of the per-hour user costs for different periods of the day into a total for the 24-hour cycle is necessary to obtain per-day user cost (If the calculations were being made to justify a per-hour lane rental fee, aggregation would of course be inappropriate).

Calculate the difference in total per-day road user costs between the two capacity states. This difference is the per-day incentive/ disincentive that the calculations justify.

APPENDIX B

Using NETSIM and MicroBENCOST to Calculate I/D Amounts

In order to derive road user cost, it is necessary to compare the performance of the affected roadway before and after construction. Depending on the situation, any or all of the following states of completion should be compared: (1) before construction begins, a state for which accurate traffic engineering information will typically be available; (2) during construction, a state – or possibly two states – for which the traffic engineering data must be predicted; (3) after construction is complete.

Step One

Characterize the geometry and traffic controls of the affected highway before, during, and after construction. Estimate the highway's capacity in each of these states.

1. Describe the current geometry and traffic controls in the facility(s) that the construction will affect. Estimate the current traffic-carrying capacity of the affected facility(s). Analyze the performance of the affected facility before construction begins.

2. Describe as precisely as possible the geometry and traffic controls that will exist in the work zone during the construction work (there may be two separate work zone scenarios if the zone opens partially during peak traffic hours or weekends), and estimate the capacity of the affected facility during construction.

3. Describe as precisely as possible the geometry and traffic controls that will exist at the completions of construction. Estimate the capacity of the affected facility.

Step Two

State the criterion that will determine how large an incentive or disincentive the contractor receives – for instance, the number of days between the completion date and ninety days after the start date – and choose the relevant capacity phases for comparison. In the typical case where the size of the incentive/ disincentive payment depends on the numbers of days from start to completion or to (re)opening to traffic, the relevant phases would be the capacity during construction and the capacity after construction.

Step Three

Quantify the volume and composition of traffic before, during, and after construction.

1. Measure the volume and composition of traffic using the affected facility prior to construction.

2. Forecast the volume and composition of traffic that will use the facility during construction. (See Appendix C)

3. Forecast the volume and composition of traffic that will use the facility after construction. (See Appendix B.)

Calculating latent demand in the NETSIM environment is complex, as the user must specify the approach volume for each movement at each leg of each intersection. A pair of simplifying assumptions would reduce this calculation: (1) changes in total vehicle-hours are shared equally among all vehicles that traverse the network; (2) all traffic flows through the network are equally sensitive to changes in travel time. Under these simplifying assumptions, a given reduction in total vehicle hours per hour will have an equal impact on every flow rate in the network. These assumptions however, especially the first, may not be true even on average for the types of projects on which NETSIM would be used.

Step Four

Analyze the performance of the affected facility during the two relevant phases.

1. *Using NETSIM*

NETSIM calculates “Cumulative NETSIM Statistics.” These include (but are not limited to) total vehicle hours (move time, delay time, and total time for all vehicles), and “Cumulative Values of Fuel Consumption and of Emissions.” The latter includes automobile hydrocarbons (HC), carbon monoxide (CO), and various nitrogen oxides (NO_x), and for all vehicle types, fuel consumption in gallons. [52]

2. *Using MicroBENCOST*

MB calculates mean running speed, mean delay, fuel consumption (gal/1,000 mi), oil consumption (qt / 1,000 mi), tire wear (% wear / 1,000 mi), depreciation (% depreciable value / 1,000 mi), and maintenance and repairs (% average cost / 1,000 mi), accident rates (acc / 100 million veh or veh-mi), and CO emission (g/mi). [61 (p A-35)] MB also translates the traffic engineering performance measures into dollars-per-day user costs. This output includes discounted motorist (user) costs ↵ time costs, vehicle operating costs, average accident costs, and total user costs ↵ as well as fuel consumption and carbon monoxide emission. MB does not impose a dollar value on CO emission.

A typical MB run will calculate the annual figures for each year under two assumptions, “without improvement” (i.e., before construction) and “with improvement” (i.e., after construction). The “with improvement” scenario can include an initial construction period, with the work zone capacity and resulting volume. As noted, the analyst has to input any added traffic volume that is expected “with improvement”.

Because a full benefit-cost analysis includes many calculations beyond what suffice to estimate per-day road user costs, a number of the data inputs that MB requires for a full benefit/cost analysis are therefore superfluous. Furthermore, as time discounting and life-cycle cost considerations are irrelevant, the user can manipulate the discount rate and the length of the analysis period arbitrarily to suit the purpose at hand. An economical MB run might specify a discount rate of zero, an analysis period of three or four years, and a completion date 2 to 3 years in the future. Then, it would specify traffic conditions as they exist prior to the start of construction (what the program calls "No Improvement") in Year 1; conditions during construction (i.e., work zone conditions) in Year 2; conditions during partial reopening of the work zone (if applicable; treated as second work zone) in Year 3; and conditions after the completion of construction in Year 4. In this manner a single MB run could produce estimates of the annual user cost (= daily cost ⇇ 365) for every relevant state of a project. Provided the discount rate is set to zero, the automatic discounting of the dollar quantities in future years will not change the totals for Years 2, 3, or 4.

Step Five

Translate the traffic analysis measures of performance into road user costs per unit time.

1. *Time Cost*

The essential statistics for a time cost calculation are the traffic volume, the space mean speed (if applicable; or its inverse, travel time per mile), the delay per vehicle (if applicable), and the value of time.

Any traffic analysis software provides the mean speed and mean delay needed for the standard travel time calculation. The cost may be calculated separately for the portions of total traffic that represent passenger cars, buses and trucks.

Time Cost ($/hr) = (Moving Time + Delay Time) ⇇ Time Value ($/veh-hr)
Moving Time = Volume ⇇ Distance ⇤ Mean Speed
Delay Time = Volume ⇇ Mean Delay
Time Value ($/veh-hr) = Avg Occupancy (pers/veh) ⇇ Time Value ($/pers-hr)

MB automates the time cost calculation. When using TRAF-NETSIM, like HCS, the analyst must calculate time cost manually or by spreadsheet from the performance statistics.

2. *Vehicle Operating Cost*

The MB VOC calculations are comprehensive, though not elegant. They rely on a set of regression equations embodied in 42 'look-up' tables. To apply them manually or via a computerized spreadsheet to TRAF-NETSIM output would be more laborious than simply using MB in the first place. If MB is chosen, the calculation of operating cost will be more detailed and possibly more accurate than calculation by one of the other methods, but the results it generates may not be comparable to those generated by one of the other methods. The results will *probably* tend to be larger.

As NETSIM output includes estimated fuel consumption, calculation of the fuel consumption component of operating cost is straightforward. To estimate the others, an analyst would have to characterize oil consumption, tire wear, depreciation, and maintenance/repairs as functions of the available statistics, namely moving time, delay time, and fuel consumption.

3. *Accident Cost*

The automatic accident rate calculations in MB depend only on traffic volume and on a limited number of geometric variables: the area type (urban or rural), the number of lanes, the type of access control, the presence or absence of a median, the type of intersection or interchange, or the type of warning device. These calculations will not capture the impact of such safety improvements as straightening or super-elevating a horizontal curve, adding a guardrail, or increasing sight distance. The MB equations can be applied manually to TRAF-NETSIM output.

4. *Pollution Emissions*

As noted above, NETSIM calculates fuel consumption and HC, CO and NO_x emissions, and MB output includes fuel consumption and CO emission.

Huckabee concluded that calculation of pollutant emissions, with the possible exception of noise, at the facility level is not practical.[3] None of the software packages under consideration here attempts to put a dollar value on emissions of noise, particulates, combustion gases, or their like.

Step Six

Calculate the difference in total per-day (or per-hour) road user costs between the relevant capacity states. This difference is the per-day incentive/ disincentive that the calculations justify.

NETSIM calculates total moving time, delay time, fuel consumption, and pollutant emissions for an arbitrary length of time chosen by the person running the simulation. These statistics, and the cost totals derived from them, must be divided by the time length of the simulation to yield hourly figures.

MB's annualized cost figures must be divided by 365 to yield daily cost figures. MB automatically aggregates cost to an annual figure; it will not output hourly cost totals. Furthermore, to pro-rate the daily cost totals on the basis of their volume shares would be complex because the relationship between travel time and volume is not linear. The analyst who needed *hourly* road user costs ↵ for instance, to calculate distinct lane rental fees that vary from one block of hours in the day to another ↵ must conduct a separate computer run for each block of hours in the day that will share a common traffic level (and a common rental rate). The resulting annual cost totals, divided by 365 and multiplied by the appropriate fraction of the 24 hours in the day, yield daily cost figures.

APPENDIX C

Using Elasticities to Estimate Induced Traffic

Much to the frustration of highway agencies, the motoring public reacts to a capacity improvement by making more peak-hour trips. The extent to which this phenomenon appears depends on two factors: the shape of the speed-flow curve at the current traffic volume, and the public's sensitivity to travel costs, especially time costs. The elasticity of travel demand with respect to travel time indicates the *percent* change in traffic volume that a *one percent* increase in travel time (or a one percent decrease in mean speed) will induce. The elasticity of travel supply with respect to travel time indicates the *percent* change in traffic volume that is possible when there is a *one percent* increase in travel time (or a one percent decrease in mean speed). Figures 3 and 4 and the text in the "Theoretical Exposition" section of the report discuss these factors, and show that for a given speed-flow curve and a given travel "demand" curve, just a single speed-volume combination is consistent both with the technical possibilities and with the wishes of the motorists.

The research reviewed in the "Selected User Cost Literature" section of this report suggests that the motoring public's elasticity of demand with respect to travel time (or speed) is more stable than its elasticity with respect to other measures of highway mobility such as capacity or lane-miles. Moreover, because no well-known traffic engineering relationship relates volume to total cost as the speed-flow relationship relates volume to travel time, elasticity with respect to travel time is more convenient to use than elasticity with respect to total travel cost.

Forecasting Changes in Volume When Elasticities Are Known

When the elasticities of travel demand and supply with respect to travel time are known, to calculate the change in travel volume that follows a given change in capacity or distance is straightforward.

Estimating the induced decrease in volume during construction

$$V_{during} = V_{before}*(C_{during}/C_{before})^{(-ED/(ES - ED))}*(L_{during}/L_{before})^{(-ES/(ES - ED))}.$$

Volume during construction will differ from the current volume if either the capacity of the facility (C) or the length of the facility (L; for instance, a detour) will be different during construction.

Estimating the induced increase in volume after construction

$$V_{after} = V_{before}*(C_{after}/C_{before})^{(-ED/(ES - ED))}*(L_{after}/L_{before})^{(-ES/(ES-ED))}.$$

Volume after completion will differ from the current volume if either the capacity of the facility (C) or the length of the facility (L) will be different at the completion of construction than it was before.

*Estimating Supply Elasticity Using HCM Tables***

Elasticity at volumes below the preconstruction equilibrium

1. Determine the level of service (LOS) and mean speed for the estimated capacity during construction, taking pre-construction volume as a given.
2. Determine the speed (S) and the *maximum* volume (V) for the LOS determined in step 1, and for the next lower LOS. If, for instance, the LOS at current volume would be 'D', determine the speeds and volumes for LOS 'D' and 'E'.
3. Calculate the quantity $E_S = -((V_E - V_D)*(S_E + S_D))/((S_E - S_D)*(V_E + V_D))$. This quantity is called the *elasticity* of travel volume with respect to time cost.

Elasticity at volumes above the preconstruction equilibrium

1. Calculate the LOS and mean speed for the estimated capacity after construction, taking pre-construction volume as a given.
2. Determine the speed and the *maximum* volume for the LOS determined in step 1, and for the next higher LOS. If, for instance, the LOS at current volume would be 'D', determine the speeds and volumes for LOS 'C' and 'D'.
3. Calculate the quantity $E_S = -((V_D - V_C)*(S_D + S_C))/((S_D - S_C)*(V_D + V_C))$.

Estimating Supply Elasticity Using the Speed-Flow Equations in MicroBENCOST

MicroBENCOST uses linear equations to approximate piecewise the speed-flow relationships in the 1985 *HCM*.[31] These linear approximations agree closely with the graphs in *HCM*, except at volume-to-capacity ratios greater than or equal to one, where MB assumes that speed will asymptotically approach about 15 mph as density continues to rise. By inspection and experimentation the author arrived at relatively simple non-linear formulae that describe the relationship between elasticity and volume in the MB equations pretty closely. These formulae, in many situations, allow a person with a pocket calculator to estimate the supply elasticity implied by the MB tables without consulting the tables.

For rural two-lane highways

$E_S \rightarrow (4*\text{Capacity} - \text{Volume})/\text{Volume}$.
This approximation is derived from the speed-flow curve in Chapter 8 of the 1985 *HCM*, p 8-5, where capacity is normally assumed to be 1400 vehicles per lane-hour.

For rural multi-lane highways

$E_S = -$ ⇢ when volume is less than 1300 veh/ln-hr;
$E_S = (9{,}720{,}000 - (V - 1300)^2)/(-2*V*(V - 1300))$ for volume between 1300 and 2200;
$E_S = -1$ for volume over 2200.
These approximations are derived from the speed-flow curves in Chapter 7 of the 1985 *HCM* (revised May 1992), where capacity is assumed to be 2200 vehicles per lane-hour.

For Freeways with free-flow speed of 70 mph

$E_S = -$ ⇢ for volume less than 1300 veh/ln-hr;
$E_S = (5{,}670{,}000 - (V - 1300)^2)/(-2*V*(V - 1300))$ for volume between 1300 and 2300;
$E_S = -1$ for volume over 2300.

For Freeways with free-flow speed of 65 mph

$E_S = -$ ⇢ for volume less than 1450 veh/ln-hr;
$E_S = (3{,}913{,}542 - (V - 1450)^2)/(-2*V*(V - 1450))$ for volume between 1450 and 2300;
$E_S = -1$ for volume over 2300.

For Freeways with free-flow speed of 60 mph

$E_S = -$ ⇢ for volume less than 1600 veh/ln-hr;
$E_S = (2{,}940{,}000 - (V - 1600)^2)/(-2*V*(V - 1600))$ for volume between 1600 and 2300;
$E_S = -1$ for volume over 2300.

For Freeways with free-flow speed of 55 mph

$E_S = -$ ⇢ for volume less than 1750 veh/ln-hr;
$E_S = (2{,}227{,}500 - (V - 1750)^2)/(-2*V*(V - 1750))$ for volume between 1750 and 2300;
$E_S = -1$ for volume over 2300.

These approximations for freeways are derived from the speed-flow curves in Chapter 3 of the 1985 *HCM* (updated October 1994), where capacity is assumed to be 2,200/lane on four-lane freeways and 2,300/lane on freeways of six or more lanes.

For urban and suburban arterials

E_S ➔ ((Running time per mile)*(Delay time per mile) + 1)/(.004868918*Volume).
Delay time per mile = (Progression Adjustment Factor)*2*$e^{0.004868918*Vol}$ is an approximation for calculating average delay time per vehicle (in seconds), derived from Table A31 in the *MB User's Manual*, pp A-73,74. [41]

The Progression Adjustment Factors, shown in Table A31A, p A-75, in the *MB User's Manual*, depend on the arrival rate at the intersections and on the type of signal timing: if arrival rate is uniform and all signals are pre-timed, the Progression Adjustment Factor (PAF) has a value of 3; if the arrival rate is heaviest just before the green phase the PAF has a value of 1; if the arrival rate is heaviest just after the green phase the PAF has a value of 5. The first derivative of Delay with respect to Volume, which must be calculated to determine the elasticity, produces the denominator in the above elasticity equation.

A simple formula to approximate average running speed or average running time per mile as a function of volume, free-flow speed, and arterial class eluded this author. The user must consult Tables 11-1, 11-2, and 11-3 in the 1985 *HCM* (updated October 1994), pp 11-4 and 11-7, to determine arterial classification and free-flow speed, and then consult Table 11-4 in the *HCM*, p 11-9, or Table A28 in the *MB User's Manual*, pp A-65 to 70, to determine the running time per mile (or else measure this quantity by some other means).