An Evaluation of Techniques for Highway User Cost Computation

A. S. LANG*, Director of Data Systems, New York Central Railroad; P. O. ROBERTS, Assistant Professor of Civil Engineering, Massachusetts Institute of Technology; and D. H. ROBBINS**, Systems Engineer, IBM Corporation

This paper compares the EA-1 (computer simulation) and AASHO methods for computing vehicle operating costs in respect to interchanges and route location. It analyzes the generalized design situation of (a) interchange vs intersection, and (b) over- vs under-grade separations for controlled-access highways.

Selected highway design problems such as (a) high vs low bridge crossing, and (b) expressway vs noncontrolled-access highway also are discussed.

● THIS PAPER discusses the use of a digital computer in analyzing the vehicle operating costs associated with certain types of highway alignments and compares these results to those of other more usual user cost analysis techniques. The computer programs involved are those developed by the Civil Engineering Systems Laboratory of the Civil Engineering Department at M. I. T. and described in the Highway Research Board paper (1961), "A New Technique for the Prediction of Vehicle Operating Cost in Connection with Highway Design."

The research reported has two objectives: (a) to test the suitability of the AASHO Report on Road User Benefit Analyses for Highway Improvements (hereinafter referred to as the "Red Book") for the determination of vehicle operating costs, and (b) to explore ways in which the computer programs (hereinafter referred to as the "EA-1 Programs") could most appropriately be used for determining such costs. This research is far from complete, but the analysis of four types of alignment problems can be discussed at this time. Both the alignment situations and the nature of their analysis were quite different in each case. Thus, this paper is essentially a report on four separate, though closely related, investigations involving the use of the EA-1 Programs. (Actually, two different program sets were used in the research described. The original set of IBM 650 programs discussed in the earlier HRB paper on this work was used for the interchange ramp problem. A newer, faster program coded in FORTRAN for the IBM 709/7090 was used for the remaining analyses.)

The first of these was a preliminary investigation of the assumption in the Red Book that vehicle performance is not significantly affected by variations in highway profile so long as the average or "composite" grade remains constant. This involved running vehicles (in the computer) over several different profiles with the same average grade and recording their performance. The variations in the results were analyzed to give some indication of the constraints that should be placed on the use of the Red Book in estimating fuel consumption under different conditions of alignment and operation.

A second investigation involved a straight-forward analysis of three alternative locations for a 10-mi section of interstate highway. This analysis was performed first with the Red Book and then with the EA-1 Programs and the results compared. Some possible restrictions on the applicability of the Red Book were also inferred from this investigation.

*Formerly Assistant Professor of Transportation Engineering, Massachusetts Institute of Technology

**Formerly Research Engineer, Massachusetts Institute of Technology.

A third investigation was concerned with the analysis of user costs on two ramps of an existing interchange as compared to the user costs on the ramps of a more elaborate replacement interchange. In this case, the computations were made by three different methods: the EA-1 Programs, the Red Book, and the unit cost tabulations given in Woods' "Highway Engineering Handbook." The results of these analyses suggest certain conclusions on the suitability of each method for the analysis of this type of alignment problem.

The fourth investigation involved a special sort of problem: that of deciding whether to take a nonconnecting secondary road over an expressway or the expressway over the secondary road where the topography does not dictate the selection of one configuration over the other. The differences in the user costs associated with such alignment alternatives are so slight as to be undetectable with the Red Book, but with high traffic volumes these differences are nonetheless significant. The EA-1 Programs can determine these differences. The results in this case were set up in a matrix showing the relative user cost advantage of one alignment configuration over the other for different combinations of expressway and secondary road traffic.

It was possible to draw a few general conclusions from these four somewhat separate investigations. These bore out earlier expectations that the Red Book was well suited to many, if not most, alignment situations, but that in situations requiring an analysis technique of high sensitivity the EA-1 Programs may be superior. In addition, it was possible to show that the basic relationships between fuel consumption and gradient now used in the Red Book need further study.

THE EFFECT OF PROFILE ON FUEL CONSUMPTION

The objective of this first investigation was to test one of the major assumptions of the Red Book method; namely, that vehicle performance is not significantly affected by variations in highway profile so long as the average or composite grade remains constant. Also of interest was the determining of fuel consumption and travel time for trucks as compared to cars, so as to determine whether truck performance could be reasonably approximated by multiplying the values obtained for automobiles by a truck factor.

Description of Grade Test

Two test vehicles were run in simulated operation over several profile configurations, each 10,000 ft long and each with an over-all average grade of 1 percent. The test was then repeated using configurations with over-all average grades of 3 percent. Two factors dictated the selection of these particular average grades: (a) average gradients below 1 percent have little effect on automobile fuel consumption, and (b) it is difficult to find many profile configurations for average grades of more than 3 percent that will not involve unrealistically large gradients (say, 7 to 10 percent) by interstate standards.

Both the 1 and 3 percent tests involved two basic types of configurations: (a) profiles made up entirely of 1 and 3 percent grades, and (b) profiles with grades that were neither 1 nor 3 percent, but that averaged to 1 or 3 percent over the total alignment. Figure 1 shows these grade configurations for the 1 percent test. The

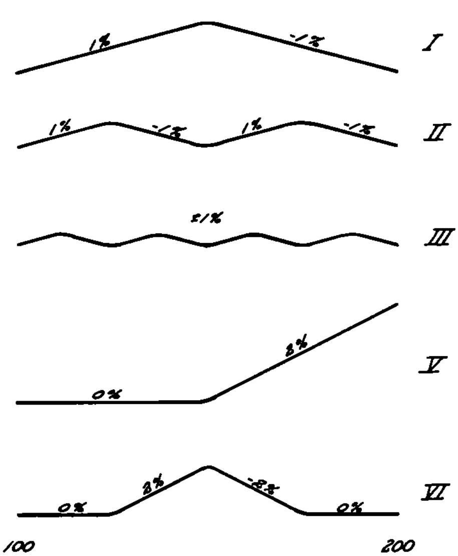

Figure 1. Alternative profiles, 1 percent average grade.

3 percent test was similar, with the following exceptions: (a) run 3 was omitted, (b) run 5 was tried with both 6 and 4 percent grades, and (c) run 6 used 4 percent grades. In all cases, the lengths of the grades were adjusted so that the average gradient over the 2-mi section was 3 percent.

In every case the test vehicles were run at three attempted speeds: 20, 40, and 60 mph.

Test Vehicles

The vehicles used for the test were a 1960 Plymouth station wagon and an International Harvester truck and semitrailer. The important characteristics of these vehicles are shown below:

1. 1960 Plymouth station wagon (8 cylinders, Torqueflite transmission):

Weight (loaded)	5,060 lb
Ratings	max. 230 hp at 4,400 rpm
	max. 340 ft-lb at 2,400 rpm
Transmission ratios	low gear 1.72
	high gear 1.00
Rear-axle ratio	3.31

2. 1960 International tractor (model R205FA) with flat-bed semitrailer:

GCW	55,000 lb
Weight (loaded)	41,480 lb
Ratings	net 166.5 hp at 2,600 rpm
	max. 182 hp at 3,000 rpm
	net 382 ft-lb at 1,200 rpm
Transmission ratios	
(Int. T51)	1st 8.03
	2nd 4.61
	3rd 2.46
	4th 1.41
	5th 1.00
Two-speed rear axle	low 7.59
	high 5.57

Vehicle Operating Conditions

The vehicles were assumed to be relatively new and in good running order. The truck was loaded, and it was assumed that it only used four forward gears.

Appropriate vertical curves were used on all alignments. Fuel consumption was computed at 2-sec increments and output was punched at 1-sec increments. It was assumed that the vehicles entered each test section at full (attempted) speed.

Results

Table 1 shows a partial summary of the test results. These particular results are for the 40-mph tests, which were most representative of usual operating conditions. The results of the 20- and 60-mph runs showed that fuel consumption is most affected at lower speeds but will generally drop to accepted values at more usual speeds.

Table 1 shows the effect of profile on fuel consumption. Tests 1, 2, and 3 show a fuel consumption of 0.069 gal, and Tests 5 and 6 show an almost 20 percent increase to 0.083 gal, even though the average grade was 1 percent in every case. The same effect can be seen on the 3 percent tests, though it is less pronounced. The variation between Tests 5A and 6A is explained by the fact that Test 5A involved 6 percent grades and Test 6A involved only 4 percent grades. Also, the difference in fuel consumption between the 1 and 3 percent tests amounted to more than 15 percent. The Red Book shows a difference of only about 5 percent between these same two sets of average grades.

TABLE 1

EFFECT OF PROFILE ON FUEL CONSUMPTION[a]

Vehicle	Fuel Consumption (gal)[b]				
	Test 1	Test 2	Test 3	Test 5	Test 6
Car:					
1 Percent	0.069	0.069	0.069	0.083	0.082
3 Percent	0.081	0.081	---	0.092	0.083
Truck:					
1 Percent	0.36	0.36	0.35	0.36	0.38
3 Percent	0.51	0.48	---	0.56	0.51

[a]Runs all at 40 mph.
[b]Per average one-way trip.

The results for the truck test were slightly different. The 1 percent runs produced almost no increase in fuel consumption in going from Tests 1, 2, and 3 to Tests 5 and 6. This is probably explained by the way in which a truck operates. By use of proper gear ratios, it can select the most efficient point in the fuel map at which to operate. The effect on the truck was thus a loss in speed rather than a loss in fuel performance. However, there was a 42 percent increase in truck fuel between the 1 and 3 percent tests. The effect of individual grades was also more pronounced in the 3 percent tests.

Conclusions

The test results suggest the following conclusions:

1. Where the individual grades in a class (as defined in the Red Book) are mixed, the composite grade assumption is probably satisfactory. Where a profile includes widely varying individual grades, the composite grade assumption is probably not too good.
2. The difference in fuel consumption between higher and lower grades becomes pronounced at the lower speeds. The AASHO values are probably satisfactory, nonetheless, at most usual operating speeds.
3. In general, the Red Book may not give entirely satisfactory results for speeds below 50 mph and average grades above 3 percent. The EA-1 Programs provide a more sophisticated method to handle these situations.
4. Fuel consumption for trucks is radically increased on higher grades. The effect on truck time may be even more significant. The Red Book has no way of determining truck performance directly. If truck performance is critical in the evaluation of a project, use of the EA-1 Programs should be considered.
5. The results of these tests appear to disagree with the Red Book fuel consumption curves for automobiles. Values for all grade classes should tend to approach the same asymptote at higher speeds. The AASHO curves do not reflect this fact.

AN INTERSTATE ROUTE LOCATION PROBLEM

A second investigation involved the analysis of a 10-mi section of interstate route for which three alternative locations were being considered. The primary objective of this investigation was to compare annual costs as computed by the Red Book with those obtained by the computer to see whether the greater sensitivity of the computer method could conceivably affect the route location decision itself.

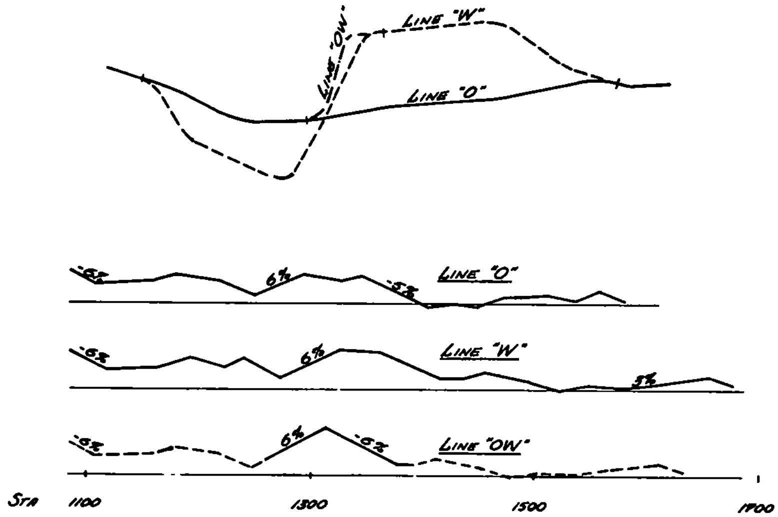

Figure 2. Interstate Route location problem.

The Problem and Its Analysis

Figure 2 shows plan and profile views of the three alignments. Line O, although a very direct route with good grades, encounters soil problems. These would increase the construction cost. Line W would have much lower construction costs, but less favorable grades. Line OW is a compromise line, with even lower construction costs, but with slightly higher gradients. Line O has a total rise and fall of 1,700 ft or a composite grade of 3.62 percent; Line W has a total rise and fall of 2,050 ft or a composite grade of 3.42 percent; and Line OW has the largest rise and fall, 2,150 ft, with an average gradient of 3.91 percent.

The problem resolves itself into a choice between Line O and Line OW. Line O, though it has higher construction costs, has lower road user costs. Line OW has a lower capital cost, but higher road user costs.

The same vehicles used in the previous profile problem were used in the computer analysis of this problem. Both automobile and truck speeds were assumed to be 55 mph. Gasoline cost was taken at $0.32 per gal. Automobile time was valued at $1.55 per hr, while truck time was valued at $4.00 per hr. For both the AASHO and the computer methods, average daily traffic was assumed to be 4,000 vehicles per day with 10 percent trucks.

In the AASHO method, truck cost was taken at four times car cost. The alignments were broken into two sections in computing the composite grade. (It should be noted that the sensitivity of the AASHO method depends on the breaking of an alignment into the various grade sections. If, on the basis of a casual glance, the average grade on the three alignments had been judged the same, the only difference in road user costs would have been due to length.)

Results and Conclusions

Differences between the road user costs as computed by the Red Book and the computer were put on a per mile basis. The results are given in Table 2.

The significant differences in total automobile fuel consumption as obtained by the two methods are readily explained. In the Red Book the basic fuel cost figures were increased by 25 percent to account for the inefficiency of present and future vehicles. If the basic fuel cost figures for the computer were increased by the same factor, the final results would be of about the same absolute magnitude.

TABLE 2

INTERSTATE ROUTE LOCATION PROBLEM

Line	Line Lgt.	Average Per Mile User Costs ($)					Total Annual User Costs[a] ($)
		Costing Method	Car Fuel	Car Time	Truck Fuel	Truck Time	
O	8.9	EA-1	0.017	0.028	0.089	0.085	131,700
		Red Book	0.026	0.028	(0.106)	(0.112)	143,000
W	11.2	EA-1	0.018	0.028	0.099	0.107	132,600
		Red Book	0.026	0.028	(0.106)	(0.112)	144,000
OW	10.5	EA-1	0.018	0.028	0.093	0.113	134,000
		Red Book	0.027	0.028	(0.108)	(0.112)	144,500

[a]ADT = 4,000; 10 percent trucks.

In any case, both automobile fuel and time costs were relatively unimportant in this problem. This was not so true of truck fuel and truck time. Although there was almost no difference in truck fuel consumption as determined by the AASHO method, the computer showed a difference of 3.5 percent for Line OW and 10 percent for Line W when compared to Line O. Differences in truck time were even more significant.

The last column in Table 2 shows the effect of these differences on user costs. The absolute difference between these alternatives reaches a maximum of $1,400 per year, but this difference is relatively insignificant. If the volume of trucks were higher, of course, this difference would have been greater.

One can conclude from this test that the road user costs obtained by the Red Book are acceptable for ordinary analysis purposes. In cases where the make-up of a composite grade is widely variant, where truck volumes are large, or where over-all gradients are large, the use of the computer programs might be preferred.

AN INTERCHANGE RAMP PROBLEM

A third investigation was concerned with the analysis of the user costs on two ramps of an existing interchange as compared to those that would be incurred on the ramps of a more elaborate replacement interchange. The objective of the investigation was to assess the amount of sensitivity needed for this type of problem. Here three different methods of obtaining road user costs were compared: the EA-1 Programs, the Red Book, and the techniques given in Woods' "Highway Engineering Handbook." Both the manner in which each method treats one-way traffic (such as that encountered on ramps) and the methods over-all ease of application were of interest.

Description of the Analysis

Figure 3 shows the alignments selected for analysis. A and B are only two of the eight ramps of each of the new and old interchanges. For simplicity, the others are not shown.

Traffic volumes through the present interchange are very high. Peak hour volumes, including a tourist peak hour, already result in serious congestion. It is expected that the volumes will increase steadily until 1970 when a new route to the east will relieve traffic conditions at this facility. Large turning movements on both ramps A and B have a serious effect on the major routes. Congestion on the ramp often results in a total breakdown of through traffic.

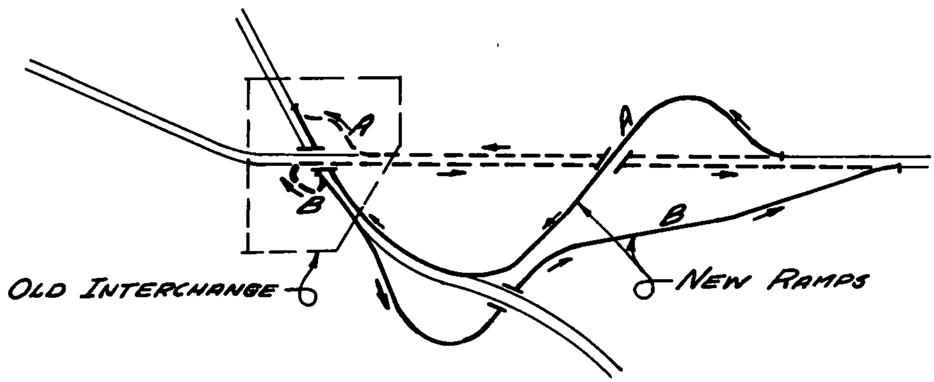

Figure 3. Interstate ramp problem.

Table 3 shows total annual user costs in 1970 as computed by the three methods. The analyses used the same 1960 Plymouth station wagon and the International Harvester tractor-semitrailer combination as in the previous examples. Speed profiles were obtained by considering several factors. The legal speed limit was assumed as the maximum speed for tangent sections. On curves, either the legal speed limit or the design speed (whichever was lower) was assumed to be the maximum speed. At the merge areas of the ramps, where congestion occurs first, these maximum speeds were reduced by an appropriate amount after considering the difference between the ramp traffic volumes and the capacity of the merge areas. (For instance, the cost for present ramp B, as analyzed by the computer, are relatively high. This figure reflects the serious congestion expected in 1970.)

TABLE 3

TOTAL ANNUAL USER COSTS - 1970

	Cost (dollars)		
	EA-1	Red Book	Woods
A:			
Present	403,000	426,000	335,000
Proposed	565,000	577,000	437,000
B:			
Present	679,000	496,000	571,000
Proposed	674,000	763,000	620,000

Results and Conclusions

The results in Table 3 are reasonably close, so it is difficult to draw sharp conclusions. As a result of observations made during the analysis, however, a few points can be made:

1. In very complicated situations, requiring the analysis of several alternatives and a consideration of small differences in grade, alignment, and time delays, the computer programs are almost as easy to use as the other two methods. (This statement must be qualified by the explanation that the use of the computer programs implies a familiarity with the programs and their use and also the ready availability of an appropriate machine.)
2. Higher sensitivity is obtained with the computer programs. This is particularly true for ramps involving one-way traffic. The other methods have no way of handling this problem.
3. The most difficult aspect of this problem is obtaining representative traffic volumes and speeds, including vehicle delays due to congestion. This must be carefully done before any of the methods considered will produce correct answers.

4. The results of the analysis for this particular interchange are inconclusive, because the effect of the ramp traffic on through-route traffic was not considered. In addition, only two of the eight ramps being considered were actually analyzed.

THE OVER-UNDER PROBLEMS

The final investigation dealt with a problem of a rather specialized nature. This involved the decision between taking a nonconnecting, secondary road over an expressway and taking the expressway over the secondary road. There are, of course, many factors to consider in such a problem. Entering grades, right-of-way considerations, and excavation quantities are only three of the important variables involved. In cases where the terrain is flat and other conditions are equal, however, the capital costs for the alternative alignments may be nearly the same, and the vehicle operating costs may therefore be decisive.

The computer programs were used to carry out a user cost analysis of such a problem. The differences in road user costs for over and under conditions were then tabulated for several different main and side road traffic volumes.

Description of the Analysis

Figure 4 shows the assumed profiles for the side road over and for the main road over. A 120-ft opening was assumed for the main road with the side road over; and a 50-ft opening was assumed for the side road with the main road over. The speed profile for the main road through was set at a constant 53 mph. The main road over speed profile was also set at 53 mph. On the side road a speed profile of 42 mph was assumed. In the case where the side road went over, the speed at the top of the bridge was dropped to 37 mph, then increased with a constant acceleration back to 42 mph for the remainder of the pass over the bridge.

A summary of vehicle performance is shown in Table 4. The fuel costs for the main road were greater than those for the side road in all cases. This is due to the increased speed of vehicles on the main road and the resulting higher fuel usage. The problem therefore becomes a study in time savings, not fuel savings.

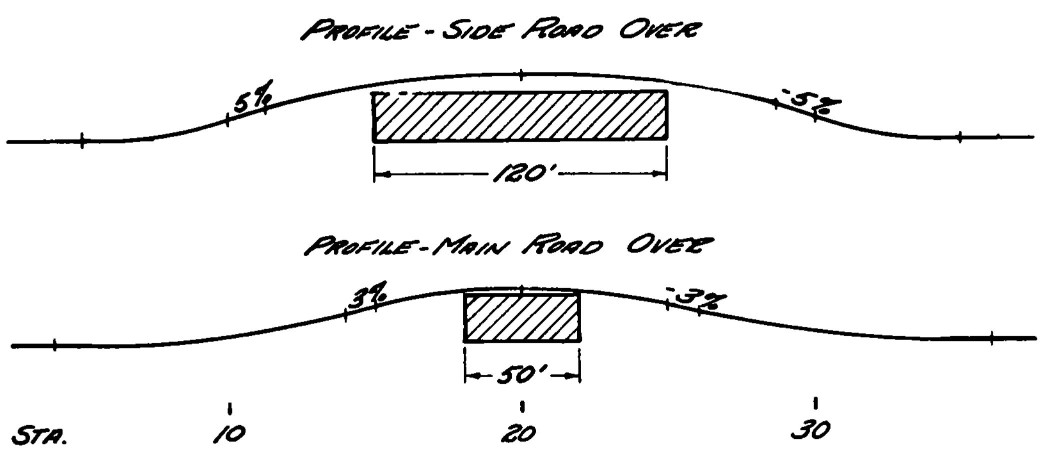

Figure 4. Over-under problem.

TABLE 4

SUMMARY OF VEHICLE PERFORMANCE

Alignment	Car			Truck		
	Speed (mph)	Fuel (gal/trip)	Time (sec/trip)	Speed (mph)	Fuel (gal/trip)	Time (sec/trip)
Side road over:						
Side road	42-37	0.028	66.0	37-32	0.145	75.6
Main road	53	0.032	51.5	53	0.158	51.5
Main road over:						
Side road	42	0.027	64.9	37	0.127	73.7
Main road	53	0.033	51.5	53	0.166	52.2

MAIN ROAD VOLUMES (ADT)

SIDE ROAD VOLUMES (ADT)	5,000	10,000	20,000	50,000	100,000
1,000	- 950	- 1,950	- 5,880	- 15,750	- 32,200
5,000	1,825	180.	- 3,100	- 12,960	- 29,400
10,000	5,300	3,650	360	- 9,500	- 25,900
20,000	12,200	10,590	730	- 2,560	- 19,000
30,000	19,200	17,500	14,250	4,380	- 12,050

NOTE Entries are total annual user cost differences in dollars

Figure 5. Over-under problem, cost difference matrix.

The results in Figure 5 show for various volumes of ADT, the savings made in road user cost by putting the main road over. Assuming a normal configuration to be the main road over, then the matrix shows that for high volumes on the main road this normal configuration actually has a negative savings (or a cost). For those figures with negative values the side road and not the main road should be put over. For a side road volume of 5,000 vehicles per day and a main road volume of 50,000 vehicles per day, for instance, the value in the matrix is $12,960. This indicates that (for the conditions assumed) the annual savings from putting the side road over could be approximately $12,960. On a present worth basis (at 10 percent) this amounts to approximately $130,000. If the cost of putting the main road over is not $130,000 less than the cost of putting the side road over, the side road should be put over instead of the main road.

Use of Results

Although the results of the test were obtained by using simplified alignment and configurations, the conditions are typical of those in many places across the U.S. Urban expressways as well as interstate routes in rural locations frequently do not connect with the road over which they pass. With large differences in traffic volumes, the user cost differences can be significant.

Tables for this sort of problem can be prepared quickly and easily using the computer programs. This can be done for different percentages of trucks or for different configurations of over-under alignments.

GENERAL CONCLUSIONS

It is possible to draw a few general conclusions from the four investigations described. The most important of these is that for usual alignment situations the Red Book offers a user cost analysis technique that is not only workable, but probably adequately accurate as well. On the other hand, in alignment situations that are not usual and where user costs are a critical factor in the choice between design alternatives, the EA-1 Programs, though more expensive to use, may offer a superior analysis technique. Unusual situations in this sense would be those where an alignment was geometrically complex, where it involved widely varying or, more especially, steep gradients (say, over 5 percent), where vehicle speeds varied widely, and where heavy trucks comprised a large share of the total traffic.

These conclusions derive from notions of the relative accuracy of the two analysis techniques. The Red Book technique is based, of course, on actual field data, albeit on fewer data than one might wish. The EA-1 method, though based on a conceptually derived model, has been tested out against empirical data with acceptable accuracy. As a result, the absolute accuracy of both techniques is subject to some doubt. It is only because the EA-1 technique is manifestly more sensitive to variations in alignment and vehicle operating conditions that one can reasonably infer it has greater relative accuracy. Given this conclusion, the authors feel such increased accuracy as the computer method affords will justify the expense of its use under the special circumstances cited.

Further, with regard to the question of relative accuracy, the grade tests reported suggest two specific deficiencies in the Red Book technique. The first of these involves the concept of average or composite grade, which apparently breaks down—insofar as fuel consumption is concerned—for profiles with grades widely variant around the average. At the least, this dictates care in the use of Red Book costs. A second problem, however, derives from the apparent errors in the fuel consumption vs grade curves used as a basis for Red Book fuel costs. The correction of these curves is a matter requiring additional study; meanwhile, the EA-1 Programs may be used as a check in alignment situations where this problem seems critical.

The interchange ramp analyses described form the basis for the suggestion that the EA-1 Programs may be superior to other techniques in treating geometrically complex alignment situations. Where the Red Book technique would require many separate detailed analyses, the computer would provide higher sensitivity at little more expense. It should be made clear, however, that this is predicated on the availability of a computer and a working familiarity with the EA-1 Programs. Though relatively simple to apply, these programs can involve the unfamiliar user in the same sort of frustrating minor difficulties that characterize the use of computers in general.

A final, very general conclusion is that, quite apart from production highway design problems, the EA-1 Programs can be a valuable research tool. Undertaking the needed revision of the Red Book fuel consumption curves just mentioned would be an excellent example of such an application of the programs. The "over-under" grade separation investigation is an example of a study with even more direct payoffs. Though the results presented in this paper may not, in themselves, be applicable to the problems of any particular state, the programs could provide this sort of information for any desired set of geometric conditions and do so at very little expense.

Other research studies that come immediately to mind are a general investigation of the relationships between profile and the performance of trucks (supplementing the empirical work heretofore done on this problem) and an investigation of the general effect of interchange geometry on vehicle performance. Specialized studies of traffic congestion on operating costs are also a possibility, though the problems involved in simulating these conditions will be extremely difficult to overcome.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the sponsors of the project, the Bureau of Public Roads and the Massachusetts Department of Public Works.

The Division of Traffic Operations of the Bureau of Public Roads, and in particular Carl C. Saal and F. W. Petring were particularly helpful in developing the equations and supplying much of the required data.

K. A. Stonex of the General Motors Proving Grounds and C. F. Taylor and A. R. Rogowski were all helpful in supplying input parameters for the vehicle data.

The M. I. T. Computation Center is gratefully acknowledged for the 709 and 7090 computer time and for the assistance and cooperation lent by its staff and personnel.

Also the Civil Engineering Systems Laboratory and its staff are thanked for their assistance in testing and running the programs.

The authors wish to acknowledge gratefully the contributions of Earl Ruiter, who carried out the investigation of user cost computation methods for interchange ramps and assisted in the preparation of data for the remaining investigations reported.

SELECTED BIBLIOGRAPHY

1. Miller, C. L., and Laflamme, R. A., "Digital Terrain Model System Manual." Photogrammetry Lab., Dept. of Civil Engineering, Mass. Inst. Tech. (Jan. 1959).
2. Saal, C., "Operating Characteristics of a Passenger Car on Selected Routes." HRB Bull. 107, 1-35 (1955).
3. Fiala, E., "Der Kurvenwiderstand von Kraftfahrzengen." Automobiltechnische Zeitschrift, 56: No. 1 (Jan. 1954).
4. "Automobile Aerodynamics." Soc. Automotive Engineers (March 1960).
5. Beakey, J., "The Effect of Highway Design on Vehicle Speed and Fuel Consumption." Oregon State Highway Commission Tech. Bull. (1937).
6. Saal, C., "An Evaluating of Factors Used to Compute Truck Performance." SAE Trans. Vol. 3 (1949).
7. Saal, C., "Hill Climbing Ability of Motor Trucks." Public Roads, 23: No. 3 (May 1942).
8. "Truck Ability Prediction Procedure, TR-82." Soc. Automotive Engineers, New York.
9. Peters, R. S., "General Engine Specifications and Drive Train Ratios for 1959 General Motors and Competitive Cars." General Motors Technical Center, Detroit.
10. Rogowski, A. R., "Elements of International Combustion Engines." McGraw-Hill (1953).
11. Taborek, J., "Mechanics of Vehicles." Machine Design (May 30-Dec. 26, 1957).
12. "Informational Report by the Committee on Planning and Design Policies on the Road User Benefit Analyses for Highway Improvements." AASHO, Washington (1960).
13. Lang, A. S., and Robbins, D. H., "A New Technique for the Prediction of Vehicle Operating Costs in Connection with Highway Design." MDPW-BPR Res. Proj. Rep. (Nov. 1960).
14. Miller, C. L., Lang, A. S., and Robbins, D. H., "Research Report on the Vehicle Simulation Cost System." Mass. Inst. Tech. (July 1961).
15. Miller, C. L., Lang, A. S., and Robbins, D. H., "650 Program Manual, Vehicle Simulation and Operating Cost System." Mass. Inst. Tech. (May 1961).
16. Miller, C. L., Lang, A. S., and Robbins, D. H., "Fortran Manual Vehicle Simulation and Operating Cost System." MDPW-BPR Res. Proj. Rep. (Aug. 1961).
17. Roberts, P. O., "Highway Location Evaluation." Proc., Electronics Committee, AASHO, Boston (Aug. 1961).