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Transportation Research Record 1509

Contents

Foreword

This volume contains 10 papers on highway maintenance management and work zone safety. The topics addressed include financial mechanisms for managing highway maintenance and ensuring work zone safety, optimal maintenance district design, computer-generated routing for winter maintenance activities, equipment used in anti-icing operations, selection of pavement markings, accidents in work zones, lane closure traffic management, truck drivers' concerns in work zones, and impacts of speed monitoring displays and changeable message signs in work zones.

Financial Mechanisms for Road Maintenance in Developing Nations

ALFONSO RICO, ALBERTO MENDOZA, AND EMILIO MAYORAL

In most developing countries, the funds allocated to maintain the principal roads have traditionally come from the governments' fiscal budgets. However, the economic restrictions of these countries, many of which are just coming out of lengthy economic crises, have compelled the governments to allocate most of their fiscal funds to other activities that are considered of higher priority (social welfare, education, etc.). Because insufficient funds are allocated to maintenance, principal roads in these countries are experiencing today an accumulated and consistent deterioration. The roads discussed in this paper are the national roads under federal government jurisdiction that carry the larger portion of national and international passenger and cargo flows. This part of the road system is commonly known in most countries as the "basic road network." Several mechanisms that could be implemented in developing nations to generate additional funds needed to adequately maintain and rehabilitate principal roads are discussed. A specific proposal for Mexico is presented. Though specifically aimed at developing nations, the criteria presented can be valid for any country.

The lack of adequate maintenance in road systems leads to inefficient operation and inappropriate use of the different modes of transportation and their interaction. It results in different kinds of energy being wasted without benefiting society at all. It seems adequate to propose a concept of social entropy with a similar meaning to that of physical systems: the energy that a society loses without any foreseeable or foreseen benefit can be assumed as added to universal chaos; that is, as an increment of social entropy. It is obvious that all social movements increase social entropy, but it is also obvious that the goal of all societies should be to minimize that increment. In fact, all excesses above the minimum, that consume resources without generating wealth for society, are undesirable and increase real social costs. Seen in this way, the fact that maintenance reduces the real costs of the countries becomes a sort of natural law. It is necessary to give punctual and concrete meaning to this law by fostering actions that generate resources for maintaining the road networks. In other words, developing nations need to find mechanisms that permit them to obtain required resources. This way, when resources are properly allocated, nations minimize social waste, which, from many standpoints, is represented by inefficient transportation.

Several mechanisms that could be implemented in developing nations to obtain the funds needed to appropriately maintain principal roads are discussed. The roads discussed in this paper are the national roads under federal government jurisdiction that carry the larger portion of the national and international passenger and cargo flows. This part of the road system is commonly known in most countries as the "basic road network." In Mexico, the total length of the roads in the basic road network is about 30,000 km.

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In most developing countries, it has been intended for the whole of these funds to come from the government fiscal budget. However, the economic restrictions of these countries, many of which are just coming out of lengthy economic crises, have compelled the governments to allocate most of their fiscal funds to other activities that are considered of higher priority (social welfare, education, etc.). Because insufficient funds are allocated to maintenance, principal roads in these countries are experiencing today an accumulated and consistent deterioration. In Mexico, for example, 60 percent of these roads, which carry more than 80 percent of the national passenger and cargo flows, are in poor condition (*1*).

This paper specifically deals with mechanisms for generating additional funds needed to adequately maintain and rehabilitate principal roads. A specific proposal for Mexico is presented. The recommendations are directed mainly toward authorities in the different countries responsible for managing public funds; it is their duty to select the most convenient alternative according to their particular conditions.

GENERAL IDEAS

The aforementioned mechanisms should meet the following four conditions (*2*):

- Be systematic. The temptation to take advantage of circumstances that allow allocation of funds within a given year but whose allocation may not be repeatable should be resisted.
- Be clearly related to national road transportation. Mechanisms that use funds from other areas are questionable because there will always be additional needs.
- Enable nations to collect funds from those that benefit from the use of roads.
- Permit nations to generate funds as positive results are attained from providing better maintenance on main roads. The funds collected should be directly proportional to the economic benefits produced by improved conditions.

It seems an obligatory matter that society as a whole should contribute to the solution of this serious problem. From this viewpoint, road maintenance should receive a similar treatment to that given to many other public services supported, in great measure, by the social group of users.

When making suggestions to the authorities responsible for allocating funds to road maintenance, several basic concepts should be addressed:

- Roads represent a public service, and should be treated similarly to other services, such as water supply, electric energy, and telecommunications (to a certain extent). It is universally accepted that the users of these services should contribute in some way to the cost to maintain them.

- It is also true that there is another group of essential services that are generally accepted all over the world as justified to receive, at least in part, government subsidy. Such policy is considered reasonable for these services as they are of fundamental importance for the nation and for the population. In general, these services have to be offered directly by the government or they have to be provided at such a low fare (so that they can be afforded by most of the population) that they lack, in themselves, the necessary capacity for generating the funds (and profits) commonly required by private investors to run them satisfactorily. Education, basic health, national defense and public administration are examples of these services. Road maintenance does not fall within these services, as apparently road users are, in general, a socioeconomic group that does not require subsidies.
- In part, road maintenance should be paid directly by the vehicle drivers that use the roads. This policy may not only allow the collection of sufficient funds for road maintenance but may also help road users to be aware of the important link that exists between the fare they pay and the higher benefits they receive in exchange. This policy would also arouse a very healthy interest of the users in road maintenance and would also generate a convenient pressure in favor of efficiency in the fulfillment of maintenance works.

REVIEW OF SOME POSSIBLE MECHANISMS

A basic idea that should be emphasized is that any mechanism suggested to a national government to obtain resources for road maintenance should be preceded by a clear and simple strategy to adequately spend these resources. Such a strategy should contain technical elements that help define the present condition of the road system, the actions that need to be accomplished to bring each particular road up to a specific level, the costs and benefits derived from such actions, and criteria that allow hierarchization and selection of the most convenient actions to be carried out within a given time period, considering the relative importance of the roads, available resources, and the development of policies toward the future. All these elements are usually assembled in what is commonly known as a pavement management system (PMS). A national strategy or PMS for managing the maintenance activities of the Mexican road network has been developed by the Mexican Institute of Transportation (*3–11*).

In the past, the idea that road maintenance could be financed through special (labeled) taxes created for that particular aim was popular. Through this mechanism, it was sought, to a certain extent, that such taxes were collected from users of the service to which the same funds would be allocated. However, this system gave rise to a lot of criticism as such taxes were frequently allocated to other different purposes. The urgent socioeconomic needs of many developing nations, particularly those experiencing fast population increase, forced the governments to integrate all resources collected into a single fund. This practice provided more flexibility to attend urgent needs that arose as a result of the daily life of society. It should be recognized that the disappointment produced by this method of "labeled" taxes for a particular service is very widespread today, and its critics seem to have very solid arguments against it.

Toll collection is another mechanism that is sometimes used to obtain funds for road maintenance. To be justified economically, this mechanism requires a certain minimum traffic level. Frequently, this minimum level is set to about 800 vehicles per day (*2,12*). For traffic levels lower than this, administrative (fixed) costs make this system less attractive. Indeed, low traffic is a factor usually argued against this mechanism in many developing countries. This system could be considered suitable for, probably, not more than 10 percent of the road networks of Latin American and Caribbean countries. Evidently, toll collection cannot be implemented throughout the basic road network. The use of this mechanism seems to be limited to freeways. In the case of Mexico, toll collection in freeways generate sufficient resources for freeway maintenance, but these funds are insufficient for providing significant maintenance for the whole network.

Studies conducted at the Mexican Institute of Transportation (MIOT) in 1994 (*2,3*) have concluded, for the moment (even recognizing that these studies could be enhanced and extended), that it would be highly convenient to analyze a mechanism based on a very slight increase in the price of fuels (gasoline and diesel). This analysis should be complemented with a general study on impacts produced by that increase in the different sectors of the economy. These impacts should then be compared with the savings obtained by national transport and its effects in those same sectors. If the final balance from this comparison results in favor of such savings, then the country as a whole would benefit from applying this alternative.

Based on the former ideas, a specific mechanism was proposed for Mexico. This proposal is directed toward maintenance of the basic road network—the national roads that are most important for the commercial and industrial life of the country (in general, for the mechanisms that support the income generation).

The proposal presented assumes that the government will continue to contribute the annual amount that has been allocated for the past several years (around $180 million) to road maintenance. This amount is considered to be sufficient for routine maintenance of the 30,000-km Mexican basic road network (crack sealing, patching, resurfacing, cleaning and repair of side slopes, signs and markings, ditches, culverts, dikes, berms, drainage channels, etc.). In addition, the proposal takes into account the need for more substantial resources to rehabilitate and structurally strengthen the basic network. By investing in these additional resources, the road network would acquire a timely and durable strength so that eventually it would not need to be strengthened as frequently nor as significantly, even under the increments in traffic and truck weight. These additional funds are needed because presently most Mexican basic roads are older than 30 years and were built for much lower traffic intensities and much lighter trucks than the ones they carry today (in 1955, the heaviest vehicle weight allowed in Mexico was 10 ton; today, present regulations allow vehicle weights of up to 65 ton). Due to this situation, the maintenance actions required in the road network for the next 10 to 20 years include substantial surface reinforcements, drainage improvements, and, frequently, important reconstruction actions.

Specifically, the proposal plans to bring the road network up to such a good condition of alignment, safety, and structural strength within an initial period of time, that after that period it can keep its satisfactory condition with regular investments like those required for routine maintenance (which are substantially lower than the ones required for strengthening or reconstruction). After this initial period, the fund-generating mechanism already implemented could be used to support the construction of new roads, which will always be required.

The studies accomplished do not consider that every road should be improved with the same target condition in mind. The strategy developed at the MIOT contains elements that permit definition of the most suitable level of quality (ideal) for each highway corridor, depending on the economic value of freight flows traveling on them (*2*). This criterion for defining such quality levels was selected because the economic value of freight moving on basic roads is directly related to their contribution to national transport and, in general, to the generation of national wealth. (The corridors were determined by integrating adjacent links with similar freight economic value.) The optimum set of projects to carry out in the road links yearly was defined by applying the PMS developed by the MIOT (*1–3*).

SPECIFIC PROPOSAL FOR MEXICO

Analyses carried out at the MIOT (*2,3*) showed that the value of the Mexican basic road network is about $30 billion (replacement value). The cost of transportation operations that will take place on this network during 1994 amounts to nearly $15 billion. This value will increase to $17 billion and $20 billion by the years 2000 and 2006, respectively, presuming the present annual traffic growth rate remains the same within the next few years (around 3.5 percent). The former vehicle operating costs include "avoidable overcosts" of about $1.2, $1.85, and $2.7 billion for years 1994, 2000, and 2006, respectively, taking into account the network's present condition and that an amount of about $180 million will continue to be allocated annually to routine road maintenance. (The term "avoidable overcosts" refers to the difference between vehicle operating costs for the network's present condition and the vehicle operating costs for the most suitable level of quality, or the ideal, defined for each corridor.) In the case of the Mexican network, the actions to attain the most suitable condition in each particular road would lead to an increase in the present network mean present serviceability index (PSI) of 2.5 [international roughness index (IRI) of 6] to about 3.5 in 10 years (IRI of 4) and to a value of 4 in 20 years (IRI of 2.5). Evidently, if road maintenance improved, the network condition would also improve and the vehicle operating overcosts would be reduced.

It should be emphasized that the above-mentioned overcosts were not determined for a global network ideal target condition but for an adequate condition of each road corridor based on its direct contribution to the generation of national income. Moreover, such a condition is compatible with the technical capabilities of Mexican engineering. The possibilities of reaching the target condition for each corridor will be higher if a PMS, like the national strategy developed at the MIOT, is applied.

On these bases, it was determined that the increase of the network's mean PSI to the annual values shown in Table 1, could produce an accumulated income in 20 years of up to $42 billion (for the highest alternative investment considered in the table) with regard to the amount that would be obtained during that same period for the present annual investment of $180 million. The data in Table 1 consider five different investment levels, allocating $180 million to routine maintenance (which would not lead to increments of the roads' structural capacity) and the rest to structural reinforcement of the network, drainage improvement, etc. The investment levels considered in the table were selected to cover the range of economic possibilities of the Mexican government (they correspond to rounded amounts in Mexican currency but become rather odd amounts when converted to U.S. dollars). The first allocation level analyzed corresponds to an initial investment of $180 million (made during Year 0), which grows in subsequent years at the same yearly rate as traffic (3.5 percent on average for the 30,000-km network considered). For this alternative, it can be observed that the present mean PSI of 2.79 becomes 2.54 after 20 years and that avoidable overcosts increase more than 100 percent within that same period.

If, on the other hand, $610 million are invested during year 0 to principal roads maintenance, with the same annual growth rate as traffic, overcosts will decrease about 60 percent in 20 years, and the road network mean PSI will improve within that same period from

TABLE 1 Investment Alternatives for Road Maintenance (Amounts in Millions of Dollars)

	Allocation Levels									
	180[a]		305				455			
Year	Mean PSI	Avoidable Overcost	Mean PSI	Avoidable Overcost	Cumulative Expenditure	Cumulative Income	Mean PSI	Avoidable Overcost	Cumulative Expenditure	Cumulative Income
0	2.79	1 699[a]	2.79	1 699	120	0	2.79	1 699	267	0
1	2.61	1 847	2.67	1 804	245	43	2.72	1 548	552	299
2	2.45	2 138	2.58	2 016	376	164	2.69	1 650	849	786
5	2.23	2 535	2.54	2 180	798	988	2.72	1 703	1 800	3 006
10	2.16	3 000	2.63	2 293	1 619	3 910	2.93	1 398	3 638	9 661
15	2.34	3 375	2.74	2 193	2 600	8 899	3.23	1 082	5 863	19 757
20	2.54	3 385	2.95	1 848	3 515	16 509	3.66	787	7 995	32 633
	Internal Rate of Return (%)				50.9				77.0	

	610[a]				760			
Year	Mean PSI	Avoidable Overcost	Cumulative Expenditure	Cumulative Income	Mean PSI	Avoidable Overcost	Cumulative Expenditure	Cumulative Income
0	2.79	1 699	415	0	2.79	1 699	570	0
1	2.76	1 443	862	405	2.80	1 350	1 106	497
2	2.76	1 462	1 321	1 079	2.80	1 341	1 773	1 294
5	2.85	1 357	2 768	4 192	3.00	1 104	3 802	5 098
10	3.25	904	5 655	13 000	3.57	632	7 622	15 402
15	3.73	639	9 077	25 443	3.86	593	9 773	28 448
20	3.90	648	10 145	39 461	3.91	641	10 637	42 505
Internal Rate of Return (%)			65.0				55.7	

2.79 to 3.9. Similar information is also presented in Table 1 for allocation levels of $305, $455, and $760 million.

In all the alternatives analyzed, the data in the "Expenditure" columns correspond to the additional funds that would be allocated yearly to road maintenance, above the present investment of $180 million. The data in the "Income" columns, however, concern the difference between the annual overcosts of a given alternative and the yearly overcosts corresponding to the initial investment of $180 million (the first alternative). For example, in Year 10 of the initial investment of $610 million, an accumulated savings in avoidable overcosts (accumulated income of the country) of around $13 billion would be obtained with respect to what will be acquired in that same year from the initial investment of $180 million.

The bottom row in each alternative shows the internal rate of return (IRR) for each additional annual amount allocated. From these values, it is evident that the most feasible alternatives correspond to initial investments of $455 and $610 million (additional allocations of $270 and $430 million, respectively, above the present investment of $180 million). The selection between these two alternatives is not easy.

Going back to Table 1, it can be observed that if the initial allocation is $455 million instead of $180 million, the cost of improving the network mean PSI up to 3.66 in 20 years will be around $8 billion (cumulative expenditure) in addition to the amount needed for routine maintenance (1994 values). If, on the other hand, the initial investment is $610 million US dollars, that same cost for improvement will be about $10 billion, but in this case, better and faster results will be obtained. It should be noted that the PSI values shown in Table 1 are not generalized values for the whole network but are a weighted average of the PSI values provisionally attained by the process of reaching the most suitable value for each corridor.

It should also be noted that there is a surprising and enormous difference between the benefits derived from appropriate maintenance over a 20-year analysis period and its corresponding costs. Such a difference practically justifies any additional funds allocated to road maintenance.

In most developing countries, it is difficult to generate additional resources to maintain principal roads. Most of these countries assign barely enough funding for routine maintenance, and often even less. Consequently, practically nothing is done to repair roads showing the effects of natural deterioration or to adapt them to conditions other than those for which they were built. Traffic demand continuously grows in all developing countries, which means maintenance resources should grow too.

Assuming that the alternative corresponding to an initial investment of $610 million is selected and that this amount is assigned by simple allocation of fiscal resources, during the first year, as shown in Table 1, the country will receive an income of $405 million—almost the additional amount initially assigned above $180 million (the expenditure in Year 0). In subsequent years, that income will become increasingly higher than the amount allocated. This way, only the initial additional investment of $430 million will be previously unrecovered investment that could be financed, for example, through a foreign loan.

Figure 1 depicts a series of economic flows for the alternative recommended in this paper (the initial investment of $610 million). The first consideration that can be made in relation to Figure 1 is that the savings (income) are distributed in some way among society, but they are not ready monies that could be used for road maintenance. In fact, the monies needed should be provided by the government. In Figure 1 a curve is shown to represent the additional amount necessary allocated above $180 million, which is considered the obligatory minimum initial investment. As stated earlier, that additional allocation increases at the same annual rate as the rate of traffic. The initial additional allocation is around $430 million.

In the same figure, a "collections" curve is represented. This curve was developed with the consideration that the government would provide fiscal resources for road maintenance, but it would also receive the amounts represented by this curve, resorting to increments in the price of fuels. To minimize possible inflationary impacts, these increments should be such that, during the first 9 years, they generate annual collections that do not exceed one-third of the savings (income) obtained from the previous year. A possible mechanism to implement this requirement would be to increment the growth, starting from Year 1, of the price of fuels in equal amounts for 7 consecutive years, until reaching a total growth of $0.015 per liter of gasoline or diesel. These tolerable increments would produce the flow of resources needed.

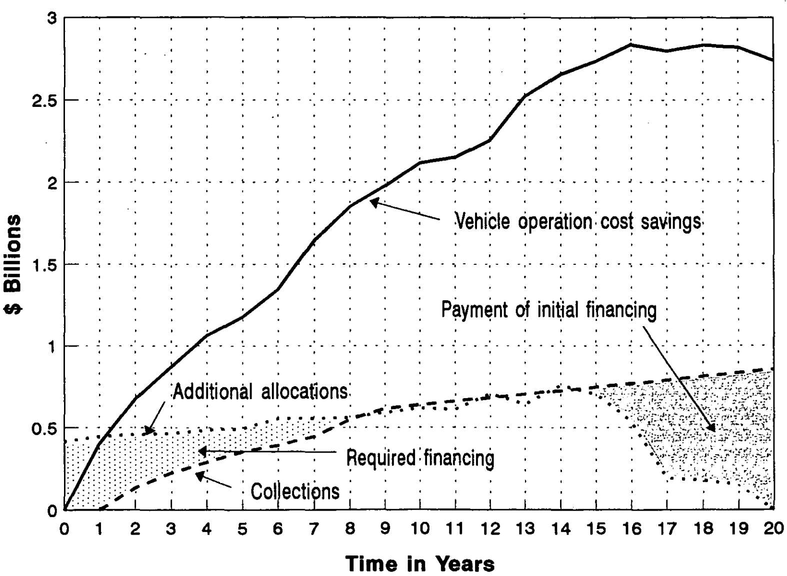

FIGURE 1 Economic flows for the $610 million alternative.

It can be observed in Figure 1 that by Year 9 the annual amount collected would already be about what is required. Figure 1 also shows a curve of yearly savings obtained due to vehicle operating cost reductions (income for the nation).

The shaded area on the left side of the figure, between the curves of annual allocations and collections, deserves particular attention. In this area, which corresponds to a time period of 8 years, maintenance receives more funds than what is collected. These annual differences could be covered through financing. Between Years 8 and 14, the funds collected are practically those that are required. After Year 14, the improved condition of the road system allows for significant reductions in the allocations needed for road maintenance. Within this period, the surplus, or the difference between what is collected and what is required, can be used for paying the initial financing. Likewise, within this period, the annual amount needed tends to become what is required for routine or preventive maintenance.

Figure 1 includes several considerations for minimizing inflationary effects derived from implementing the mechanism proposed herein. First, collection starts after the first year, when savings for road transport have already occurred. Second, as mentioned earlier, collection in a given year never exceeds one-third of the savings obtained the year before. Finally, the recommended alternative requires a maximum annual collection of $610 million. The fact that after Year 9 the collected amount exceeds this maximum collection level is just due to normal traffic growth derived from the growth of the gross national product.

The proposal described herein has been formulated in greater detail than presented above. For example, impacts produced by fuel increases in different sectors of the economy were assessed. Essentially, it was shown that except for the fishing sector, savings transferred to different areas of the economy will always be higher than the cost increase produced by the fuel increments. Therefore, the collections proposed are not inflationary and help make road transport and the national economy more efficient.

The expenditure of funds collected will not produce inflation either, as these resources will go to the sectors of construction and professional services, both of which have available labor.

Annual amounts of financing during the first years, as well as financing conditions, will not generate serious negative effects because there is a clear mechanism for recovering investments.

The proposal suggested has other additional significant benefits:

- Part of the savings attained in different sectors of the economy will turn into profits for private firms, thus increasing the collection of taxes.
- In a competitive system, an additional part of the savings will lead to reductions of transportation prices charged by the truckers, with corresponding benefits for different sectors of the economy.
- Improved road maintenance leads to lower fuel consumption. It was determined that by improving the condition of the road network to the level corresponding to the suggested alternative, the daily refining of nearly 100,000 barrels of oil will be eliminated (or the importation of fuels around the annual cost of $1 billion).
- Reductions in vehicle deterioration will also eliminate the importation of equipment and parts by an additional $800 million annually.
- In addition, the alternative suggested will lead to the creation of 100,000 new direct jobs and 200,000 indirect jobs.
- Finally, improving the road network will help improve the Public Administration image.

CONCLUSIONS AND RECOMMENDATIONS

Road maintenance is of special interest to the authorities and individuals involved in this activity. It is also an element of great importance for the economy of any nation. The concern for generating funds for road maintenance is, indeed, a consequence of that interest.

This paper proposes a mechanism for Mexico to acquire funds for maintaining principal roads appropriately. The most outstanding aspect of this mechanism is that it reduces road transport costs, which benefits most sectors of the economy. In addition, the mechanism is not inflationary. For all these reasons, these suggestions deserve serious consideration.

Though developed for developing nations, the criteria given may be valid for any country. The financial system proposed can also be extended to include maintenance of other kinds of road networks (urban, secondary, etc.) after carrying out the specific studies.

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Optimal Design of Maintenance Districts

PADMA KANDULA AND JEFF R. WRIGHT

Two optimization models are presented and compared for use in partitioning a transportation network into service districts for which snow and ice control routes are subsequently designed. The models are used to redistrict a winter maintenance service area in northern Indiana. The service areas created by these models are shown to be compact with centralized locations of depots/garages, enhancing the efficiency of routes that can be designed to cover these areas.

Maintenance of the intrastate highway system is an enormous undertaking both financially and logistically. Typical activities for which state departments of transportation (DOTs) are responsible include crack sealing and pothole repair, painting and striping, pavement and facilities inspection, weed control and median maintenance, and snow removal and ice control. For many northern U.S. states, winter snow and ice control is the most resource intensive of all network maintenance activities.

Most maintenance activities are characterized by a service being performed according to a set schedule or following established service routes. Service routes are typically designed to cover a partition of the network assigned to a particular depot. One of the goals of DOTs is to provide the necessary service at the lowest cost without compromising quality.

The quality of snow removal routes in Indiana, for example, is evaluated based on the following criteria:

- Frequency of service. Based on the volume of average daily traffic (ADT), roads are categorized into three classes. A required frequency of service is specified for each.
- Quantity of deadhead travel. Travel by service vehicles is classified as either service travel, with the vehicle plowing snow off the road or spreading material, or deadhead travel, with the truck traversing the road segment to begin servicing another road segment. Total deadhead travel should be minimized.
- Class continuity. Each route should be homogeneous in class as far as possible to allow for a clear hierarchy in the importance of a particular route.

In addition to these three criteria, it is desirable that service is cost-effective in that the lowest possible number of vehicles is used.

In general, service routes are designed to best cover a predesignated partition. Partitions are not designed to best support the design of service routes. The premise of this research is that an efficient design of network partitions can greatly enhance the quality of service routes that can be designed. Specifically, the problem being addressed herein may be stated as follows:

> Given a fixed set of P service depots on a transportation network, find the optimal assignment of arcs to those depots as measured by the quality of service routes that can be designed to service all segments of that network.

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The problem of winter snow and ice control in the state of Indiana provides the context for this study. Although the focus for these models is winter snow and ice control, other districting problems, in which service is provided to network arcs, can be accommodated.

TRANSPORTATION NETWORK MAINTENANCE ENGINEERING

Many engineering management systems require decisions concerning the location of facilities and the allocation of workload. Brief summaries of some of the methods applicable to such problems and earlier studies focusing on improving road network maintenance operations, winter maintenance operations in particular, are presented.

Location-Allocation Models

Location-allocation models try to simultaneously (a) select locations for facilities and (b) assign workloads that are either continuously distributed in the area or specified on a network to those facilities so as to optimize some specified measurable criteria. Ghosh and Rushton (*1*) review several early works and present an overview of the methods developed in the last few decades to solve these problems. They discuss exact solution methods and heuristic methods both in continuous space and for networks.

The problem of locating p facilities in p potential sites so as to minimize the average weighted or unweighted distance between the facilities and the clients they serve is called the p-median problem. Many location-allocation problems can be posed as variations of the p-median problem. ReVelle and Swain (*2*) demonstrate a method by which the network p-median problem can be solved to optimality using linear programming. Hillsman (*3*) presents a unified linear model (ULM) for location-allocation analysis based on the structure of the p-median problem.

More recently, Densham and Rushton (*4*) have shown that the processing costs for most heuristics for location-allocation algorithms can be reduced by exploiting the spatial structure inherent in these problems. Rose et al. (*5*) outline a systematic analytic framework for examining decisions concerning the location and size of depots responsible for road maintenance in the state of Victoria, Australia. This system provided a basis for a defensible long-term depot location policy.

Operations Research and Winter Network Maintenance

Savas (*6*), Russell and Sorenson (*7*), and Cifelli et al. (*8*) describe some early attempts made to improve the snow removal operation. Cook and Alprin (*9*) and Tucker and Clohan (*10*) used simulation to predict whether the planned fleet size and deployment of equipment would function adequately under different conditions for urban snow removal settings.

The snow removal problem requires both the development of good routes and the assignment of these routes to depots. In practice, either clustering is done first and routing second, or vice versa. England (*11,12*) describes the methodology that is of the former type, and Reinert et al. (*13*) take the second approach.

Evans and Weant (*14*) describe the use of a computer-based routing system and indicate the advantages in using such a system. A more specialized multi-objective decision support system for computer-aided route design taking into account spatial network data, road classification, and direction restrictions is presented by Wang and Wright (*15*).

SPATIAL OPTIMIZATION APPROACH

The districting problem faced by DOTs can be formulated as a location-allocation problem. One variable is assigned to each decision that needs to be made (assignment of arcs to partitions, vehicles to depots, etc.). The goal of the model is expressed in terms of decision variables and is referred to as the objective function. The limitations within which a solution is sought can also be expressed as mathematical expressions termed as constraints. If a solution satisfying the constraints can be found, a feasible solution is said to exist. If the goal and all the constraint equations can be formulated as linear equations, the model is termed a linear program (LP). Several commercial software applications that can find the optimum solution to such systems rapidly are available.

In some cases, the value of certain decision variables should be integers for reasonable physical interpretation (for example, the number of vehicles). Variables depicting yes/no type decisions can be represented by binary variables that take the value of 0 or 1. Solutions to problems involving integer and binary variables tend to be more computationally intensive. Solutions to such problems are frequently found by a branch and bound enumeration scheme that involves relaxing the integer requirements and solving a series of LPs with upper or lower bounds set on the values of these variables until an integer solution is found. Tighter bounds on the range of values allowable for these integer variables helps reduce the number of enumerations required.

Two optimization models for solving the location-allocation problem as it relates to transportation network maintenance have been developed and are presented in the following sections. They can be used to develop partitions that are compact and have centralized locations of depots. Because solutions can be found within a reasonable time period, this approach can offer valuable support to a decision maker considering trade-offs between alternatives, modeled as problems with different limits on the constraints or as problems with slightly varying sets of constraints.

Discrete Variable Arc Partitioning Model (DVAP)

Network maintenance by the state of Indiana is administered out of service depots distributed throughout the state. The network partitions assigned to these depots are called service units. Four or five units are grouped together as subdistricts for administrative convenience. Four or five subdistricts are similarly grouped together and constitute a district. Each depot is responsible for different maintenance activities associated with the service unit assigned to it in addition to the routing considerations mentioned earlier. Designing each unit to be compact affords both accessibility and flexibility for those operations as well as in real-time snow removal operations. For instance, in the event of a breakdown, trucks servicing adjacent routes may assist by assuming extra loads more easily if the partitions are compact and well-connected.

A major goal in the design of service routes is to minimize the total amount of deadhead travel incurred during service. Except for very small units, which are not economically viable, it is impossible to design a set of routes incurring no deadhead. As the distance between the depot and the roads it services increases, it may become necessary to deadhead over larger distances to be able to complete service to a route within the set target time for that class of road. (Deadhead travel generally allows for higher travel speeds than service travel.) Further, deadhead is essentially a consequence of the location of the depot in relation to the network it services. A central location of the depot with access to many routes (such as a junction) should help reduce deadhead. Even where relocating the existing depots is infeasible, accessibility may be improved by repartitioning the network.

Maximum utilization of available resources is essential to efficient network maintenance. The number of service vehicles required in each unit is a function of the workload associated with that unit. Because fractional truck assignment is not physically possible, the workload assigned to each depot must be adjusted to require as close to an integer number of vehicles as possible. Also, it is reasonable to expect that eliminating wasteful travel in deadhead will help reduce the requirement for trucks. It must be noted that while these models try to minimize the estimated number of routes, the routes themselves are not being designed. It is assumed that routing will be done subsequently within each service unit. There is a relatively small range for the number of trucks required, with a lower limit specified by the kilometers of roadway (considering all lanes) requiring service and the plowing speed, assuming no deadhead. The maximum number of trucks worth considering is in the range of the number currently used. Thus, the knowledge implicit in past designs can be used to limit the branch-and-bound searches in terms of number of trucks.

The number of units that are needed to provide satisfactory service can vary between the number currently used and a lower limit based on (*a*) the number of kilometers requiring service in a region and (*b*) the number of kilometers that can be serviced out of a given depot. Currently all depots are designed such that no more than 13 to 15 routes can be serviced out of each.

Maximizing Compactness of Network Partitions

Requiring the networks to be compact implies that as many kilometers as possible are included within any given area. This in turn results in maximizing the connections within a given area. Let L_{ijp} be the sum of the distances from depot p to the endpoints i and j if the road segment having endpoints i and j is assigned to depot p for service, and 0 otherwise. Minimizing the sum of the shortest distances from depot p to the road segments that are serviced from depot p for all depots becomes a surrogate compactness measure.

$$\text{Minimize} \sum_{p} \sum_{(i,j)} L_{ijp} \qquad (1)$$

Model Constraints

Consider a set of potential service depots indexed as p. Define N_p to be the number of trucks required to service partition p. The number of trucks assigned to a depot p must be sufficient to service the total length of road segments assigned to that depot. Because all routes may require service simultaneously, the number of service trucks is also equal to the number of routes. Vehicular resources necessary to service a given route depend on (*a*) the length (workload) of that route and (*b*) the quality of service required for that route.

The workload of a road segment (W_{ij}) is specified in terms of the total kilometers (all directions) of that segment. Consider a road segment having endpoints i and j (endpoints of a road segment might be intersections or vehicle turnaround areas). If X_{ijp} is a binary decision variable that assumes a value of 1 if a road segment having endpoints i and j is assigned to partition p, and 0 otherwise, then $\sum_{(i,j)\ pairs} W_{i,j} X_{ilp}$ is the total workload assigned to depot p.

The frequency of service that must be provided to a given road segment depends on the classification of that segment (based on historical ADT across that segment). The class of a given route is determined by the classification of the highest-classed road segment assigned to that route. Given fixed service and deadhead speeds, the length of a route that a truck services depends on the class of that route. For example, in the state of Indiana, every portion of a route that includes a Class 1 road segment (ADT of 5,000 or greater) must receive service (plowing and/or spreading of abrasives and chemicals) every 2 hr. Assuming a plowing speed of 32.2 km/hr (20 mi/hr), a truck assigned to a Class 1 route can cover 64.4 km (40 lane mi). Trucks assigned to Class 2 and 3 routes, which require service every 3 hr, can cover routes 96.6 km (60 lane mi) long. While all routes may not be designed to be homogeneous in class, calculating the number of trucks based on the kilometers of each class of road, accounting for deadhead by a suitably chosen factor, will provide an estimate of the number of trucks required. The quality of the estimate depends on the validity of the factor selected. Efforts will be made in the future to relate the factor to the location of the unit as well as the workload assigned to the partition associated with it.

Define N_p^1 to be the number of trucks needed for servicing all Class 1 routes serviced out of depot p, and similarly for N_p^2 and N_p^3. N_p is the total number of trucks required in the area. Let CL_p^1, CL_p^2, and CL_p^3 be the kilometers of Class 1, 2, and 3 roads (all lanes), respectively, assigned to partition p and dhf_p be the deadhead factor used for partition p. Based on such homogeneous routes, a lower bound on the number of trucks required for servicing all road segments assigned for service out of depot p is determined by the following model constraints:

$$\sum_{(i,j) \in Class\ 1} W_{ij} \cdot X_{ijp} - CL_p^1 \leq 0 \quad \forall p \tag{2}$$

$$\sum_{(i,j) \in Class\ 2} W_{ij} \cdot X_{ijp} - CL_p^2 \leq 0 \quad \forall p \tag{3}$$

$$\sum_{(i,j) \in Class\ 3} W_{ij} \cdot X_{ijp} - CL_p^3 \leq 0 \quad \forall p \tag{4}$$

$$40N_p^1 - dhf_p \cdot CL_p^1 \geq 0 \quad \forall p \tag{5}$$

$$60N_p^2 - dhf_p \cdot CL_p^2 \geq 0 \quad \forall p \tag{6}$$

$$60N_p^3 - dhf_p \cdot CL_p^3 \geq 0 \quad \forall p \tag{7}$$

$$N_p - N_p^1 - N_p^2 - N_p^3 = 0 \quad \forall p \tag{8}$$

Upper and lower bounds on the required number of trucks can be derived as explained earlier. Let *NUMT* be the maximum number of trucks to be used such that

$$\sum_p N_p \leq NUMT \tag{9}$$

Likewise, let *NUMU* be the number of units to be operative at any time:

$$\sum_p U_p = NUMU \tag{10}$$

Both *NUMT* and *NUMU* are selected to be within the ranges discussed earlier.

If CAP_p is the workload capacity of depot p, assumed known for all depots, then a set of model constraints may be included to ensure that service to a partition from depot p can only be provided if that depot is opened ($U_p = 1$), and may not exceed CAP_p:

$$\sum_{(i,j)} W_{ij} \cdot X_{ijp} - CAP_p \cdot U_p \leq 0 \quad \forall p \tag{11}$$

The model must include a number of additional logical network constraints. First, each road segment identified for winter service must be assigned to exactly one service depot p:

$$\sum_p X_{ijp} = 1 \quad \forall (i,j) \tag{12}$$

All arcs in a unit must be connected to allow design of routes having continuous stretches for plowing. To model this, imaginary flows through the network from depots to the nodes in the unit they serve are introduced. Figure 1 shows the pattern of imaginary flows through a small network. Only arcs assigned to a partition may be used to carry this flow. Define Y_{ijp} as the flow from i to j in the arc (i,j) in partition p, and define Y_{jip} as the flow from j to i in the same arc. These flows may be in either direction (but not both) and be of any quantity up to some assumed maximum flow (*MF*):

$$Y_{ijp} - MF \cdot X_{ijp} \leq 0 \quad \forall (i,j), p \tag{13}$$

$$Y_{ijp} - MF \cdot X_{ijp} \leq 0 \quad \forall (i,j), p \tag{14}$$

In this example, flow originates in a super node (0) and flows into the depots (4, 5, and 15). Flow leaves the system only through non-depot nodes to return to node 0. Flow into the system is represented by Y_{0dp}, where d is any depot node, and flow out of the system is represented by Y_{i0p}, where i is any non-depot node. At each node, the following flow balance constraints must be satisfied:

$$\sum_k Y_{kip} - \sum_j Y_{ijp} - Y_{i0p} = 0 \quad \forall i \text{ non-depot nodes} \tag{15}$$

$$\sum Y_{kdp} - \sum_j Y_{djp} + Y_{0dp} = 0 \quad \forall d \text{ depot nodes} \tag{16}$$

Each non-depot node must conduct at least some positive flow out of the system. This ensures that each node is connected to at least one partition. In this formulation, the flows ensure connectiv-

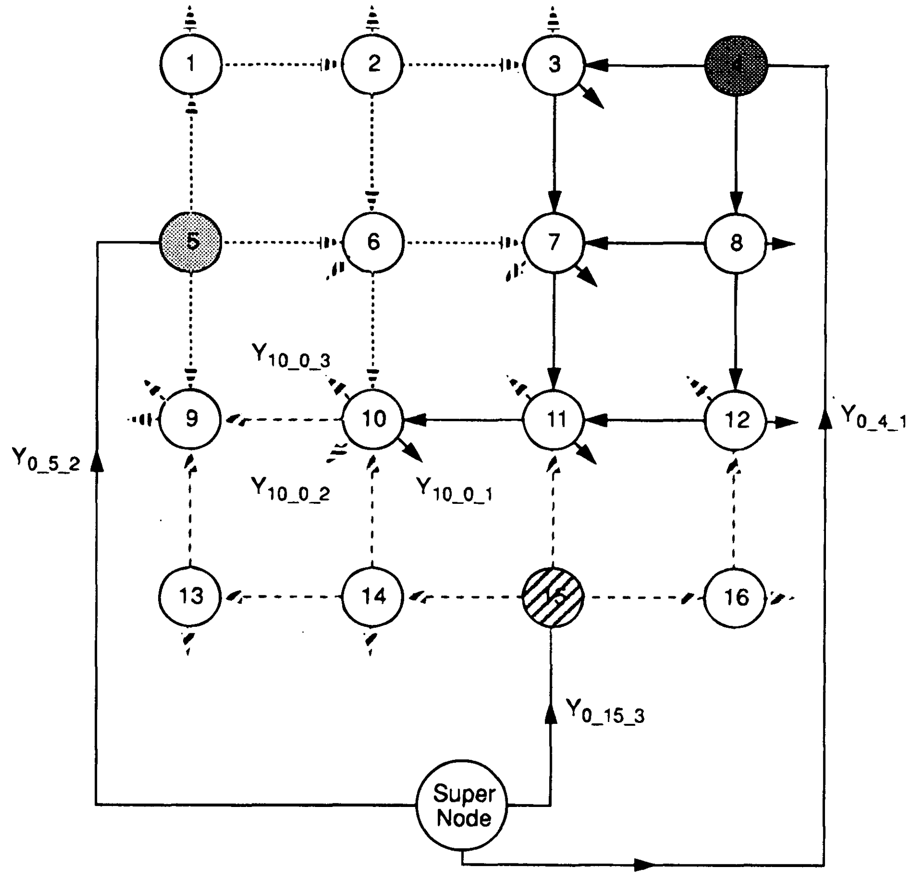

FIGURE 1 Connectivity enforced by imaginary flows in a hypothetical example.

ity, though they have no physical significance. The minimum flow is assumed to be 1:

$$\sum_{p} Y_{i0p} \geq 1 \qquad \forall i \text{ non-depot nodes} \tag{17}$$

The sum of flows into depots must be sufficient to meet the demands at all the nodes. Because each non-depot node has a demand of at least one unit, the total inflow should be greater than or equal to the number of non-depot nodes (*ND*):

$$\sum_{p}\sum_{d} Y_{0dp} \geq ND \qquad \forall d \text{ depot nodes} \tag{18}$$

Each depot is associated with a particular unit. For instance, Node 25 may correspond to a depot that services arcs assigned to Unit 2 (if open). If U_2 is 0 and the depot at Node 25 is not open, no arcs may be assigned to Unit 2. Node 25 cannot be the depot of any partition other than Unit 2. This is ensured by requiring any flow from the Supernode 0 into 25 to be zero for all partitions other than Unit 2. Thus

$$Y_{0dp} = 0 \tag{19}$$

if d is not in partition p.

Any arc can be assigned to a partition only when both ends are connected to that partition.

$$X_{ijp} - Y_{i0p} \leq 0 \qquad \forall (i,j), p \tag{20}$$

$$X_{ijp} - Y_{j0p} \leq 0 \qquad \forall (i,j), p \tag{21}$$

The sum of the shortest distances to both ends of an arc (i,j), L_{ijp} for all arcs (i,j) connected to the depot in partition p is nonzero only when the arc is assigned to that partition. The shortest distances to the ends i and j from the depot in unit p (SP_{ip} and SP_{jp}) are precalculated. L_{ijp} may be calculated as

$$L_{ijp} - SP_{ip} \cdot X_{ijp} - SP_{jp} \cdot X_{ijp} = 0 \qquad \forall (i,j), p \tag{22}$$

LMAX is the maximum of L_{ijp} values over all partitions:

$$LMAX - L_{ijp} \geq 0 \qquad \forall (i,j), p \tag{23}$$

LMAX should be less than some maximum permissible limit (*ML*):

$$LMAX - ML \leq 0 \tag{24}$$

The sum of L_{ijp} in any partition p ($SUML_p$) offers a means of comparing the quality of the compactness of one solution with another and is computed using

$$\sum_{(i,j)} L_{ijp} - SUML_p \leq 0 \qquad \forall p \tag{25}$$

The total cost for the selected number of trucks and units (*COST*) can be estimated as

$$COST - C^T \cdot \sum N_p - C^U \cdot \sum_{p} U_p = 0 \tag{26}$$

where C^T is the cost per truck and C^U is the cost per unit.

The complete model formulation follows.

$$\text{Minimize} \sum_p \sum_{(ij)} L_{ijp}$$

Subject to

$$\sum_p X_{ijp} = 1 \qquad \forall(i,j)$$

$$\sum_{(i,j)} W_{ij} \cdot X_{ijp} - U_p \cdot CAP_p \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 1} W_{ij} \cdot X_{ijp} - CL_p^1 \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 2} W_{ij} \cdot X_{ijp} - CL_p^2 \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 3} W_{ij} \cdot X_{ijp} - CL_p^3 \leq 0 \qquad \forall p$$

$$40N_p^1 - dhf_p \cdot CL_p^1 \geq 0 \qquad \forall p$$

$$60N_p^2 - dhf_p \cdot CL_p^2 \geq 0 \qquad \forall p$$

$$60N_p^3 - dhf_p \cdot CL_p^3 \geq 0 \qquad \forall p$$

$$N_p - N_p^1 - N_p^2 - N_p^3 = 0 \qquad \forall p$$

$$\sum_p N_p \leq NUMT$$

$$\sum U_p = NUMU$$

$$Y_{ijp} - MF \cdot X_{ijp} \leq 0 \qquad \forall(i,j), p$$

$$Y_{ijp} - MF \cdot X_{ijp} \leq 0 \qquad \forall(i,j), p$$

$$\sum_k Y_{kip} - \sum_j Y_{ijp} - Y_{i0p} = 0 \qquad \forall i \text{ non-depot nodes}, p$$

$$\sum_k Y_{kdp} - \sum_j Y_{djp} + Y_{0dp} = 0 \qquad \forall d \text{ depot nodes}, p$$

$$\sum_p Y_{i0p} \geq 1 \qquad \forall i$$

$$\sum_p \sum_d Y_{0dp} \geq ND \qquad \forall d \text{ depot nodes}$$

$$Y_{0dp} = 0 \qquad d \text{ not in partition } p$$

$$X_{ijp} - Y_{i0p} \leq 0 \qquad \forall(i,j), p$$

$$X_{ijp} - Y_{j0p} \leq 0 \qquad \forall(i,j), p$$

$$L_{ijp} - SP_{ip} \cdot X_{ijp} - SP_{jp} \cdot X_{ijp} = 0 \qquad \forall(i,j), p$$

$$LMAX - L_{ijp} \geq 0 \qquad \forall(i,j), p$$

$$LMAX - ML \leq 0$$

$$\sum_{(i,j)} L_{ijp} - SUML_p \leq 0 \qquad \forall p$$

$$COST - C^T \cdot \sum_p N_p - C^U \cdot \sum_p U_p = 0$$

$$U_p, X_{ijp} \in (0,1)$$

$$Y_{ijp}, Y_{i0p}, Y_{0dp}$$

$$N_p, N_p^1, N_p^2, N_p^3 \in \{integers\}$$

where

CAP_p = capacity of partition p,
CL_p^k = number of class k kilometers in partition p,
$COST$ = total cost of alternative,
C^T = cost of a truck,
C^U = cost of unit operations,
dhf_p = deadhead factor for partition p,
L_{ijp} = sum of the shortest distances to the node i and the node j from the depot in the partition p to which the arc (i,j) is assigned,
$LMAX$ = maximum of all L_{ijp},
MF = maximum imaginary flow in any arc,
ML = maximum allowable $LMAX$,
ND = number of non-depot nodes,
N_p = total number of trucks in partition p,
N_p^k = number of trucks for class k routes in partition p,
$NUMT$ = number of trucks chosen to service the area,
$NUMU$ = number of units chosen to be operative,
SP_{ip} = shortest path to i from depot in partition p,
$SUML_p$ = sum of L_{ijp} in partition p,
U_p = 1 if depot p is open and 0 otherwise,
W_{ij} = workload associated with arc (i,j),
X_{ijp} = 1 if arc (i,j) is assigned to depot p and 0 otherwise,
Y_{ijp} = flow in arc (i,j) assigned to partition p,
Y_{0dp} = flow into depot d from Supernode 0, and
Y_{i0p} = flow out of non-depot node i as a result of flow in arcs assigned to unit p.

Continuous Variable Arc Partitioning Model (CVAP)

Realizing that proximity considerations are sufficient in most cases to ensure connectivity within a unit's boundary, the flow constraints (Equations 13 through 21) can be relaxed as well as the requirement that X_{ijp} be a binary variable. In this formulation, variable X_{ijp} is the fraction of arc (i,j) assigned to partition p. Some interpretation as well as adjustment of the values of X_{ijp}'s may be required to understand which portion of the arc to assign to which partition as well as when an arc is assigned to more than two partitions. Using the same symbols (except for X_{ijp}), the complete formulation is included below.

$$\text{Minimize} \sum_p \sum_{(i,j)} L_{ijp}$$

Subject to

$$\sum_p X_{ijp} = 1 \qquad \forall(i,j)$$

$$\sum_{(i,j)} W_{ij} \cdot X_{ijp} - U_p \cdot CAP_p \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 1} W_{ij} \cdot X_{ijp} - CL_p^1 \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 2} W_{ij} \cdot X_{ijp} - CD_p^2 \leq 0 \qquad \forall p$$

$$\sum_{(i,j) \in Class\ 3} W_{ij} \cdot X_{ijp} - CL_p^3 \leq 0 \qquad \forall p$$

$$40N_p^1 - dhf_p \cdot CL_p^1 \geq 0 \qquad \forall p$$

$$60N_p^2 - dhf_p \cdot CL_p^2 \geq 0 \qquad \forall p$$

$$60N_p^3 - dhf_p \cdot CL_p^3 \geq 0 \qquad \forall p$$

$$N_p - N_p^1 - N_p^2 - N_p^3 = 0 \qquad \forall p$$

$$\sum_p N_p \leq NUMT$$

$$\sum_p U_p = NUMU$$

$$L_{ijp} - SP_{ip} \cdot X_{ijp} - SP_{jp} \cdot X_{ijp} = 0 \qquad \forall (i,j), p$$

$$LMAX - L_{ijp} \geq 0 \qquad \forall (i,j), p$$

$$LMAX - ML \leq 0$$

$$\sum_{(i,j)} L_{ijp} - SUML_p \leq 0 \qquad \forall p$$

$$COST - C^T \cdot \sum_p N_p - C^U \cdot \sum_p U_p = 0$$

$$U_p \in (0,1)$$

$$X_{ijp} \geq 0$$

$$N_p, N_p^1, N_p^2, N_p^3 \in \{integers\}$$

RESULTS

Both of the models presented in the previous section can be used to (a) select a prespecified number of depot locations from a set of potential sites (nodes on the network) and assign arcs to these depots or (b) repartition the network among existing depots. Service routes based at each depot are designed through a separate modeling process. The overall goal is to develop network partitions that best support the development of "good" routes. The quality of partitioning is measured in terms of compactness and the size of the fleet required.

A real data set representing an area served by four depots in the La Porte district of Indiana was used (63 nodes, 79 arcs) in testing both models. Mathematical programming formulations were generated using these data and solved using the CPLEX Mixed Integer Optimizer with barrier code, Version 2.1.

Discrete Variable Arc Partitioning Model

In the DVAP model presented above, the parameter *LMAX* was defined as the maximum allowable value for *L* (the sum of the shortest distances to the ends of the arc from the depot to which they are assigned). The selection of an appropriate value is essential in eliminating sites that cannot serve all areas adequately.

Figure 2 shows the existing service territories that are currently being used in an area in La Porte District. The total compactness measure is 2,600 km (1,615 mi), and *LMAX* is 84 km (52.2 mi). Figure 3 shows the service territories as suggested by DVAP for the same region. The total compactness measure is 2,236.9 km (1,389.4 mi) with *LMAX* restricted to being less than or equal to 56 km (35 mi). Through visual inspection of the service areas designed, it can be seen that this model can be quite effective in developing compact partitions.

DVAP uses a deadhead factor to account for deadhead in each partition. The deadhead in any partition would likely depend on the location of the depot, the portion of network assigned to it, and the number and quality of routes designed. A model that predicts the

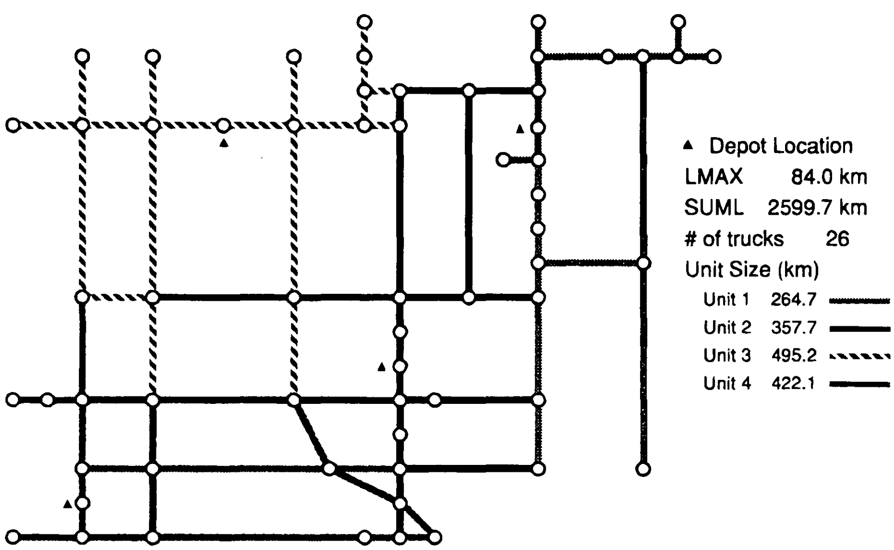

FIGURE 2 Existing service partitions in the test area.

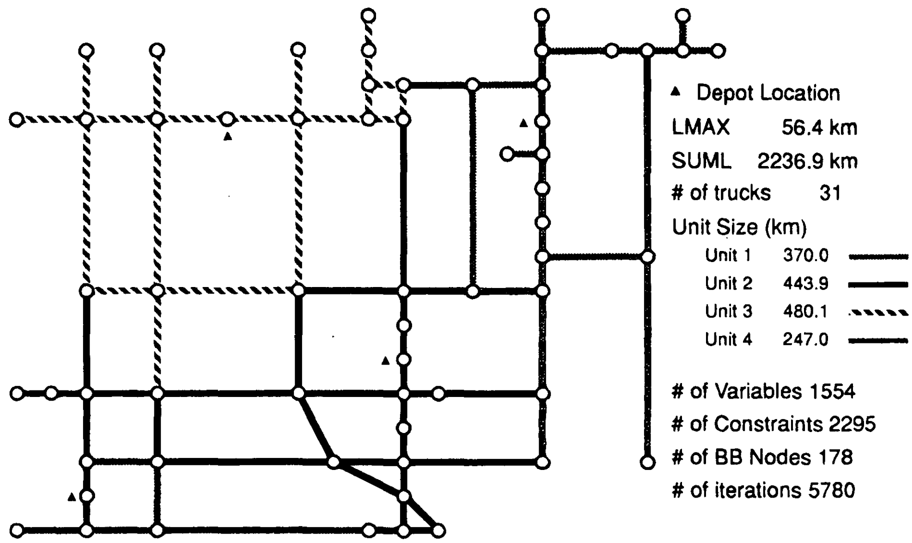

FIGURE 3 Partitions for the test area designed by the DVAP model.

deadhead factor prior to the development of partitions cannot consider the variation of deadhead with the size of the partition. Even if it is assumed that deadhead will not vary much within the range of partition sizes that are to be considered (400 to 565 service km or 250 to 350 service mi), the pattern of connectivity within the partition cannot easily be incorporated into the deadhead factor prediction. The estimate of the number of trucks allows for deadhead. Its accuracy also depends on the accuracy of the deadhead estimate.

An accurate prediction of the number of routes to be used is essential to decision makers because the costs associated with the number of routes are recurring. The minimum number of routes determined to be essential by the model (31) is greater than what is currently being used (26). This is partly because this model assumes that routes are homogeneous in class. In the current version of DVAP, mileage of each road class is used to calculate the number of trucks. Such homogeneous routes are, in general, not practical because homogeneous road segments are not necessarily contiguous and/or the workload for some road classes requires a fractional number of trucks. In practice, routes consisting of arcs of more than one type are designed. In estimating the number of trucks, therefore, it may be more practical to consider nonhomogeneous routes assuming an average route length, which is closer to 2 hr if there is a dominance of Class 1 roads and closer to 3 hrs otherwise.

Another factor that has led to overestimating the number of trucks is that the higher speed available for a truck that is deadheading has not been incorporated. The length of routes considered, 64.4 or 96.6 km (40 lane mi or 60 lane mi) are based on the service speed. These factors will be considered in future studies.

Continuous Variable Arc Partitioning Model

The same data set was used with the continuous variable version of the arc partitioning model, resulting in partitions as shown in Figure 4. Relaxing the integrality restrictions on arc assignment through the use of CVAP model reveals interesting characteristics of the trade-off between the operational practicality of a solution and the computational burden of the model. A comparison of solutions is summarized in Table 1.

The solution using CVAP on the same real data set used previously for DVAP produces the same solution. However, a feasible solution was found using the CVAP model and restricting the number of trucks to 26, the actual number of vehicles currently being used (Figure 4). A visual comparison of the two solutions presented in Figures 3 and 4 suggests that the two are quite close in terms of compactness and central depot locations. But from an operations standpoint, the CVAP solution would seem to be inferior to the DVAP solution for two reasons: (a) several arc assignments are fractional (arcs with two different shadings in Figure 4) and (b) one partition is not contiguous (upper right in Figure 4). Such solutions would require some means of adjustment, manual or otherwise. Some interpretation is necessary to decide which fraction of the arc is assigned to which partition. However, the cost associated with the CVAP solution clearly dominates that of DVAP (the cost of 26 vehicles instead of 31).

As expected, the CVAP solution is cheaper to implement than the DVAP solution from a computational standpoint as well. The continuous model required 670 variables and 751 constraints as compared with the 1,554 variables and 2,295 constraints required for the discrete formulation. CVAP found the solution with 172 branch-and-bound nodes and 484 iterations as compared with 178 branch-and-bound nodes and 5,780 iterations with DVAP. The continuous formulation can provide fairly good solutions more rapidly. The compactness requirement is, to a large extent, sufficient to enforce connectivity.

CONCLUDING REMARKS

Comparing the results obtained using CVAP and DVAP, it appears that the level of discretization of the network requires further consideration. CVAP uses the same set of equations to estimate the number of trucks required and is able to find feasible solutions

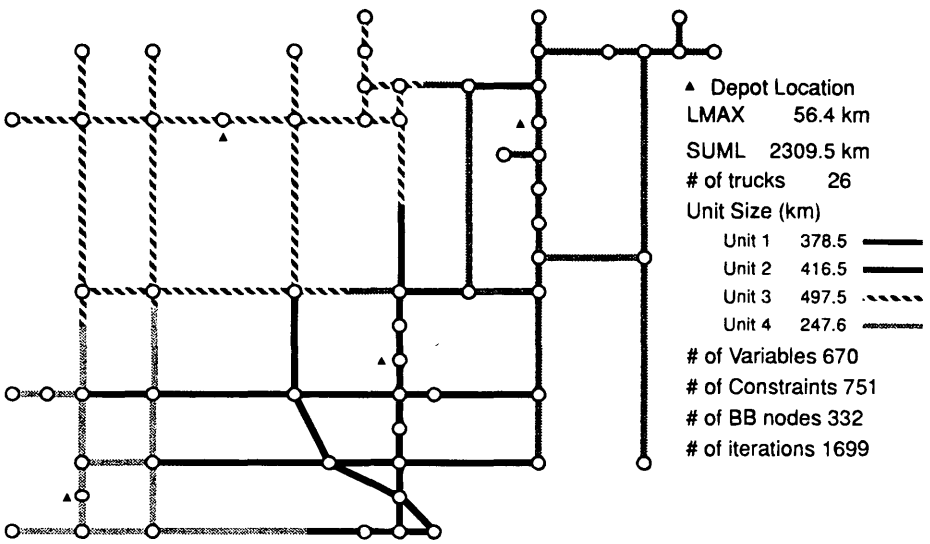

FIGURE 4 Partitions for the test area designed by the CVAP model.

TABLE 1 Comparison of DVAP- and CVAP-Generated Partitions for the Test Case

Model	Number of Variables	Number of Constraints	Number of Branch & Bound Nodes	Number of Iterations	Number of Trucks
DVAP	1554	2295	178	5780	31[a]
CVAP	670	751	172	484	31[b]
CVAP	670	751	332	1699	26[c]

a.Number of trucks necessary for a solution to exist.
b.Feasible solution does exist for a lesser number of trucks (c).
c.Number of trucks restricted to a maximum of 26.

requiring fewer trucks than the DVAP model. However, the solution using fewer trucks (Figure 4) requires fractional assignment of arcs. If a trade-off between the number of trucks and compactness was being studied using DVAP and the current data set, this solution would not have been considered. Yet if the network discretization had been such that those split arcs were in fact considered as two adjacent smaller arcs, DVAP might have been able to find a comparable solution. The selected network representation could influence the quality of solutions found and should therefore be chosen carefully. It is possible that solutions using CVAP could provide information to make such a choice.

Both models show some promising directions for future research and practical applications. While the solutions generated by the DVAP model are integer feasible, the computational effort needed to solve the model is significant. The CVAP model is simple and easy to solve, and may be considered if heuristics are to be used to account for routing considerations and deadhead. Additional studies on test cases may suggest enhancements to the models as well as suitability of these models to find solutions to larger districting problems. Evaluation of the quality of solutions through the routing phase of design is essential.

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Evaluation of Computer-Generated Routes for Improved Snow and Ice Control

JIN-YUAN WANG, PADMA KANDULA, AND JEFF R. WRIGHT

A route design decision support system was developed for maintenance engineers of the Indiana Department of Transportation (INDOT) to use in designing snow and ice control service routes. This system, known as CASPER—Computer Aided System for Planning Efficient Routes—incorporates a multiple objective heuristic optimization procedure to identify routes that have excellent serviceability and efficient resource usage. Routes designed using CASPER were placed into service and carefully evaluated by INDOT maintenance officials. The evaluation showed a significant improvement in network service and, at the same time, a 10 percent reduction in the size of the service fleet required. Cost savings to date are conservatively estimated at $5 million and are expected to exceed $14 million projected over a 10-year period when the system is implemented statewide.

The efficiency of Department of Transportation (DOT) winter maintenance activities depends, to a large degree, on the routes the maintenance personnel use to conduct these important operations. The snow route design problem faced by most DOT maintenance engineers may be characterized as follows:

> Given a partition of the transportation network to be serviced using resources issued from a single depot located on that partition, find the noninferior set of configurations for *N* service routes that collectively service that network partition.

Recent research aimed at improving the configuration of winter service routes for the Indiana Department of Transportation (INDOT) demonstrated that significant cost savings may be realized through the systematic integration of operations research methodologies with spatial network data [geographic information systems (GIS)] to solve this routing problem (*1*).

The decision support system that was developed to address the snow vehicle routing problem is called CASPER—Computer-Aided System for Planning Efficient Routes. Upon completion of the CASPER system prototype in the fall of 1992, a systematic testing procedure was started in early 1993. Through this process, INDOT maintenance engineers used CASPER to produce detailed snow route designs for a portion of the transportation network that was previously serviced by 430 service vehicles. The new route configurations produced using CASPER for the same service area required only 396 service vehicles. The new routes were put into service during the 1993–94 snow season and were shown to provide significantly better service than the original routes.

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WINTER NETWORK MAINTENANCE PROBLEM

Maintenance operations within INDOT are administered from six district offices, each of which is further divided into five or six subdistricts. Each subdistrict oversees operations that are conducted from five to six service depots (also called units). Each unit is responsible for providing service to a portion of the network using a fleet of trucks, each servicing a specific route. Logistically, route designations may be quite complicated and interrelated. For example, consider a small hypothetical service area that is to be serviced using two vehicles, as shown in Figure 1. Two different routes are shown: a black route and a gray route. Service travel for both routes is shown with solid lines, and deadhead travel is indicated by dashed lines. For example, upon initiation of the snow fighting operation, both trucks leave the service depot heading due west with the black route performing service (spreading and/or plowing) to Point A, and the gray route deadheading. At Point A the truck servicing the black route turns north while continuing to service the road surface, and the truck servicing the gray route continues east and initiates service. Because this service district includes a portion of an interstate, tandem service (service by both vehicles together) is required. Consequently, the vehicles must meet at the on-ramp entrance (Point B) to initiate this service. Tandem servicing might continue in a southeasterly direction to Point C (a median turnaround location) at which the vehicles reverse direction. Leaving the interstate portion of their routes near Point B, the vehicles separate and continue servicing/deadheading on their respective routes, returning to the service depot for replenishment of their supplies. If additional servicing or clean-up activities are needed, the routes are repeated until the operation is completed.

The number of routes assigned to a depot ranges from 5 to 15 and are class dependent. INDOT uses a method of road classification based on the average daily traffic (ADT). There are three classes of roads. Class I roads have an ADT of 5,000 vehicles or more; Class II roads are those with an ADT between 1,000 and 5,000 vehicles; and Class III roads have an ADT of 1,000 vehicles or fewer. Routes take the class of the highest ranked road segment they contain. Routes should preferably be homogeneous with respect to class. When some mixing of classes is unavoidable, it is preferable to avoid mixing Class I roads with Class III roads.

Travel by service vehicles on the network is classified as either (*a*) service travel, with the truck plowing snow off the roadway and/or the truck spreading material on the roadway or (*b*) deadhead travel, with the truck traversing that road segment in order to travel to another location to begin servicing another road segment. Deadhead travel generally allows higher travel speeds, while different service types (plowing versus spreading) may have different speed requirements. A major goal of route design within INDOT, especially for snow and ice control operations, is to minimize the amount of deadhead travel.

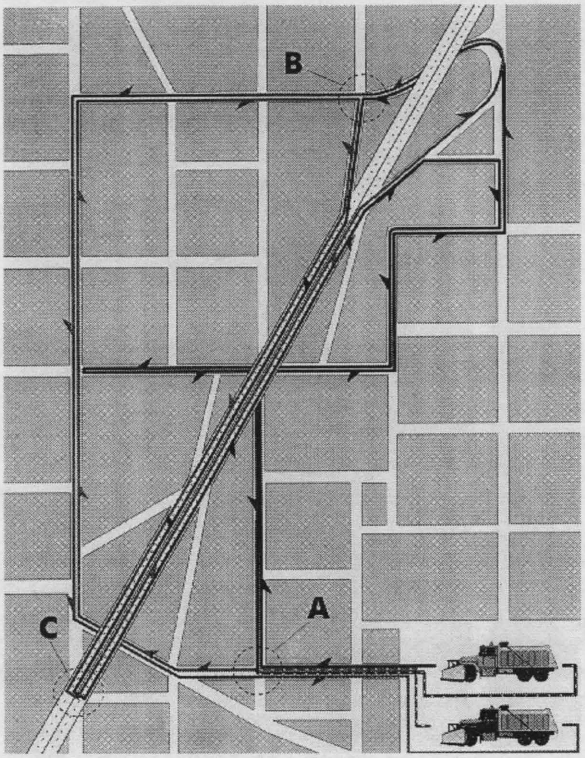

FIGURE 1 Schematic representation of the multivehicle, single-depot snow route design problem.

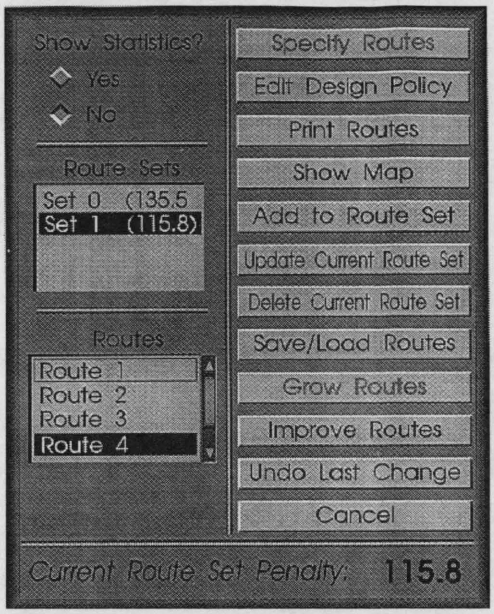

FIGURE 2 Main route design dialogue box within the CASPER graphical user interface.

INDOT's guidelines indicate that good Class I routes should receive service every 2 hr and Class II and III routes every 3 hr. The routes are, therefore, designed to be 2 and 3 hr long so that consecutive passes on the same routes achieve the required frequency.

CASPER ROUTE DESIGN SYSTEM

CASPER was designed and developed to assist in the design of a set of feasible routes originating and terminating at a specific depot to service a preselected portion of the network. In the current implementation, the selected portion of the network conforms to the boundaries of the unit partitions that have evolved through the years. In generating a feasible route set from which to proceed, CASPER estimates the number of trucks required to service the area based on the number of lane miles requiring service, the average service speed, and the service time limitations on that length of the route. Arcs (road segments) are then assigned to each truck such that the trucks provide mutually exclusive and collectively exhaustive coverage of the network. A one-step-ahead search is used to guide route growth in the direction that looks most promising. A shortest-path–based method is used to determine the minimum possible time required to finish servicing the current route should a particular arc be accommodated in the route.

Starting from the initial set of routes, CASPER can be used to improve the routes in a manual mode or an automated mode, much like using an intelligent computer aided design (CAD) system to plan a physical facility layout. The user may select from a number of design modules using a convenient graphical user interface. A typical design dialogue box is shown in Figure 2, with press bars to invoke models and CAD display routines on the left-hand side of the menu, and routing statistics and route sets on the right. The routes designed in either case are assigned a value based on a penalty structure with user-specified weights for the different objectives. The total penalty score for the "current" route set is displayed at the bottom of the dialogue box shown in Figure 2.

The penalty score that drives the design process is pre-established by the user and is a function of the three design objectives discussed previously: (*a*) minimize deadhead travel distance, (*b*) maximize road class continuity, and (*c*) minimize deviation from target service times. The user provides weights or relative priorities for these objectives by setting values (sliders) in a "routing policy" dialogue box (Figure 3). The user may also establish design constraints, such as restrictions on mixing road classes, and tandem servicing restrictions. The user may also elect to fix or "freeze" individual routes such that the model may not make subsequent changes automatically.

In the automatic mode, CASPER uses Tabu Search, a strategy that has achieved impressive success in many combinatorial optimization problems (*2,3*). The search moves to an improved solution in the neighborhood of the current solution, except when the current solution is a local optimum. Tabu Search, unlike purely improving search strategies, avoids getting trapped at a local optimum by allowing nonimproving moves out of the vicinity of a local optimum. Cycling is avoided by forbidding moves likely to take the search back to the recently visited local optimum. At any time during the process, the best solution found is called the incumbent solution. The user explores the solution space using this procedure repeatedly until he or she is satisfied that the incumbent solution is close to optimal or until some preset maximum number of iterations has been reached.

A tabu list is a list of moves that are forbidden. The tabu list is of limited length, and once it is filled, any addition to the list causes the oldest member on the list to be deleted from the list. The length of the tabu list determines the length of the cycles that are prevented and is a parameter that needs to be carefully selected based on the

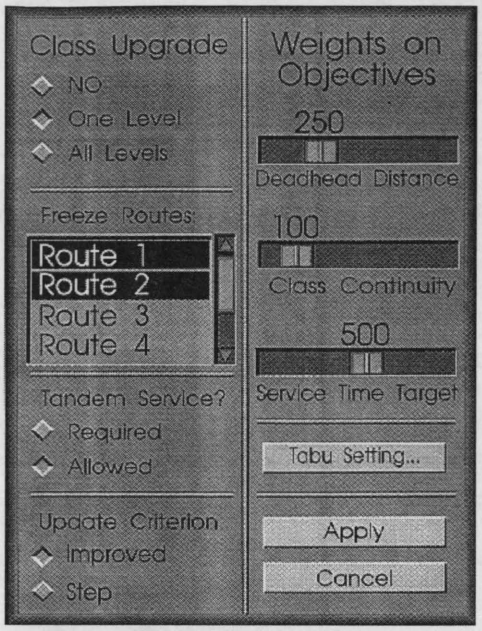

FIGURE 3 Route design policy dialogue box of the CASPER graphical user interface.

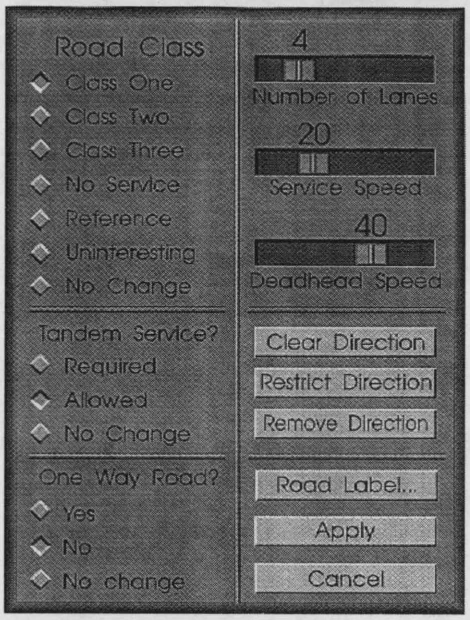

FIGURE 4 Design template for road classification in the CASPER graphical user interface.

application. Aspiration criteria provide conditions under which the tabu restrictions may be overridden. The tabu lists and aspiration criteria provide a control mechanism to constrain and free the search procedure. The user may change the tabu lists and aspiration criteria through the design policy dialogue box of the graphical user interface (Figure 3).

CASPER uses a spatial description of the network based on the U.S. Geological Survey Digital Line Graph (DLG) data. In addition to the network connectivity provided by the DLG data, information related to routing is needed to design feasible routes. Such information includes the road classification based on ADT, number of lanes in each direction, vehicle travel speeds while servicing and deadheading, points where the trucks fitted with snow plows can maneuver a U-turn safely and conveniently, depot locations, and direction restrictions. Direction restrictions include one-way roads as well as certain intersections (such as at an entrance ramp) in which left turns are not allowed. The CASPER prototype includes mechanisms for reclassifying standard DLG data files to develop these data bases. This is accomplished by users who are knowledgeable about the service areas and who compose data templates describing the relevant features of individual road segments and network nodes (intersections, turnaround areas, etc.). Dialogue boxes used for data-base development are shown in Figures 4 and 5, for roadway and node classification, respectively.

It is emphasized that the data discussed above are an integral part of the CASPER methodology. The success of the system results from the use of explicit objectives within the search heuristic to converge on good solutions and the ability of a knowledgeable user to select the best solution among them based on additional constraints and requirements specific to the particular area. The level of detail reflected by the spatial representation of the network is essential for the user to evaluate different options.

The multi-objective snow route design problem can be summarized as a multi-objective optimization model having the following form:

Objectives:

- Minimize the deviation from the target service times.
- Minimize deadhead.
- Maximize road class homogeneity.

Constraints:

- Each arc must be serviced only as part of one route.
- Routes must be designed to be continuous.
- Contributions toward the route service times must be appropriately calculated based on whether the arc is being serviced or being used to deadhead over.
- Routes should start and end at the depot.
- Subtours must not be allowed.

CASPER incorporates this model into a framework that allows a user who is knowledgeable about the winter maintenance operation to design efficient route configurations. The specific algorithm used in CASPER is summarized as six iterative steps (*4*):

1. Generate an initial feasible solution and designate this as the current solution. This is also the incumbent solution or best solution found so far.
2. The neighborhood of the current solution is the set of solutions differing from the current solution by a pair of arcs. Generate possible candidate solutions to move to in the neighborhood of the current solution.
3. Select the best admissible candidate. The best admissible candidate is the candidate solution showing the greatest improvement (or least worsening if the current solution is a local minimum) that (*a*) is not forbidden (tabu) or (*b*) is forbidden but satisfies the aspiration criteria.
4. Make the best admissible candidate the current solution. Update the incumbent solution if it is better than the incumbent solution currently stored.

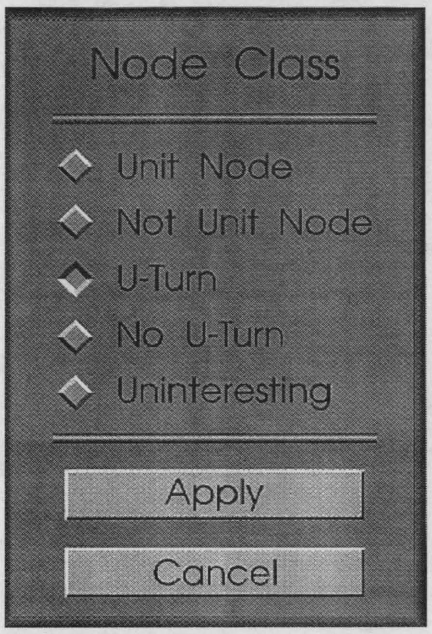

FIGURE 5 Design template for node classification in the CASPER graphical user interface.

5. Update the tabu list by adding the best admissible solution used. The tabu list is of limited length; therefore, the oldest member on the list is deleted if the list length maximum has been reached.
6. Check whether the stopping criterion (specified number of iterations or satisfactory solution) is met. If not go to Step 2. Else stop.

The six-step search procedure is driven by penalties assessed according to model objectives described earlier and is consistent with user-specified weights on those objectives. The following section discusses the use of the model to date within the state of Indiana.

ROUTE DESIGN PROCEDURE

To achieve a comprehensive evaluation of the CASPER route design system, the initial design of service routes was planned as a three-phase procedure. First, a team of researchers and maintenance engineers established a uniform design policy that would be used for all service areas. Second, routes would be designed by teams consisting of local maintenance personnel and a project manager who would participate in all design activities. Third, new routes would be placed into service for a winter season, after which maintenance personnel would be interviewed as to the quality and efficiency of service in comparison to previous routes. Each of these phases is discussed below.

Establishing a Design Policy

Before INDOT could begin designing snow routes for the state, a design policy and protocol for using the prototype software had to be established. CASPER was originally conceived to design routes with a flexible user-definable policy. That is, CASPER designs routes based on several objectives for which the user has the ability to set relative levels of importance. Specifically, the amount of deadhead mileage, adherence to class continuity, and time limit for each class of route can each be given a value on a scale of 0 to 100 that defines how important that objective is relative to the other two.

At a meeting held before the beginning of the route design process for the state, it was decided to design the state's first set of routes with a uniform and fixed policy. This three-part policy is commonly referred to as the CASPER penalty function.

The CASPER penalty function is used by the route designer to help evaluate the "*goodness*" of any given set of routes. After several discussions with INDOT personnel and testing in a typical district, the following criteria were used to determine the penalty score for all routes designed by INDOT. As discussed previously, any given route's penalty score comprises three contributing factors: total service time, deadhead distance, and class continuity.

Total Service Time

Class I routes have a target service time of 2 hr, and class II and III routes have a target service time of 3 hr. Service times are based on a deadhead speed of 64.4 km/hr (40 m/hr) and a service speed of 32.2 km/hr (20 m/hr). For Class I routes, a penalty value of 0 is assessed for routes that have a service time between 90 and 120 min, corresponding to the ideal service time window. For Class II and III routes, the ideal service time window with 0 penalty value is between 150 and 165 min. For any class route, if the service time is either below or above the ideal service time window, then a cubic function is used to determine the penalty value based on the number of minutes the route is below or above the lower or upper bound of the window. For example, if a Class I route has a service time of 85 min, then the total service time penalty value contribution to the route's total penalty score would be $5^3 = 125$ points for the 5 min the route was below the lower bound of the ideal service time window (90 min).

Deadhead Distance

For any class route, 1 deadhead mi (1.6 km) equals one penalty point for each deadhead mile in the route.

Class Continuity

For any class route, the number of off-class miles in the route divided by 3 equals the number of penalty points for the route. The value 3 was chosen to cause deadhead mileage to be roughly three times more important than class continuity or the number of off-class miles in a route.

This penalty structure causes total service time to be the most important consideration when designing routes. If a route is more than 10 min above or below the ideal service time window, then its penalty score will be at least 1,000 and deadhead or class continuity will not significantly affect the penalty score. It should also be noted that the function is exponential, which creates the potential for very large penalty values. Deadhead and class continuity become the dominant factor when the route is within the ideal service time window or very close.

Design Process

Following the completion of the CASPER prototype route design system, a team of maintenance engineers was assembled to redesign service routes for INDOT. This team consisted of

- A project leader, who would have major design responsibility within the entire state and had extensive experience with winter maintenance operations;
- Two to three maintenance personnel with local or regional knowledge at the subdistrict level; and
- A technician for assisting with data and computer operations.

Model parameters (including weights on objectives), constraint settings, and tabu search parameters were kept constant throughout the operation to ensure that a uniform design policy was used for evaluative purposes.

During the winter season following the redesign of service routes for the northern districts of INDOT, the routes were put into service and later evaluated by INDOT maintenance personnel. The following section describes the performance of the new routes based on the design objectives used.

Performance Based on Design Objectives

Service routes were developed using CASPER for several units in the four northern districts of Indiana: LaPorte, Ft. Wayne, Crawfordsville, and Greenfield. The effectiveness of CASPER in identifying efficient service routes within the context presented above is summarized in Table 1. A total of 430 routes were redesigned for four northern INDOT district offices: LaPorte, Ft. Wayne, Crawfordsville, and Greenfield. In each case, the aggregate penalty score was reduced by a considerable margin—95 percent to 99 percent.

More dramatic than the overall improved level of service afforded by the redesigned service routes is the reduction in overall cost of the entire operation, as shown by Table 2. In that table, data are presented for two route configurations for the region: (*a*) the routes in place before the use of CASPER and (*b*) the routes redesigned using CASPER, which are now used. The total number of routes to provide service to a constant area has been reduced by 34 (see Columns 2 and 6 in Table 2). Using an estimated cost per route over a 10-year period of $140,000, the total cost reduction indicated for the routes designed so far amounts to $5 million. Here the cost per route (truck) is the sum of vehicle cost, cost of mounted equipment, annual maintenance cost, fuel cost for winter service, and labor cost for maintenance (present value of cost flow over 10 years).

Total cost savings resulting from the redesign of all service routes are estimated to be at least $15 million.

TABLE 1 Evaluation Using CASPER's Penalty Structure

District	Penalty Scores	
	Previous routes	CASPER routes
Greenfield	673943.3	7818.3
LaPorte	7887880.9	196433.6
Ft.Wayne	2360264.0	48877.0
Crawfordsville	10285596.8	534522.4

Although the service routes developed using CASPER clearly dominate those previously employed by INDOT, a more detailed comparison of the routes before and after CASPER uncovers an interesting paradox. Consistently, the design team was willing to sacrifice two objectives—minimize deadhead distance and enforce class continuity—in favor of the third objective—minimize deviation from the target service times. As is shown in Table 2, the contribution to the overall penalty for deadhead distance and class homogeneity objectives usually increased, in general, during the use of CASPER. For example, in Crawfordsville district, which contains about 7,240 km (4,500 lane mi) of road, the earlier route configuration used 144 service routes with a total of 2,070 km (1,286 lane mi) of deadhead and 862 km (536 lane mi) of off-class road segments. Following the use of CASPER to redesign routes for the same network partition, the resulting deadhead and off-class miles increased to 2,267 km (1,408 mi) and 1,609 km (1,000 mi), respectively. Yet the overall penalty score decreased from more than 10 million to 550,000 (Table 1). When questioned about this seeming contradiction, in the stated policy used in model design versus policy used in route design, the response for the new route designs was enlightening: "All routes should receive the highest level of treatment maintaining bare pavements for as long as possible. The lower level of service for class II and class III roads comes into play only when it is impossible to maintain class I level of service for the entire region. As such, for these routes that are meant to be used for 'average' storms, the class continuity requirement is not as binding. Real time adjustments can then be made as required based on the actual intensity and areal extent of the snow event. As such, the requirement for class continuity in the routes designed for the average storm is not as important."

"The problem with deadheading is mostly connected with the public perception. Deadheading is viewed to be evidence of inefficient operation, and complaints arise when citizens observe trucks deadheading over road segments that have not been serviced. With improvement in the overall quality of the set of service routes designed, citizens are likely to be less frustrated. It is a fact that deadhead can never be totally eliminated using the existing depots or a comparable number of depots. However, any other means to reduce deadhead are worth considering."

The departure from the stated policy in the matter of class continuity was acceptable because a higher level of service was being provided. The stated policy was interpreted to be the least acceptable level of service. On the other hand, a reduction in deadhead would be desirable.

Characteristics of CASPER Solutions

Although the performance of the CASPER methodology can be evaluated explicitly using the penalty structure with specified weights on objectives or costs associated with the operation, an evaluation of other characteristics of the routes designed in different units reveals additional considerations. The premise of this research is that some factors, such as reduction of deadhead travel, might better be addressed at the partitioning level, and factors that are not considered in CASPER, such as compactness of the area served by a given depot, can affect the quality of the routes designed. A study of the route design with respect to some of these factors reveals information about the decision makers' acceptance levels for certain routing criteria and features of favorable network topology. This information can be used to improve the base data

TABLE 2 Comparison of Snow Removal Operations in Districts Before and After Redesign Using CASPER

District	Before CASPER				After CASPER			
	# of routes	Total Distance (km[a])			# of routes	Total Distance (km)		
		Service	Deadhead	Off-class		Service	Deadhead	Off-class
Greenfield	57	2929.6	7312.6	681.2	58	2850.0	857.5	769.4
La Porte	113	5595.7	2312.0	406.8	99	5394.1	1673.4	1225.2
Ft.Wayne	116	5687.0	1907.7	975.0	108	5683.9	2045.7	1644.6
Crawfordsville	144	7238.4	2070.6	862.3	131	7251.1	2266.6	1609.2

a.1 km = 0.62 miles

(network partitions) that are subsequently used by CASPER in designing routes.

In reviewing the route sets developed by CASPER and agreed upon by the design team, two factors surfaced as being most important favoring good designs: (a) the location of the unit with respect to the network partition to be serviced from that unit and (b) the size of the unit (number of service miles assigned to a particular unit). Of these factors, the former is intuitive but the latter is not.

It was generally agreed by the design team that the most important factor in achieving a good set of routes for a predetermined partition of the network was the location of the unit servicing that partition. Although difficult to quantify because both the location of the units and the network partition of each were fixed and constant through the design process, all agreed that designs for units that were centrally located were better than for those that were not. This result is not surprising. Given a fixed network partition, a central unit location will tend to reduce redundant travel in reaching the most distant road segments within the specified target times. Unit locations adjacent to multilane highways were also found to result in superior performance to those on more restricted access road segments.

Field Testing and Final Evaluation

An attempt had been made to redesign approximately one-third of the state's snow routes up to that point, and it was thought that the limited amount of resources available to the project would be better used in implementing an accounting system that would provide a means for evaluating the redesigned routes. Also, any new routes that would be designed that late in the year could not be implemented for the current season.

The preliminary results of using the CASPER prototype system required field testing and verification. It was anticipated that some units would require modifications to be made to their route sets and possibly even an entire redesign after the field testing. With the possibility of some units requiring an additional truck after redesign and others implementing new configurations, the net increases in improved efficiency should remain about the same.

One of the intangible benefits of the CASPER software system is the computer-based design and decision support environment that it provides its users. As the unit and subdistrict personnel become more familiar with the system and have the opportunity to customize or effect changes on its design, they will inevitably use it more often to perform analyses, designs, comparisons, and what-if or hypothetical testing of ideas. They will view the system as a valuable tool to manage their limited resources and provide a better level of service to the public.

INDOT maintenance management staff developed the CASPER snow route evaluation procedure and forms. This procedure established a four-step process by which each unit could provide feedback as to the usability and goodness of each route it had designed using CASPER. The goal of the process was to evaluate how effectively CASPER had designed routes by obtaining feedback from the unit foreman and snow plow driver levels.

The first step of the process was to document each new route. After each unit completed its CASPER session, color printouts were produced of the routes the unit had designed. These printouts were taken to the subdistrict offices, where they were used to create INDOT route documents (directions). INDOT documents each of its routes with a tabular and map representation form. The subdistrict and unit personnel were also asked to strictly adhere to each CASPER route with only one truck so that a true and accurate evaluation of the CASPER routes could be performed.

The second step in the procedure was to simply test the routes on a dry run basis and train the drivers. Each driver was to drive his or her route in dry pavement conditions so that they could learn and become comfortable with it. They could also document any problems that they might foresee with the route at that time, such as traversal time.

The third phase of the procedure was to formally document each traversal of each route during a snow event. A standard evaluation form was produced for this purpose. The form for each route consisted of spaces for the designed traversal time, actual traversal time, road condition, and whether the truck was plowing or spreading on that pass. A remarks section for documenting problems or the lack thereof also was included. Each driver completed these forms for every pass he or she made of his or her respective routes, and the subdistrict offices collected the forms.

The fourth and final part of the procedure was to synthesize the evaluation forms. If a route was found to be absolutely unusable, then the subdistrict was to locally fix the problem in whatever way it deemed necessary. All other documented problems were to be sent to the state office for compilation. With this information, the state could track and compile statistics on the effectiveness and usability of the CASPER routes.

The results for the 1992–93 snow season have been compiled for 262 routes (66 percent of the total number of routes redesigned), and 72 percent of the CASPER-designed routes were found to be acceptable. The subdistrict acceptance rates varied greatly from 23 to 100 percent. The reasons behind the large variance in acceptance have yet to be fully investigated at this point, but the variance could be related to problems with the base data, the constant travel speeds that were assumed during the design, or minor problems that are being perceived as major.

At this writing, all remaining route design problems identified during testing have been resolved without the need for systematic redesign using CASPER. Work is in progress to develop models to redistrict service areas and to adapt this methodology to other maintenance activities

ACKNOWLEDGMENTS

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Spreader Equipment for Anti-Icing

EDWARD J. FLEEGE AND ROBERT R. BLACKBURN

In the development of anti-icing technology, the need to apply a small amount of chemical in a very uniform pattern on the roadway surface was identified. All known manufacturers of spreader equipment were contacted to develop a master list of sources of application equipment and to learn about their testing procedures. It was determined that there are no procedures in the United States for evaluating highway spreader equipment under field conditions. The German government has standards for testing spreader equipment. Also, the European equipment manufacturers have testing procedures for evaluating their own equipment. A testing procedure will be of use to agencies who wish to evaluate available equipment to integrate anti-icing technology into their snow and ice control operations.

Limited experience of mainly European and Scandinavian countries has shown that applying a chemical freezing point depressant on a highway pavement before or very shortly after the start of frozen precipitation minimizes the formation of an ice-pavement bond. This anti-icing practice reduces the task of clearing the highway to bare pavement conditions and requires smaller chemical amounts than are generally required under conventional de-icing practices.

To accomplish anti-icing effectively, it is desirable to utilize spreader equipment that can meter a precise small quantity (such as 10 g/m^2 or 130 lb/lane mi) of applied chemical and spread it uniformly across the roadway.

Under SHRP Contact H-208 dealing with anti-icing technology, one of the objectives was to identify spreader equipment that can control the application rate and spreading pattern for solids, prewetted material, and liquid chemicals. The results of that portion of the study are reported in this paper.

In late summer of 1991, all potential American sources of spreader equipment used to apply de-icing chemicals were contacted. In addition, an effort was made to learn if and how U.S. highway spreader manufacturers tested their equipment's performance. This information was to be used to develop the necessary testing protocols for proposed American testing standards for winter maintenance spreaders. It was determined, however, that the highway spreader industry does not test its equipment's operating characteristics under actual field conditions. One exception was the Salt Institute, which has developed a procedure to measure the application rates of a spreader in a stationary mode. This standard was not useful to this study, however, because information was needed on spreader equipment tested in a dynamic mode.

The only standard test method found in spreader equipment literature from the United States was that developed by the American Society of Agricultural Engineers, ASAE Standard S341.2, Procedure For Measuring Distribution Uniformity and Calibrating Granular Broadcast Spreaders. However, this procedure is used with fertilizers, which have a narrow gradation band in comparison to salt. Furthermore, this standard does not pertain to application on a hard surface.

From the survey, it was evident that it would be necessary to develop a protocol that could be used to test and to evaluate spreader equipment. This standard would have to provide results that are accepted as valid by the spreader industry.

In developing a testing protocol for evaluating spreader capabilities, the researchers assigned fixed values to some of the test variables whereas other variables were measured and evaluated. A number of concepts were tested to evaluate the variables influencing material application rate and material distribution patterns.

First, the project team measured the application rates of some typical highway spreaders in a dynamic mode. Truck speeds of 24, 40, and 56 km/hr (15, 25, and 35 mi/hr) were selected as typical speeds used during salt application. Because the trucks usually travel in third or fourth gear at these speeds, it was first necessary to determine the respective engine rpm during actual operation. Next, the rear axle was lifted off the ground so that the drive wheels cleared the surface. The amount of material dispensed from the feed mechanism over a measured time and for a specific control setting was collected and weighed at each engine rpm to establish the material application rate (i.e., mass/unit time).

It was found that the material application rate varied substantially, both from spreader to spreader and from that specified by the spreader control manufacturer. Also, a number of the spreader vehicles had faulty hydraulic systems, which prevented the controls from providing accurate or repeatable results from setting to setting.

A series of spreader tests was performed to develop the most efficient method for measuring the material distribution pattern. A Schmidt spreader mounted on a Unimog truck was used for tests conducted during cold weather at an inactive truck weigh station along I-35 near Duluth, Minnesota. Three different methods of collecting salt spread during the tests were evaluated: hand sweeping, collection pans, and vacuuming of pavement strips. Dry rock salt meeting ASTM D632 Grade 1 was used.

Three test series were conducted. The arrangement shown in Figure 1 was used first. (Note that the vehicle wheel tracks are located between Sampling Locations 4 and 5 and Locations 6 and 7.) The amount of material collected by two different types of collection pans (i.e., one plastic and one aluminum) was compared with the hand sweeping of the equivalent area of the pavement at Sampling Location 5 along Line AB. Tests were conducted at actual vehicle speeds of 23, 32, and 40 km/hr (14, 20, and 25 mi/hr), with three passes made at each speed. A hand-held radar unit was used to measure the truck speeds.

The material distribution patterns for truck speeds of 23, 32, and 40 km/hr (14, 20, and 25 mph) as determined by hand sweeping are shown in Figure 2. Figure 3 shows a comparison of hand sweeping and pan collection at Sampling Location 5 (i.e., the area directly beneath the spinner), the center of which is 5.2 m (17.3 ft) from the left edge of Sampling Location 1. As indicated by the hand sweep-

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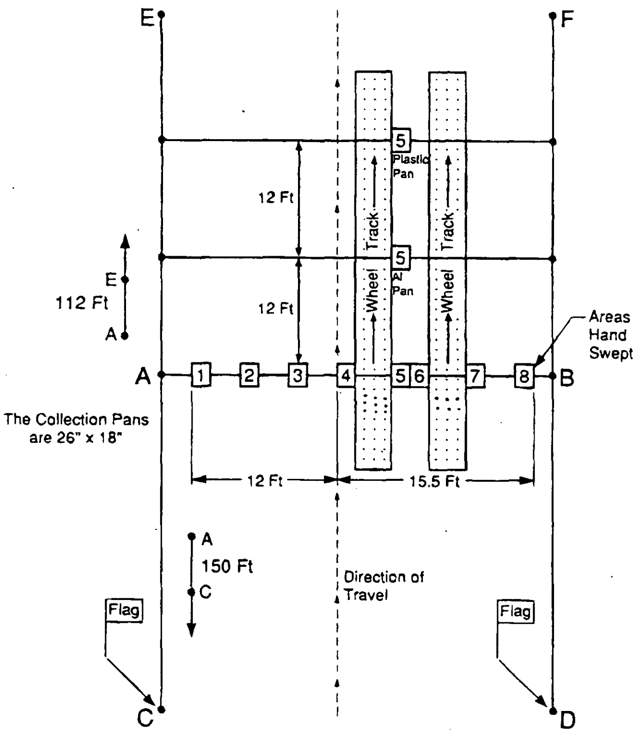

FIGURE 1 Experimental arrangement for first series of spreader tests (1 ft = 0.305 m).

ing data (Figure 2), the amount of material applied by the spreader varies with both vehicle speed and sample location.

The second test series was performed with the same vehicle but using hand sweeping, two different types of collection pans, and vacuuming of 15 m by 0.4 m (50 ft by 1.35 ft) strips of pavement using an industrial vacuum cleaner (Figure 4). Again, three passes were made during each test at vehicle speeds of 23 and 32 km/hr (14 and 25 mi/hr). The data obtained by vacuuming were compared to those obtained by hand sweeping and pan collection at selected locations.

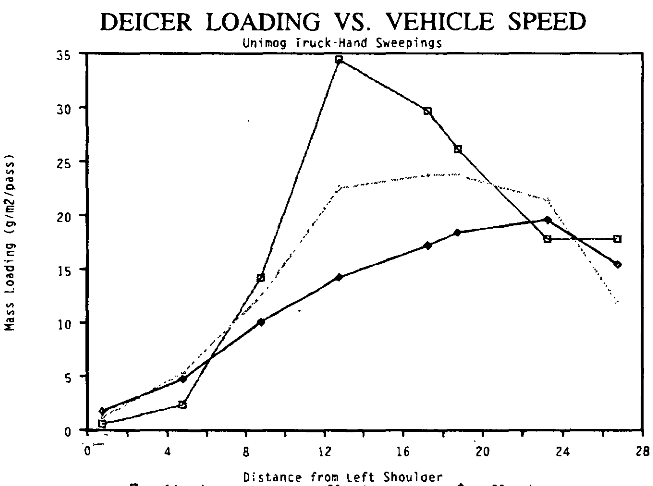

FIGURE 2 Deicer distribution patterns determined by hand sweeping (March 17, 1992).

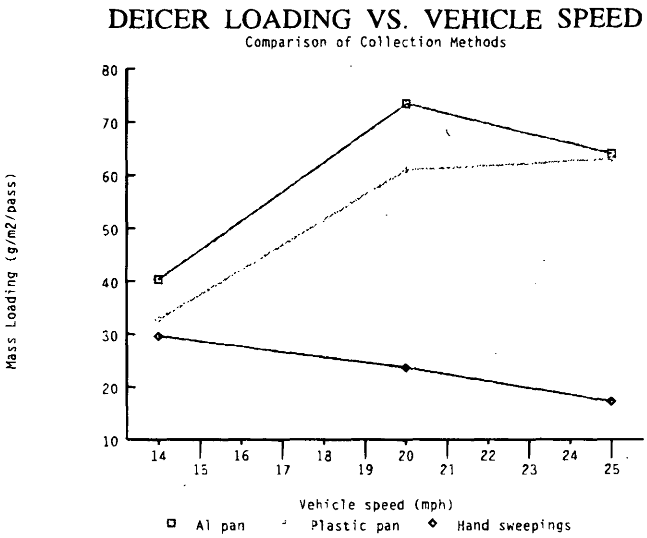

FIGURE 3 Deicer loadings determined by hand sweeping compared with those determined by collection pans (March 17, 1992).

The material distribution pattern is shown in Figure 5 for truck speeds of 23 and 40 km/hr (14 and 25 mi/hr) as determined by vacuum sweeping. Although material loading does vary somewhat with transverse distance and vehicle speed, the vacuuming data show a relatively consistent distribution pattern from one speed to another. This indicates that the distributor control system may be operating in the "ground-oriented" manner intended by the manufacturer. Comparing the various collection techniques in the aforementioned tests (see Figures 6, 7, and 8) suggests that hand sweeping and vacuuming are relatively comparable at the boundary of the distribution pattern where loadings are low, but they are not comparable at higher loadings close to the spinner (i.e., center of pattern).

In the last set of experiments, material distribution data were obtained from an array of plastic collection pans and compared with equivalent vacuum sweeping data using the arrangement shown in Figure 9. The same vehicle was driven at speeds of 23, 32, and 40 km/hr (14, 25, and 35 mi/hr). Three passes were made at each speed.

The material loadings obtained from the collection pans during the last set of tests (Figure 10) are substantially higher than those obtained by vacuuming for truck speeds of 23, 40, and 56 km/hr (14, 25, and 35 mi/hr). In addition, no consistent relationship could be found between the collection pan results and those results obtained by vacuuming. These findings indicate that additional work is needed to establish the most appropriate collection method to evaluate spreader patterns.

Therefore, numerous foreign sources were contacted by letters to obtain information on various types of anti-icing equipment that is used and their testing procedures. Follow-up interviews were held with a number of users and manufacturers in the various European and Scandinavian countries. It appears that most of the research and development on spreader equipment has been conducted in Europe. In the discussion with users and manufacturers, it was clear that there is a great interest in the development and utilization of spreader equipment that dispenses very small amounts of salt during snow and ice control operations. This interest comes from the great concern European and Scandinavian countries have regarding the protection of their surface groundwater from winter maintenance operations.

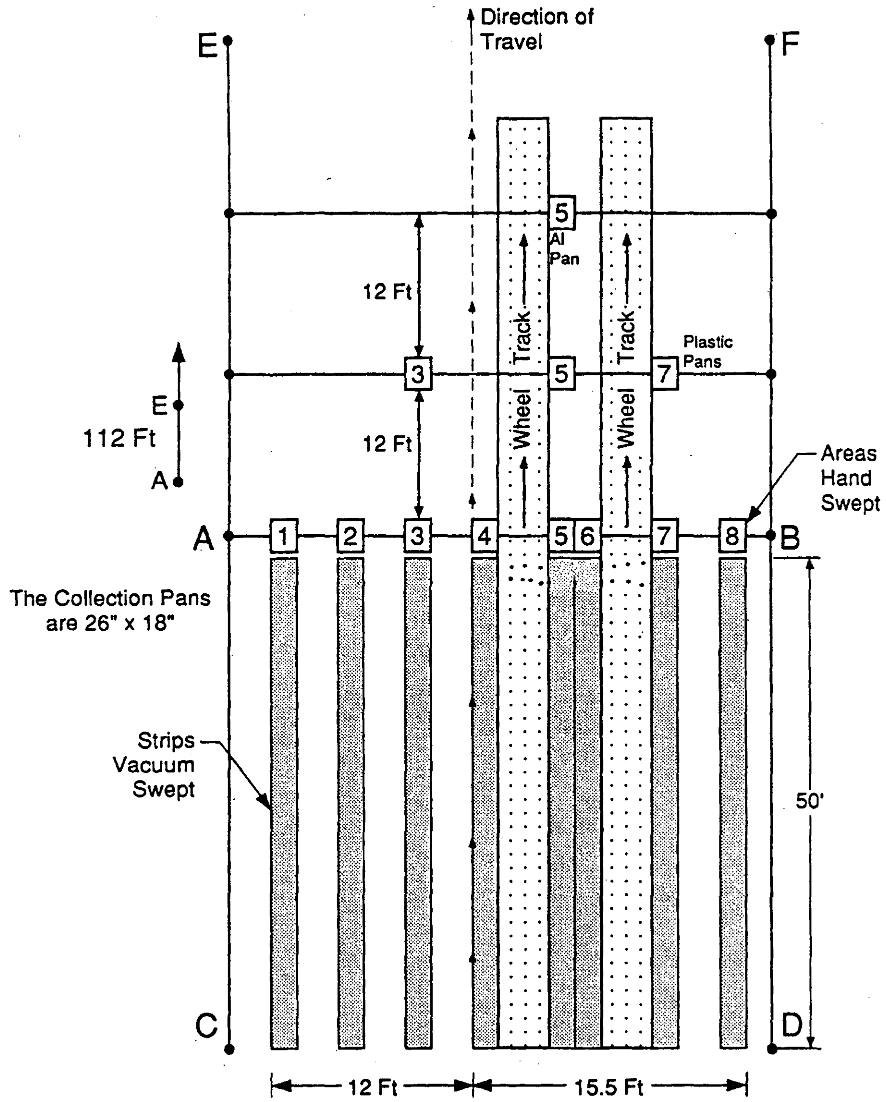

FIGURE 4 Experimental arrangement for spreader tests involving collection pans, areas, and strips (1 ft = 0.305 m).

A number of European governments require spreader equipment manufacturers to demonstrate that their equipment controls and monitors the application rate and spread pattern before the equipment can be commercially marketed in those countries.

The German government has prepared technical specifications and standards for winter spreader equipment used by its Road Maintenance and Traffic Department. These standards address such factors as technical data for equipment position, equipment height, spreader attachments, safety protection, and spread-material output. Within the spread-material output standard, requirements and testing procedures are detailed for mass loading rate, spread pattern, and speed. The German test protocol pertains specifically to the spread of dry material (salt and abrasives).

A version of the test protocol for prewetted salt is available currently only in draft form. However, German equipment manufacturers evaluate their equipment by testing spread pattern for prewetted salt in a stationary position. The wetted salt is spread from a stationary position for 2 min with the control setting at 40 g/m^2 (520 lb/lane mi) and a spreading width of 6 m (19.7 ft). Then the wetted salt is shoveled longitudinally into a row that is transverse to the center line of the spreader. This row is subdivided from the spinner location. Each subdivision of wetted salt is then collected and weighed.

The German spread pattern test for dry salt is conducted at a speed of 20 km/hr (12 mi/hr) with control settings of a spread width of 4 m (13 ft) and a spread density of 20 g/m^2 (260 lb/lane mi). With its hopper loaded to approximately half capacity, the spreader is driven over a marked grid system spreading salt. The salt samples are vacuumed into paper filters from the surface of the grid system. The mass of the salt vacuumed from each sampling rectangle is weighed to an accuracy of 0.1 g (0.04 oz) and then recorded. The data are analyzed to show the characteristics of the distribution overall, both longitudinally and transversely.

The total mass of material collected on any one transverse strip should not differ from the mean mass collected on the three strips by more than ±30 percent. The total mass of material collected on either overspread strip (U_l, U_T) should not exceed 5 percent of the total mass collected. The mass of material collected on either side strip (R_l, R_T) should not be less than 5 percent of the total mass col-

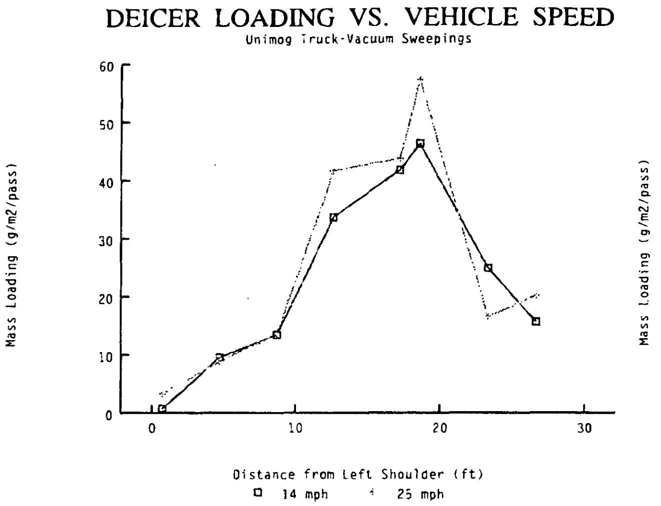

FIGURE 5 Deicer distribution pattern determined by vacuum sweeping (March 18, 1992).

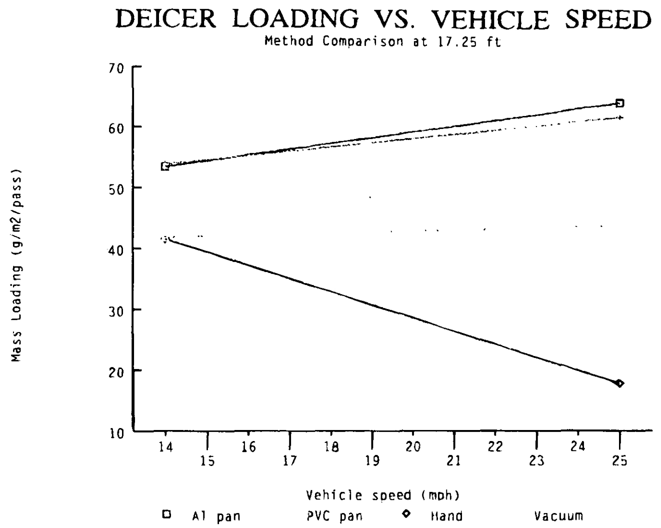

FIGURE 7 Comparison of deicer loadings for four different collection methods at Sampling Location 5 (March 18, 1992).

lected. The allowed deviation of the computed spread density (SD) for the inner lengthwise strips between the side strips from the average SD of all the rectangles in the grid system should not be less than 90 percent nor greater than 50 percent.

The mass loading rate test addresses the amount of material released from the spreader in a unit of time. The amount depends on the spread density SD (g/m^2), spread width b (in meters) over which the material is to be dispersed, and on the speed v of the spreader vehicle (km/hr).

Using the lower and the upper limits of these variables, a three-dimensional operational space is described within which all possible operating points must lie.

The requirements for mass loading exactness are related to the deviation between the measured and control setting value for SD. This deviation, ΔSD, must be within $\pm$6 percent. The mass loading rate of the spread material should be regulated so that the selected SD remains constant when the vehicle is operated at speeds that range between 10 and 40 km/hr (6.2 and 24.8 mph). The SD also cannot change with adjustments of the spread width between 3 and 8 m (9.8 and 26.2 ft).

EQUIPMENT DESCRIPTION

All the various major European spreader manufacturers conform to the standards for spreading dry salt through the use of patented equipment. All the manufacturers supply hopper boxes for use by highway agencies. The capacity of these hoppers will vary from 6 m^3 up to 9 m^3. The spreaders can be demountable or chassis mounted. Because most of the countries hire rental trucks in the winter for snow and ice control operation, a large percentage of the

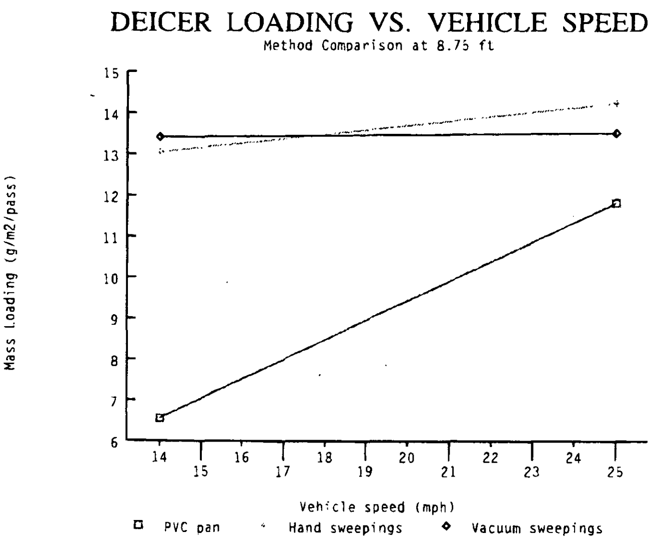

FIGURE 6 Comparison of deicer loadings for three different collection methods at Sampling Location 3 (March 18, 1992).

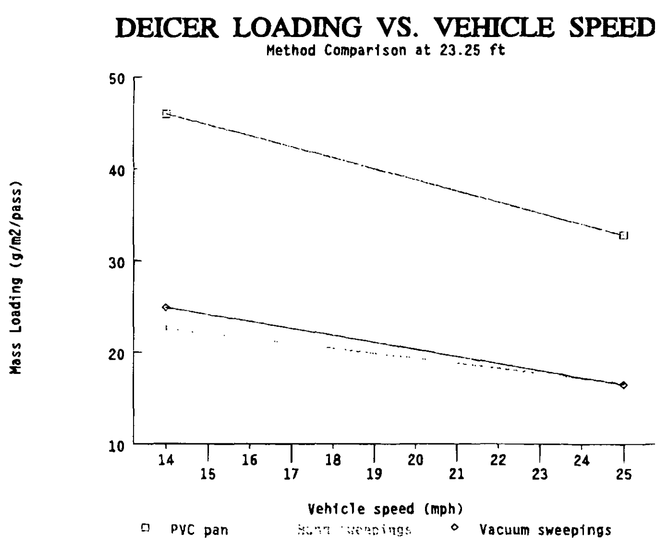

FIGURE 8 Comparison of deicer loadings for three different collection methods at Sampling Location 7 (March 18, 1992).

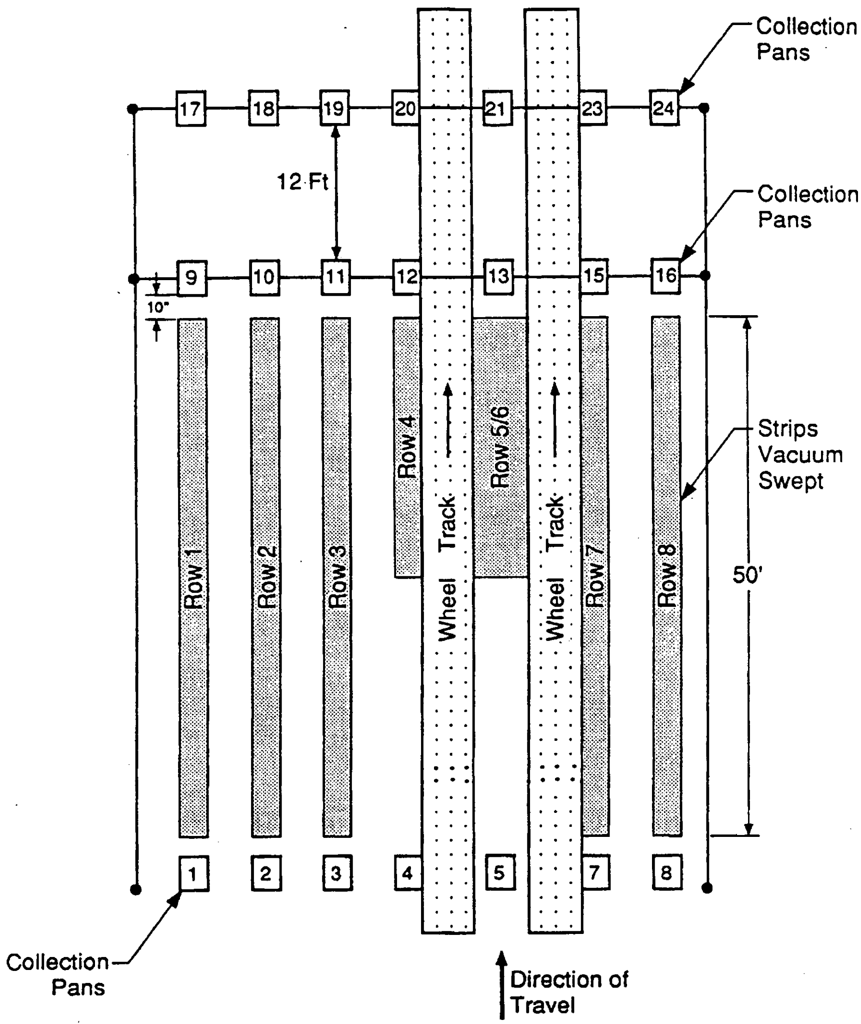

FIGURE 9 Experimental arrangement for final series of spreader tests (1 ft = 0.305 m).

spreaders that are marketed are demountable. It takes about 15 min to load or unload a spreader from a truck.

The method of conveying the material from the hopper box to the spinner varies depending on the manufacturer. One method utilizes a large auger that runs the length of the box. The auger is either a solid or an open type. In addition, a number of manufacturers incorporated a parallel shaft with fingers, which were used to break up lumps of material before being augured out of the hopper. A second method used a smooth belt conveyor or one with raised herringbone ridges to convey the material from the hopper.

The material transported from the hopper is dropped through a closed chute and onto a specially designed disk spinner. All the manufacturers utilized curved fins. The design of the curvature and the number of fins will vary with the patent. Generally all the disks were slightly concave and constructed of stainless steel. A number of the spinners utilize a fluted hub.

Depending on the manufacturer, the diameter of the spinner will vary from 500 mm to 800 mm. One manufacturer has a uniquely designed disk spinner. The patented spinner has a series of three different radii by which the disk acquires an almost triangular configuration. This shape provides for variant lengths of curved vanes or fins on the disk.

There are two methods of controlling spread distribution patterns (symmetrical or asymmetrical) on the roadway. One method is to control the position where the material lands on the spinner. The second method is to control where the location is changed by rotating the whole spinner assembly to change the direction of the pattern.

When the spreader equipment is designed for prewetting salt at the spinner, the liquid is pumped with a positive displacement pump and through a check valve just above the spinner. The liquid is discharged either directly onto the spinner near the center or through an overflow chamber and then onto the spinner. The dry material and brine become mixed as they travel along the curved vanes.

The system controls for all spreader equipment utilizes a microprocessing unit to control the density of the application, spreader width, and percentage of prewetting. Some of the controls are programmable, which provide the user with enhanced flexibility over the control settings. Some companies use digital indications, and others use knob settings on the control box.

The digital controls have the following capabilities:

- Density—has a range of 0 to 40 g/m^2 for salt with increments of 1 g/m^2.

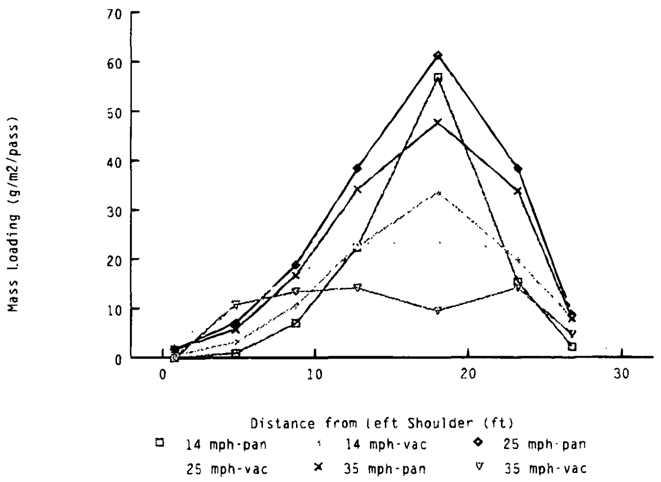

FIGURE 10 Comparison of deicer distribution patterns for two different collection methods (March 27, 1992).

- Percentage of prewetting—has a range of 5 to 40 percent with increments of 1 percent.
- Spreader width—has a range of 2 to 8 m with increments of 0.1 m.

The knob controls have the following capabilities:

- Density—has a range of 5 to 40 g/m^2 for salt with increments of 2.5 g/m^2 up to 20 g/m^2 and with increments 5 g/m^2 from 20 g/m^2 to 40 g/m^2.
- Percentage of prewetting—has settings of 10, 20, and 30 percent. One company has only 30 percent.
- Spreader width—has a range of 2 to 8 m with increments of 1 m.

The control units for prewetting salt are similar to those used for the dry salt controls. The amount of liquid brine being added is controlled by using a percentage of the total prewetted material. As the amount of prewetting liquid application is increased, the amount of dry material is decreased proportionally so that the desired density remains a constant.

A number of the controls also have the capability to download information on spreading and plowing operations. The information provided is the density of application (g/m^2), percentage of prewetting, spreader width, speed, distance traveled while spreading at a given setting, distance traveled while plowing, total distance traveled, and time of day. The printouts also provide a summary of the total kilograms of material spread and kilometers traveled.

In observing the action of salt during spreading operations in Minnesota, turbulent air flow behind the truck is an important factor in the resultant distribution pattern of salt. One manufacturer has addressed this issue by developing an air deflector which is mounted just behind the hopper box and projects above the box. The idea is for the air deflector to force the material down on the roadway. The Motor Research Industry Association of the United Kingdom has been conducting testing on this concept also.

Due to the practice of applying liquid salt to the roadways in Scandinavian countries, a number of companies have designed and manufactured liquid spreaders. There are two basic types of liquid spreaders: one incorporates spray nozzles, and the other uses a dish spinner(s).

DISCUSSION OF RESULTS AND RECOMMENDATIONS

To integrate anti-icing technology into an agency's snow and ice control operations, it will be necessary to use spreader equipment that can effectively dispense small amounts of material in a uniform pattern on the roadway. A preliminary procedure has been developed to measure the ability of the spreader to control the distribution pattern and the application rate of spread material. The distribution pattern should be evaluated at speeds of 20 km/hr (12 mph) and 40 km/hr (25 mph) with control setting values delivering 20 g/m^2 (260 lb/lane mi) of spread material over a 6 m (19.7 ft) width. The spreader should be driven over a marked grid system during spreading of the dry salt. The application rate test should measure the accuracy of the spread material released in accordance with the normal operational range of the spreader. In addition to controlling the dispensing of material, the American manufacturers should investigate ways of obtaining consistent application rates from truck to truck. The presently available spinner design used on U.S. manufacturer spreader equipment also needs to be evaluated.

American manufacturers are working to develop microprocessing units that can control the dispensing of small quantities of material. (However, these controls were not tested in this research project.) In addition to controlling the dispensing of the material, the hydraulic systems, spinner design, and prewetting systems on spreader equipment presently available on the domestic market need to be upgraded.

The experience of the authors indicated there is a lack of testing procedures for spreader equipment. This may be one factor inhibiting the development of precision equipment essential to anti-icing operations. The European governments require spreader equipment manufacturers to demonstrate that their equipment can control and monitor the spreading of material.

ACKNOWLEDGMENTS

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Selection of Pavement Markings Using Multicriteria Decision Making

CHRISTIAN F. DAVIS AND GERARD M. CAMPBELL

A decision support system (DSS) that was developed to aid in the selection of pavement marking materials is described. The DSS is based on multicriteria decision making, a technique that enables a variety of considerations to be brought into the analysis. Through a series of interactions with a Connecticut Department of Transportation task force, the key criteria were identified and structured into a goals hierarchy. Safety, costs, and convenience are the major categories for the goals. The task force helped to establish an objective function that quantifies how each goal and subgoal contributes to the overall goal of selecting the best pavement marking. This objective function was incorporated into a computer-based model using off-the-shelf personal computer software.

Transportation agencies use numerous types of materials to mark pavements and curbs. These materials vary from relatively inexpensive water-borne paint to longer lasting, but more expensive, thermoplastic. Each of the materials has unique placement requirements, performance characteristics, and costs.

There are numerous criteria that must be considered when selecting a pavement marking material for a given application (i.e., a given stretch of roadway). These include safety, durability, ease of application, and cost. The literature on performance characteristics of such materials is extensive. The work by Dale (*1*), is just one example. However, very little attention has been given to the very significant question of what material is the most appropriate for use in a given application. Thus, the primary objective of the project described in this paper was to develop a decision support system (DSS) for the Connecticut Department of Transportation (ConnDOT) that could consider the relevant multiple criteria in a systematic way.

MULTICRITERIA DECISION MAKING

The specific analytical technique used in this paper—multicriteria decision making (MCDM)—is just one type of method that could be incorporated into a DSS. A survey of DSS applications between 1971 and 1988 is given by Eom and Lee (*2*), and a review of decision analytical software is given by Buede (*3*). Keeney and Raiffa (*4*) provide a comprehensive presentation of MCDM, including descriptions of numerous applications. Applications of DSSs in general and MCDM in particular to transportation are described in an interim report for NCHRP Project 20–29 (*5*).

The simplest kind of MCDM model uses an *objective function* based on the assignment of *weights* to measurement values associated with the various *criteria*. For example, consider a decision to be made on the purchase of a piece of machinery. Clearly, one of the criteria for the decision would be to minimize cost. Assume the only other criterion for the selection is to minimize noise. In general, there will be a trade-off between the criteria, and one desires to somehow mathematically weight their relative importance. Suppose weights of .7 and .3 have been assigned to cost and noise, respectively. To use these weights, it is necessary to first quantify the two criteria by choosing numerical measures for each of them. Suppose one of the alternatives under consideration costs $30,000 and produces 130 decibels when in operation. If the weights were applied directly to these measures, it is clear that adding the results would be meaningless. This problem can be solved by introducing the concept of "utility"—an indication of desirability that is measured on a scale ranging from 0 to 1. This concept is described more fully below. The two single-measure utilities that an alternative receives for the two criteria may then be multiplied by the associated weights, and the results added together to obtain an overall utility for the alternative. The alternative with the highest overall utility would be the most preferable. A slightly more complicated situation arises when one or more of the measures are not directly quantifiable, such as, for example, aesthetics. This situation arises in the pavement markings problem and is discussed more thoroughly below. However, the basic idea of weighting the various criteria remains essentially the same as in the simple example just described.

Perhaps the most challenging aspect of using MCDM is obtaining inputs to build the model from those persons most knowledgeable about the decision at hand.

MODEL DEVELOPMENT

The process of developing the pavement markings MCDM model was an iterative one. Initially, a meeting was held between the principal investigators and all ConnDOT task force members. This was followed by additional meetings between the principal investigators and individuals and subgroups from the task force. During these meetings, individuals were asked to identify goals that are relevant to the selection of pavement markings. Based on inputs from the individual and group meetings, a *goals hierarchy* was developed. At subsequent group meetings, the goals hierarchy was reviewed and revised by the task force, resulting in the goals hierarchy shown in Figure 1.

While refining the goals hierarchy, the task force concurrently identified measurement scales to be used for evaluating pavement marking alternatives. All goals at the lowest tier of the hierarchy must have measurements associated with them. The goals hierarchy shown in Figure 1 includes 12 measures (shown in ellipses). For each measure, a scale has been defined. Some of the scales use discrete

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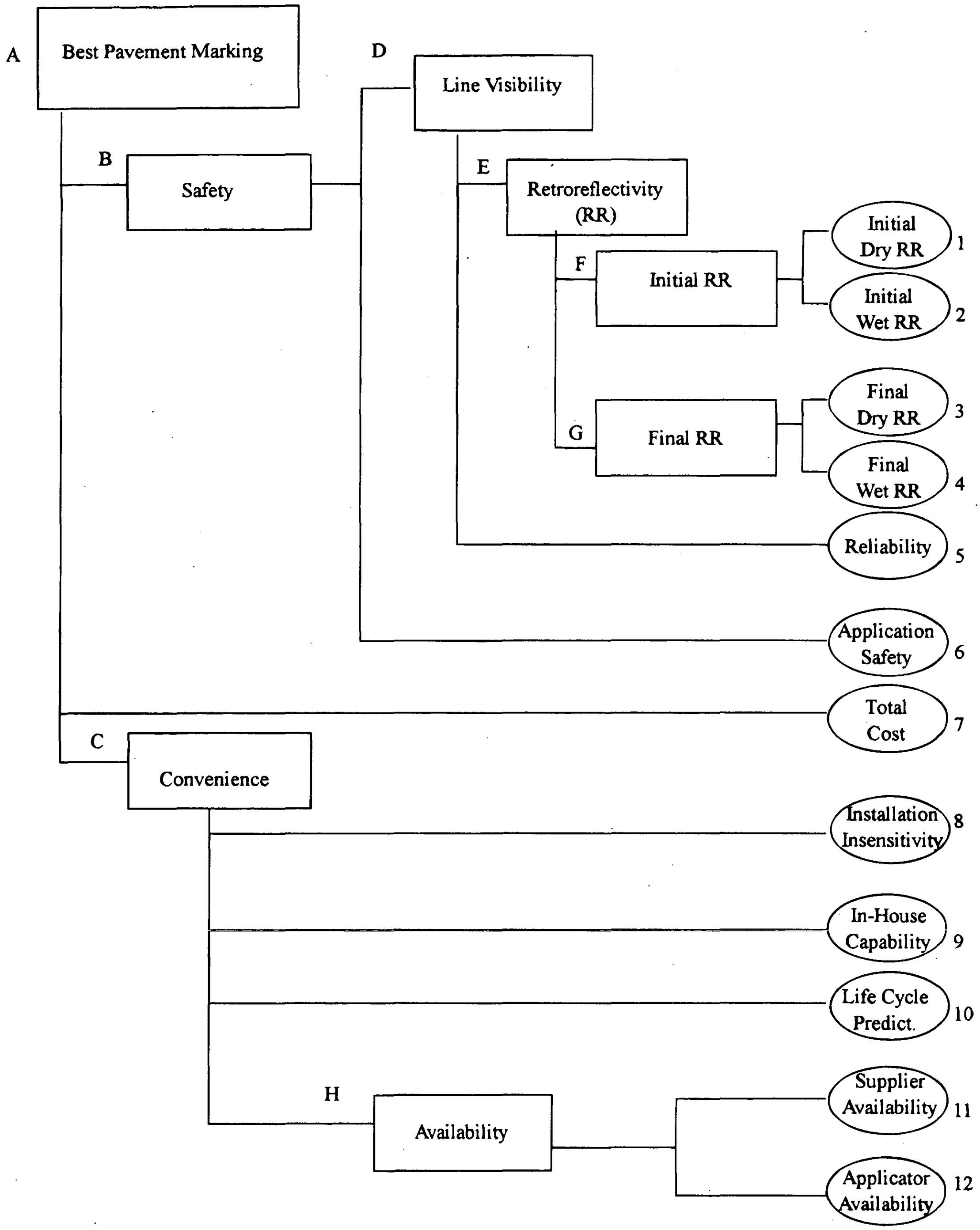

FIGURE 1 Goals hierarchy.

values ranging from 1 to 5 while others use continuous scales based on units such as dollars per meter per year. (The 12 measures in the pavement markings model are discussed later in this paper.)

As a final step in the development of the model, the task force established the weights and single-measure utility functions needed to quantify the model's objective function. With that completed, all of the inputs required for the computer-based model were defined. The model was built using the software package called Logical Decisions for Windows (Logical Decisions, Golden, Colo.).

To help demonstrate the model, an example problem defined by the task force will be used. In this problem, the *application* is lane striping of a six-lane, unilluminated, interstate highway with a 90 km/hr (55 mi/hr) speed limit, an annual average daily traffic (AADT) of 85,000, and a Class 1 surface 12 years old. The application is further defined by noting the existing markings are epoxy and that ConnDOT has full control over the time of application. Recall that an *alternative* is defined by the material and frequency of application. In the example problem, the alternatives under consideration are epoxy applied every year, epoxy applied every 2 years, and preformed plastic applied every 4 years. This example problem is the subject of analysis presented in a software users' guide by Anderson and Braun (*6*).

GOALS HIERARCHY

The goals hierarchy (shown in Figure 1) was developed through close cooperation between the principal investigators and the pavement markings task force. It represents a consensus regarding the criteria that are most important to consider when selecting pavement markings.

The goals at the higher levels of the hierarchy are general and have relatively straight-forward meanings. Sub-goals are more specific, until and at the lowest levels, very specific measurable attributes are defined. Measurement scales and mathematical functions that precisely define each measure and goal are presented later. For now, a more general discussion of the considerations that the various goals and measures are intended to capture is in order.

The safety goal is the more complex of the two goals at the second tier of the hierarchy. The two major components of safety relate to safety during application (Measure 6), and safety after the material has been applied, which is based on the line's visibility (Goal D). Application safety is related to the safety of the traveling public and of workers as pavement markings are being applied.

The other aspect of safety, line visibility (Goal D), is of major importance. This goal relates most directly to the practical function of pavement markings. Under Goal D, the hierarchy shows retroreflectivity (Goal E) and reliability (Measure 5). Broadly speaking, retroreflectivity relates to the visibility of the marking material, given that the material is still on the road. The reliability measure is intended to indicate the likelihood that the marking will remain on the road for the marking's specified life.

There may be a high degree of confidence that the marking will still be on the road at the end of its specified life, but this is only one aspect of the marking's durability. The other key aspect of durability is how visible the marking is at that time. Final retroreflectivity (Goal G) captures this aspect of durability. As mentioned earlier, a pavement marking *alternative* is defined by a marking type and a specified life span. For example, epoxy paint applied every year is a different alternative than epoxy paint applied every 2 years. In terms of the goals hierarchy, these two alternatives would achieve the same score for initial retroreflectivity (Goal F), but their final retroreflectivity measures would certainly be different (as would their costs).

For both initial and final retroreflectivity, dry-pavement and wet-pavement measures are both relevant. [The retroreflectivity measures (1 through 4) are discussed in more detail later in this paper.]

The next major branch of the hierarchy includes the cost measure. The reasons for including cost minimization as a major goal are obvious. Measure 7, total costs, is intended to capture all costs associated with a pavement marking alternative over a 10-year time horizon.

Other considerations that were mentioned by the task force relate to convenience and ease of planning and control. These considerations, which are included under Goal C in the hierarchy, are not as important as the cost and safety concerns, but they do play a role in selecting among pavement marking alternatives, especially when the alternatives are comparable in terms of costs and safety. The four components of the convenience goal are installation insensitivity, in-house capability, life-cycle predictability, and availability. Availability is further broken down into measures reflecting the number of suppliers of the pavement marking material and the number of applicators available to install it. (Each of these aspects of convenience is further discussed later.)

A more detailed discussion of the measures included in the goals hierarchy follows. A more detailed description of how the hierarchy relates to the model's mathematical objective function is provided later.

MEASURES

As far as the MCDM model is concerned, any given pavement marking alternative is completely described by the 12 measures shown at the lowest levels of the goal hierarchy in Figure 1. Given the central role that the measures play in the evaluation of alternatives, it is important that the alternatives be defined as clearly as possible. This section is devoted to a detailed discussion of the 12 measures and their associated measurement scales.

Measures 1 through 4—Retroreflectivity

Measures 1 and 3

Measures 1 and 3 are both dry-pavement retroreflectivities, measured in millicandles per square meter per lux. The advantages of these measures are that they are objective and the measurement scales are well defined. However, the disadvantages are that there may be difficulties associated with obtaining representative values of these measures for specific pavement marking alternatives. For example, it has been noted that the markings' performances can depend on the type of pavement to which it is applied. Procedures for establishing retroreflectivity values must be defined. Possibilities include using published data, taking measurements on a sample of Connecticut roads, or using some combination of sampling and published data.

Measures 2 and 4

Measures 2 and 4 represent pavement marking performance under moderate rainfall conditions. A scale ranging from 1 (barely visible) to 5 (excellent) was developed by ConnDOT for these measures because task force members knew of no standards or published data regarding retroreflectivity measurements under wet conditions. Should a standard technique for measuring wet-pavement retroreflectivities become available, the model can easily be changed to incorporate it into Measures 2 and 4. (This is discussed further in the Conclusion.)

Measure 5—Reliability

The reliability measure is quantified based on the five-point scale ranging from 1 ("ConnDOT has had experience with or strong reason to suspect premature failure.") to 5 ("There is strong evidence that the material has a high probability of lasting for its specified life."). A reliability measure needs to be established only once for any particular pavement marking alternative, and that value will then remain fixed unless new information about the alternative becomes available (e.g., based on additional experience with the material).

Measure 6—Safety

The measure for installation safety will also remain fixed for a given pavement marking alternative. In fact, it is simpler than the reliability measure in that it does not depend on the specified life span of the alternative (which might affect Measure 5).

For Measure 6, the pavement markings task force has proposed the measurement values shown in Table 1. These scores, which are based on ConnDOT's experience with marking types, correspond to specific explanations of different measurement values. **In these scales, higher scores are more desirable.** A discussion of how these ratings are converted to application safety and overall safety utility values through mathematical functions that consider the roadway characteristics of AADT and speed limit is given later in this paper.

The measure for installation safety is based on a five-point scale. As before, a value of 1 on the scale corresponds to the least desirable rating; that is, "Characterized by a combination of two or more constraints of long duration and/or unattached devices, and/or more than one normal lane occupied, and/or application time constraints." Conversely, a value of 5 corresponds to the most desirable rating; that is, "Characterized by short duration, no unattached devices, no more than one lane occupied, and no time constraints."

Measure 7—Costs

The total cost measure is more application-specific than some of the other measures. This cost measure is designed to incorporate all costs associated with the pavement markings that are expected to be incurred over a 10-year time horizon. The costs are broken down into several components, as shown in Table 2. The components are then combined to result in a cost measure that is in units of dollars per meter per year. As with all of the measures, it will be necessary to update the various cost components as new information becomes available.

Measures 8 through 12—Convenience

The five measures that relate to convenience are measured using ConnDOT-developed scales as described below. All of these measures are such that scores need to be defined only once for any particular pavement marking alternative; after that they only need to be updated if new information causes them to change. The task force has established the measurement values shown in Table 1 for two of the five convenience-related measures. It should not be difficult to establish similar tables for Measures 11 and 12.

Measure 8—Installation Insensitivity

This is measured on a five-point scale ranging from 1, "Characterized by being sensitive enough to substantially limit application to controlled conditions." to 5, "Characterized by being relatively insensitive."

Measure 9—In-House Capability

This is the simplest measure because it just requires a yes/no response to indicate whether ConnDOT has the capability to install the pavement marking material itself.

Measure 10—Life-Cycle Predictability

This is measured on a five-point scale ranging from 1, "Considered unpredictable due to past experience or a lack of experience," to 5, "Considered highly predictable."

TABLE 1 Values of Measures 6, 8, and 10 for Various Materials' Marking Types

Marking Type	Measure 6 Installation Safety	Measure 8 Installation Insensitivity	Measure 10 Life-Cycle Predictability
Paint:			
Solvent Based	5	5	5
Water Based	4	4	5
Epoxy	4	4	4
Acrylic	3	3	2
Preformed Plastic:			
Automatic Dispenser	3	1	3
Manual Installation	1	1	3
Thermoplastic:			
Extruded	4	4	2
Sprayed	4	4	2

TABLE 2 Breakdown of Costs (Measure 7) Based on a 10-Year Period

A.	Cost of Materials and Installation[a] for each Application.
B.	Expected Number of Applications in 10 Years.
C.	Maintenance Costs over 10 Years .[a]
D.	Cost of Each Eradication .[a]
E.	Expected Number of Eradications over 10 Years.
F.	Other Costs Incurred over 10 Years .[a]
Measure 7[b] = [(AxB) + C + (DxE) + F] / 10	

[a]$/m
[b]$/m/yr

Measures 11 and 12—Supplier and Applicator Availability

These are both measured on a five-point scale ranging from 1, "very limited," to 5 "plentiful."

Identification of Alternatives and Measure Values

As discussed above, much of the determination of measure values for a given alternative will be a simple matter of looking up measurement values in various tables. The development and updating of these tables, however, require that those most familiar with the pavement marking alternatives exercise careful judgment.

Another area where judgment is important is in the identification of alternatives. It should be noted that the system is set up to help decide among *viable* alternatives. When an alternative is unacceptable for any reason, the user should not enter measurement values for that alternative into the DSS.

Once the 12 measurement values have been entered into the DSS for each viable pavement marking alternative, the DSS can proceed with an analysis of the alternatives. How this analysis is performed is dictated by the form of the model's objective function.

OBJECTIVE FUNCTION

Measurement values for a particular alternative are transformed into an overall score for the alternative through the objective function. This transformation involves two major steps: (a) converting each measurement value into a single-measure utility value and (b) weighting single-measure utility values to obtain multimeasure utility values. (The conversion of measurement values into common units through the use of single-measure utility functions is discussed later in this paper.) For now, take as given that conversions of this type result in the following for each measure:

$$0 \leq SU_y(V_y) \leq 1 \tag{1}$$

where

V_y = the measurement value for the yth measure, and
$SU_y(V_y)$ = the single-measure utility value for the yth measure, given a measurement value of V_y. (This is abbreviated as SU_y throughout this paper.)

As discussed earlier, a particular pavement marking alternative will have a measurement value for each of the 12 measures included in the goals hierarchy. These will then be converted to utility values (SU_1 through SU_{12}) through single-measure utility functions, which need to be defined only once.

Multimeasure Utility Values

This next section focuses on how the single-measure utility values are combined to obtain multimeasure utility values. Multimeasure utility values are best explained by referring to the structure of the goals hierarchy. Consider, first of all, the goal of initial retroreflectivity (IRR), which is labeled Goal F in Figure 1. Given single-measure utility values for Measures 1 and 2 (dry IRR and wet IRR, respectively), the multimeasure utility associated with IRR is obtained as follows:

$$MU_F = W_1SU_1 + W_2SU_2 \tag{2}$$

where

MU_F = the multimeasure utility value associated with Goal F,
W_y = the weight given to the utility score for measure (or goal) y, and
$(W_1 + W_2) = 1$.

The weights W_1 and W_2 were established based on the task force's collective judgment regarding the relative importance of the dry-surface and wet-surface retroreflectivities. These weights remain fixed within the model.

A similar multimeasure utility function is established for Goal G (final-month retroreflectivity) as follows:

$$MU_G = W_3SU_3 + W_4SU_4 \tag{3}$$

where $W_3 + W_4 = 1$.

The utility scores for Goals F and G are then combined to obtain a utility score for Goal E as follows:

$$MU_E = W_FMU_F + W_GMU_G \tag{4}$$

where $W_F + W_G = 1$.

Note that Equations 2 and 3 could be substituted into Equation 4 to obtain Goal E's multimeasure utility in terms of a series of single-measure utility values and associated weights. This can be done for any goal to obtain its multimeasure utility function in terms of the measures that appear beneath it in the goals hierarchy.

The multimeasure utility function for Goal D, line visibility, is as follows:

$$MU_D = W_EMU_E + W_5SU_5 \tag{5}$$

where $W_E + W_5 = 1$.

Measure 6, application safety, has a slightly different functional form, which is introduced as follows:

$$SU_6(\text{Adjusted}) = A_6 SU_6 \tag{6}$$

where A_6 is an "adjustment factor," defined as follows:

A_6 = (expected number of years between installations)/6.

This adjustment factor, which will have values ranging between 0 and 1, is introduced to account for the frequency of installation. Its effect is to make alternatives that require frequent reapplication appear less desirable.

Goal B, overall safety, which is another adjustment factor, is introduced as follows:

$$MU_B = A_S(W_D MU_D + W_6 SU_6) \tag{7}$$

where

$W_D + W_6 = 1$, and
$A_S = .5 \times$ (AADT of roadway/100,000) $+ .5 \times$ (speed safety adjustment factor).

A_s, the "safety adjustment factor," is introduced to account for the traffic volume and speed limit of the roadway. This acknowledges that safety should be more heavily weighted when there are higher traffic volumes and/or higher speed limits. The Speed Safety Adjustment Factor (which has values ranging from 0 to 1) is defined as a function of roadway speed limit and is described later.

The branch of the hierarchy dealing with costs is relatively straightforward because cost utility functions are generally linear. Assuming a maximum cost of $3.28/m/yr ($1/ft/yr) for any pavement marking alternative, the following single-measure utility function is defined:

$$SU_7 = 3.28 - V_7 \tag{8}$$

[The cost measurement (V_7) is the only measurement in the hierarchy for which higher values are less desirable. Consequently, Equation 8 is such that lower costs result in higher utility values.]

The last major branch of the goals hierarchy is that under Goal C, convenience. The multimeasure utility function for convenience is as follows:

$$MU_C = W_8 SU_8 + W_9 SU_9 + W_{10} SU_{10} + W_H MU_H \tag{9}$$

where $W_8 + W_9 + W_{10} + W_{11} = 1$.

Note that the single-measure utility value for Measure 9, in-house capability, equals either 0 or 1. This corresponds to the yes/no nature of that measure.

Goal H, availability, requires further explanation. The two components of the availability goal combine as follows:

$$MU_H = SU_{11} \times SU_{12} \tag{10}$$

This multimeasure utility function is a multiplicative function of the two component single-measure utility functions. This functional form is appropriate because low scores on either supplier availability or applicator availability could result in inconvenience, even if the other measure is at a high level.

The only goal in the hierarchy for which a multimeasure utility function has yet to be defined is the overall goal of finding the best pavement marking alternative. The overall utility score for an alternative is calculated as follows:

$$MU_A = W_B MU_B + W_7 SU W_7 + W_C MU_C \tag{11}$$

where $W_B + W_7 + W_C = 1$.

Using Equations 2 through 10, Equation 11 could be expanded into a function of the measures (1 through 12), the roadway's AADT and speed limit, and the marking's expected time between applications.

WEIGHTS AND UTILITY FUNCTIONS

To complete the objective function discussed here, the weights (W_y) and the single-measure utility functions (SU_y) need to be defined.

Weights

Weights are used to quantify the way utilities associated with subgoals or measures are to be combined to form multimeasure utility values for goals. For example, Equation 2 states that the multimeasure utility value for initial retroreflectivity (Goal F) is obtained by adding (a) W_1 multiplied by the single-measure utility value associated with Measure 1 and (b) W_2 multiplied by the single-measure utility value associated with Measure 2. The weights W_1 and W_2 must sum to 1. Because both SU_1 and SU_2 have values between 0 and 1, MU_F will also range between 0 and 1. This will be true for all single-measure and multimeasure utility values.

The following seven sets of weights had to be defined for the model's objective function:

$$W_1 + W_2 = 1 \tag{12}$$

$$W_3 + W_4 = 1 \tag{13}$$

$$W_F + W_G = 1 \tag{14}$$

$$W_E + W_5 = 1 \tag{15}$$

$$W_D + W_6 = 1 \tag{16}$$

$$W_8 + W_9 + W_{10} + W_H = 1 \tag{17}$$

$$W_B + W_7 + W_C = 1 \tag{18}$$

Note that these equations correspond directly to the way that branches in the goals hierarchy merge together when moving from bottom to top. The only exception is the combination of Measures 11 and 12, which combine in a multiplicative rather than an additive manner, as shown in Equation 10.

The seven sets of weights needed for the model were established by the pavement markings task force.

Single-Measure Utility Functions

For each of the 12 measures shown in the goals hierarchy, a function had to be defined to convert measurement values into common units of utility. Utility is a measure of desirability. The utility scale for each measure has a range from 0 to 1, with 1 being the most preferred. Thus, a utility of 0 must always be assigned to the least preferred level of a measure and a utility of 1 to the most preferred level of a measure.

While the extreme values of all measures are known to have utilities of 0 and 1, the utility values corresponding to intermediate measurement values must be further defined. The correspondence between measurement values and utility values is described by a single-measure utility function.

Single-Measure Utility Functions for the Pavement Markings Problem

Single-measure utility functions had to be defined for each of the measures in the pavement markings model. There is, however, one measure for which a utility function was obvious. For Measure 9, in-house capability, a "yes" simply corresponds to a utility of 1, and a "no" results in a utility of 0. Utility functions for the other 11 measures are shown in Figures 2 through 7. Note that each of these functions is piecewise linear, and the line segment endpoints that define the functions are shown on the figures. These functions are all based on the inputs of the pavement markings task force.

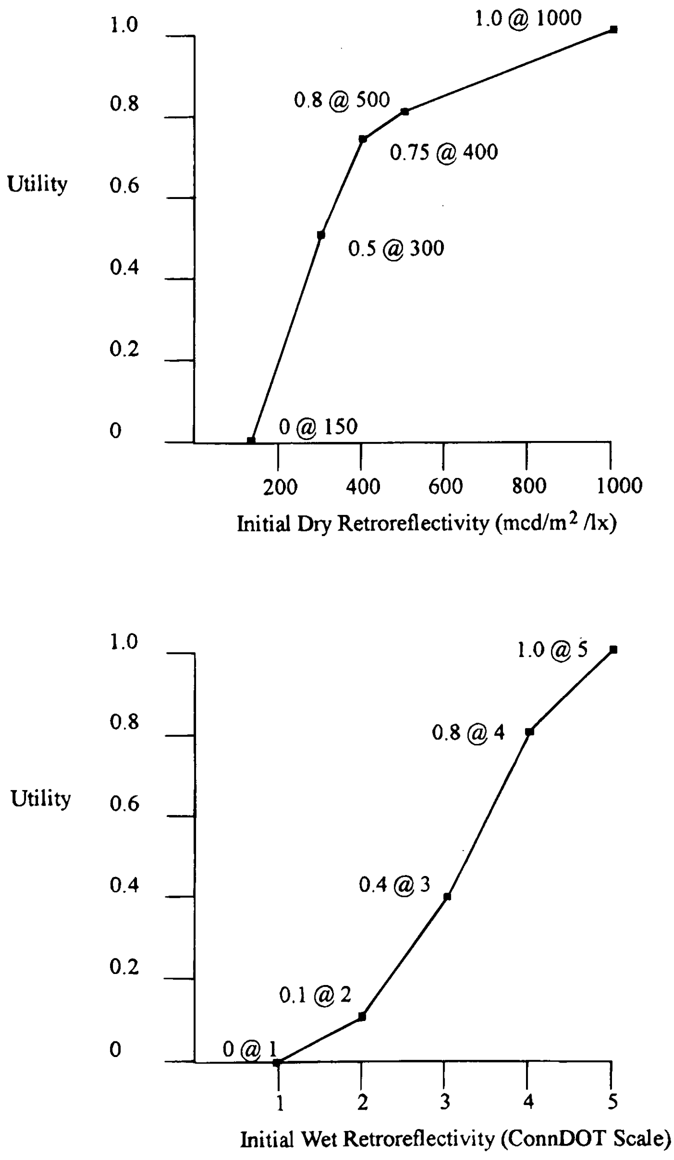

FIGURE 2 Single measure utility functions for initial retroreflectivity: (*top*) dry; (*bottom*) wet,

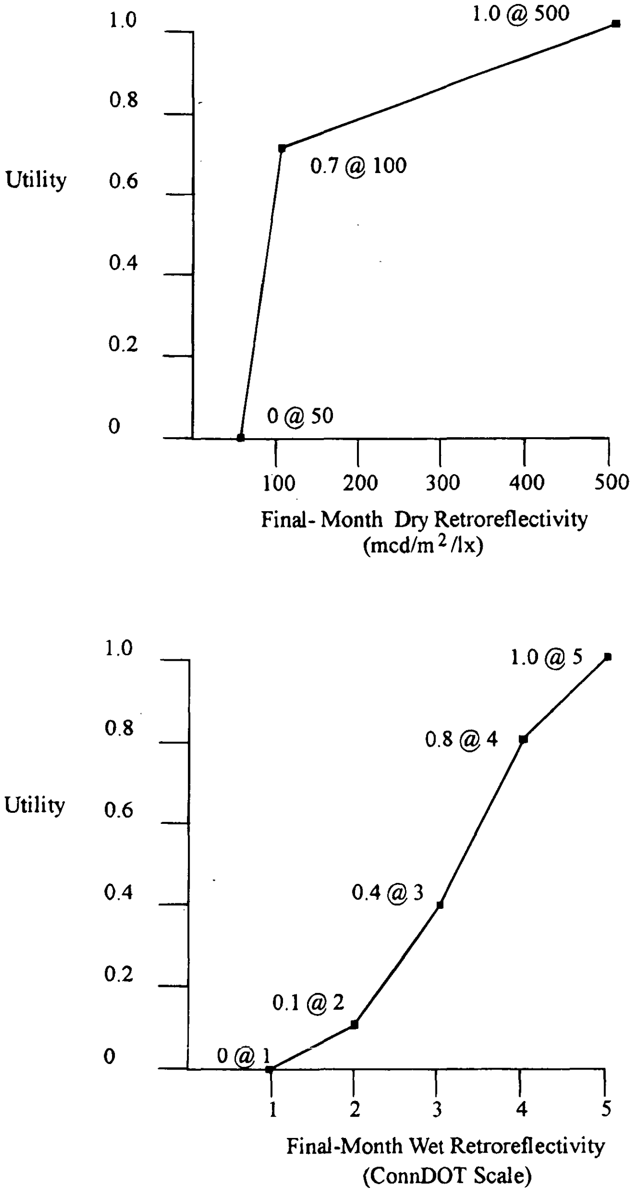

FIGURE 3 Single measure utility functions for final-month retroreflectivity: (*top*) dry; (*bottom*) wet.

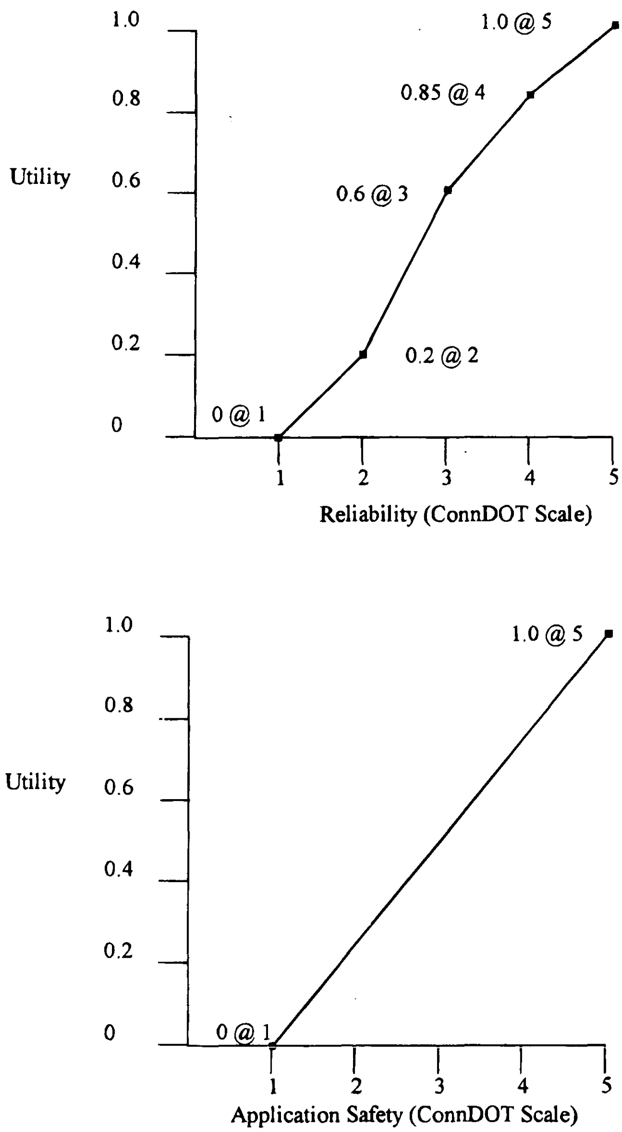

FIGURE 4 Single measure utility functions for (*top*) reliability; (*bottom*) application safety.

Speed Safety Adjustment Factor

Another mathematical relationship that had to be defined for the model is how the speed limit of a roadway relates to the speed safety adjustment factor, which is included in the multimeasure utility function for the safety goal (as shown in Equation 7). This relationship is shown at the bottom of Figure 7 (*b*). As with the utility functions, the function shown was defined by the pavement markings task force.

With the 12 functions and the 7 sets of weights defined, the model's specification is now complete. Pavement marking alternatives can be evaluated using the model, as long as 12 measurement values are available for each alternative.

SUMMARY AND CONCLUSIONS

This paper has presented the details of a multicriteria decision making model for choosing among pavement marking alternatives. The model development process has been outlined, the goals hierarchy has been presented and discussed, and the mathematical details of the model have been reported. The model has been entered into the software package called Logical Decisions for Windows, resulting in a PC-based decision support system that is ready for ConnDOT to use.

The model described in this paper and programmed into the DSS is changeable. By changing certain aspects of the base model, a knowledgeable user might be able to gain insight into a pavement

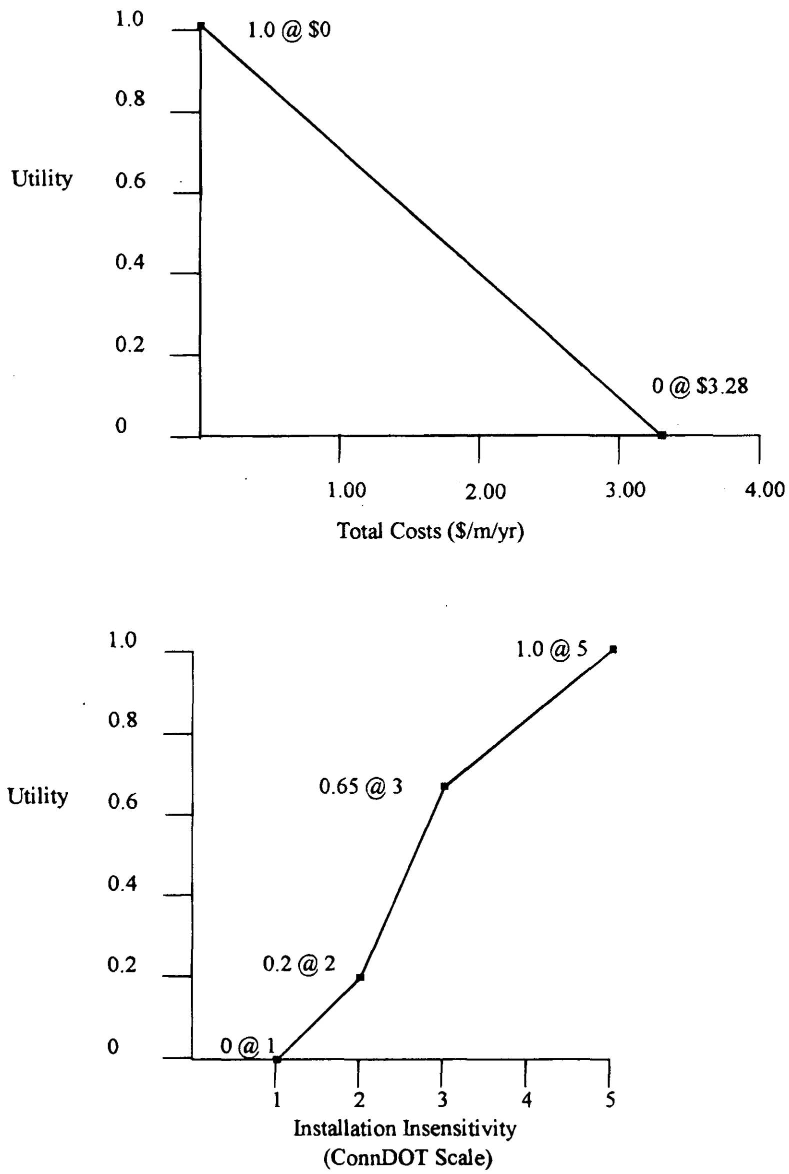

FIGURE 5 Single measure utility functions for (*top*) total costs; and (*bottom*) installation insensitivity.

marking selection problem that could not be obtained just by using the standard sensitivity analysis features provided by the software. Also, as new information and measurement techniques become available, it might be desirable to make permanent changes to the base model itself. For example, should standard techniques be established for measuring retroreflectivities under wet-pavement conditions, changes could be made to the scales and utility functions for Measures 2 and 4 within the model.

The process of developing the DSS has provided much insight into the pavement markings selection problem. By keeping the DSS's model up-to-date, the results of this project can be taken advantage of for years to come. ConnDOT has made a policy decision to begin using the DSS described in this paper for its next round of markings selection.

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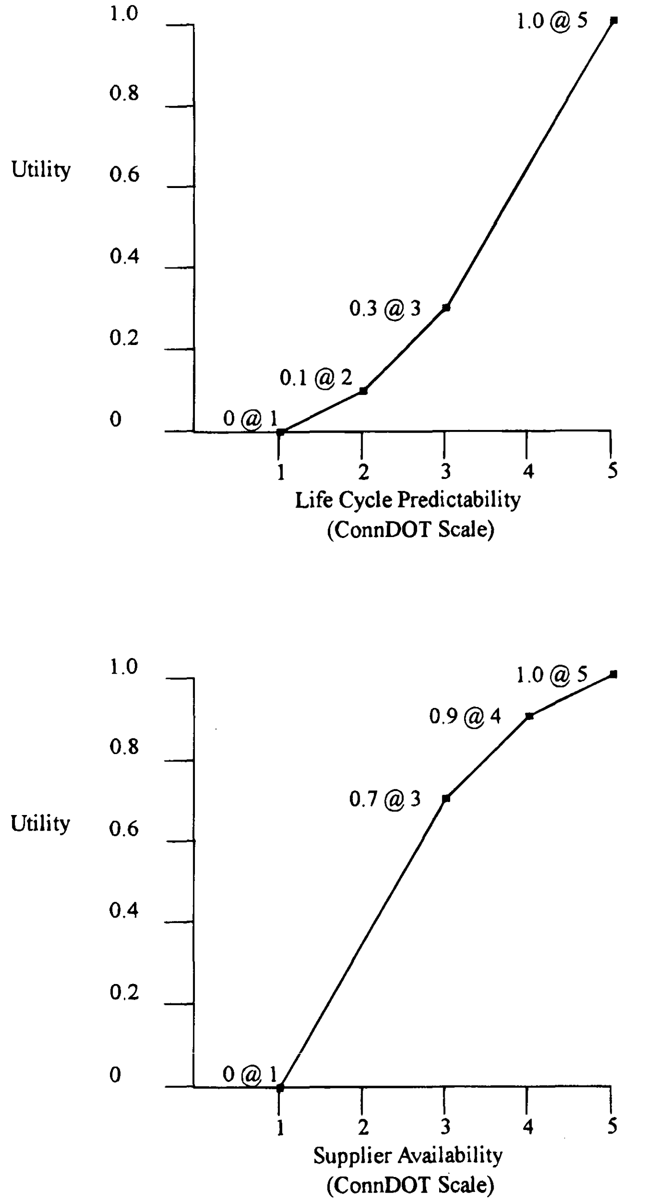

FIGURE 6 Single measure utility functions for (*top*) life-cycle predictability; and (*bottom*) supplier availability.

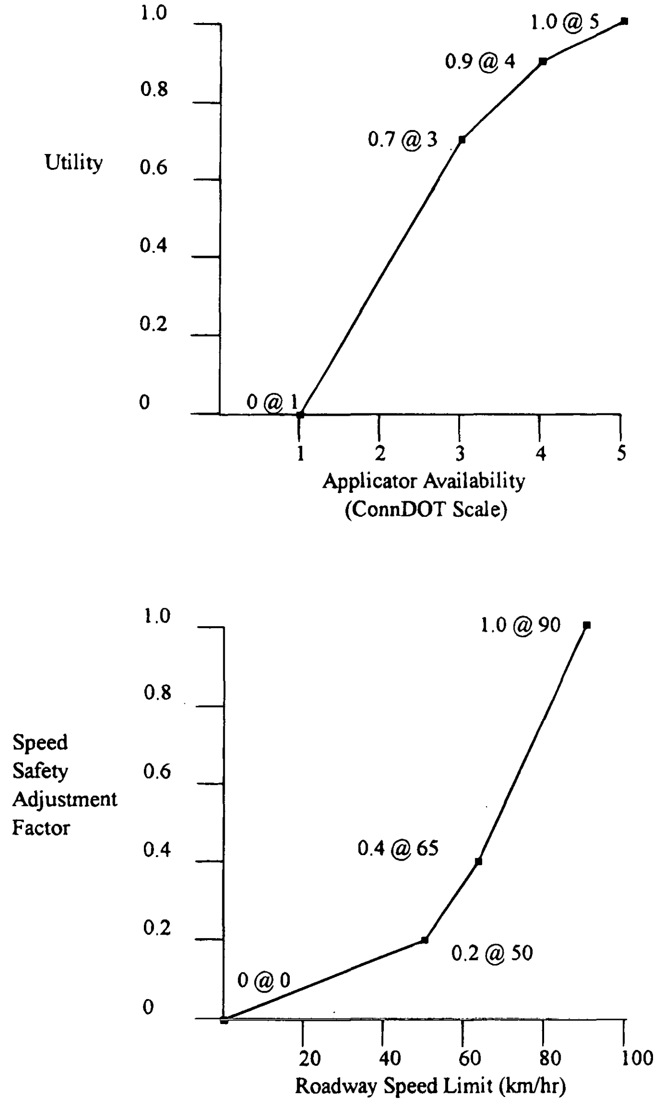

FIGURE 7 Single measure utility function for (*top*) applicator availability; and (*bottom*) speed safety adjustment factor.

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Detailed Study of Accident Experience in Construction and Maintenance Zones

TAE-JUN HA AND ZOLTAN A. NEMETH

The objective of this study was to identify means by which improved traffic control can improve traffic safety in work zones. The accident data base (1982–86) was derived from the coded information stored in the computerized data bank of the Ohio Department of Highway Safety. (The department has since been renamed the Ohio Department of Public Safety.) Coding errors and unreported accidents were recognized as limitations of the data base. Statistical analysis of statewide aggregate data failed to identify cause-and-effect relationships between accident characteristics and traffic control. The study was expanded to include the review of individual accident reports at nine construction sites. This approach proved very effective. The accident reports, which always included a sketch and a description of the event, often indicated that specific traffic control procedures and standards needed to be improved. It has become clear to the researchers that certain types of accidents at a given work zone can suggest specific problems with traffic control plans and/or with the implementation of the plans. Monitoring work zone accidents as they happen is of course the best way to recognize and eliminate problems. In fact, independently from this study, a Work Zone Task Force of the Ohio Department of Transportation that included engineers with intimate knowledge of work zone traffic control practices based on field experience has already recommended improvements in traffic control standards and practices.

Work zones present an abnormal highway environment in that motorists accustomed to a clear, unobstructed roadway are required to recognize and obey an array of instructions conveyed by a wide variety of traffic control devices. They introduce conflict between road users, construction activity, and equipment. The adjacent roadside, usually free of fixed objects, is occupied by warning devices, protective barriers, equipment, and workers. In many instances, the normal roadway capacity is physically reduced by the closing of one or more lanes. The effect of these restrictions is increased delay, which adds to motorist frustration. Work zone traffic control and work zone safety have been a national concern for several years. Reconstruction activities will not diminish in the near future. Driving through work zones will continue to be an everyday driving experience.

There are many well-recognized work-zone-related problems and challenges that are to be faced by transportation departments. The following incomplete list was excerpted from a Federal Highway Administration (FHWA) survey:

- Urban freeway reconstruction;
- The lack of training of contractor personnel;
- The need for specialized equipment, changeable message signs, etc.;
- Motorists driving too fast in work zones;
- Management of both construction and traffic control; and
- The rising number of liability suits.

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NATIONWIDE WORK-ZONE ACCIDENT EXPERIENCE: A LITERATURE REVIEW

Accident Experience

Seven studies were compared in terms of accident experience (*1–7*). Table 1 summarizes the changes in accident experiences during construction. All of these studies show an increase in the accident rate at construction sites. Increases in accident rates during the construction period varied significantly from study to study and very likely depended on specific factors related to traffic, geometry, and environment.

Accident Severity

Ten studies were compared in terms of accident severity (*1–3,5,7–12*). As is illustrated in Table 2, there was a great deal of inconsistency in the findings.

Specific Location of Accidents

The construction zone, which might be several miles long, consists of specific sections. Only four papers discussed the location of accidents within these areas (*2,5,11,13*). These studies involved lane closure situations, except for the Ohio Turnpike study, which included two-way two-lane operation (TWTLO) zones.

Table 3 shows the distribution of accidents at the different areas of the work zone. Once again, there was a lack of consistency in the findings. Clearly, the frequency of accidents in various parts of the work zone varied significantly among the studies because of the different roadway types and traffic controls involved.

Contributing Factors

Seven papers have investigated the factors causing or contributing to work zone accidents (*2,5,7,9,11–13*). The results are summarized in Table 4. These results show more consistency than any of the previous tables, perhaps indicating a relatively uniform use by the reporting offices of the options offered by the crash reporting form.

TABLE 1 Accident Experience During Construction Period

Study	Study Site	% Change in Accident Rate
California (*1*)	California	+21.4 to +7.0
Virginia (2)	Virginia	+119.0
Georgia (*3*)	Georgia	+61.3
Midwest Research Institute (*4*)	Colorado Georgia Michigan Minnesota Ohio New York Washington	+6.8
Ohio (*5*)	Ohio	+7.0
Rouphail (*6*)	Unknown	+88.0
New Mexico (*7*)	New Mexico	+33.0 (Rural Interstate) +17.0 (Federal-Aid Primary) +23.0 (Federal-Aid Secondary)

Specific Findings

Specific findings from past studies varied. The only findings identified by more than one of the past studies are limited to the following:

- The predominant type of accident was rear-end (*5,7,8,11,12*).
- Ineffective attempts were made to reduce speeding problems (*5,8*).
- Improper traffic control was one of the problems in the construction zone (*7,13*).
- Involvement of trucks in accidents at crossovers was significant (*4,13*).

OHIO WORK ZONE ACCIDENT EXPERIENCE (1982–86)

Research Objective

This study had two objectives:

- To identify the nature and seriousness of the work zone safety problem and
- To identify the major cause-and-effect relationships of accidents in work zones and make recommendations.

General Approach and Results

The primary data base (1982–86) was derived from accident reports submitted by law enforcement agencies to the Department of Highway Safety. In the first stage of the study, statewide (i.e., rural state system) accident statistics were reviewed and work zone accident characteristics were compared with statewide accident characteristics. It was observed that

- Work zone accidents were not more severe than all other accidents;
- Work zone accidents were underrepresented at night (i.e., accidents at night were proportionally lower than those during daylight) and under adverse weather conditions;
- Trucks were overrepresented;
- Object and rear-end accidents were overrepresented; and
- Law officers reported "no driver errors" more frequently at work zones.

These observations are based on accidents per time unit as no reliable measures of exposure (e.g., vehicle miles) were available. These results are not counterintuitive and offer no clues to relationship between accidents and traffic control at work zones.

Next, 60 projects were selected for further, more detailed study. The relatively high frequency of accidents on a roadway during the study period and the availability of complete information were the two criteria applied in the selection of this sample. The correlation among accident variables was investigated. Some of the highlights of the findings include (*a*) injury accidents were associated with rear-end and angle accidents, heavy vehicle damage, and multiple vehicle accidents; (*b*) night accidents were object-type accidents, whereas rear-end accidents were frequent during the day, and (*c*) single vehicle accidents were dominant at night whereas two-car accidents were more frequent during daylight. These findings also failed to produce new insights or cause-and-effect relationships.

In the final stage of the project, nine sites were selected as case studies, and the accident reports (OH–1 forms) were studied in detail. Based on the information presented in the accident reports, the authors were able to form some conclusions regarding the operation of most work zones. From some of the specific problems identified at these nine sites, the authors were able to generate recommendations that could improve traffic control at work zones in general.

Data Limitations

Most data bases were subject to two shortcomings: (*a*) uncertainty involving the correctness of the information and (*b*) uncertainty involving the completeness of the data base. Accident records

TABLE 2 Accident Severity Comparison (Change Versus Overall Accident Characteristics)

Study	Severity	
	Fatal	Injury
California (*1*)	Higher	NA[a]
Virginia (*2*)	Higher	Higher
Georgia (*3*)	Higher	Higher
Ohio (*5*)	Higher	NA[a]
New Mexico (*7*)	Same	Same
Graham (*8*)	Same	Same
Flowers (*9*)	Higher	Higher
Richards (*10*)	Low	Low
Kentucky (*11*)	Higher	Higher
Hargroves (*12*)	Lower	Lower

[a]NA = Not Available

derived from police reports are continuously maintained, and because they are computerized, the records are readily accessible. However, problems associated with this data base are well documented and widely recognized (*14*). Problems usually cited included the lack of detail, inaccuracy, and inconsistency in nomenclature and definitions.

When the police reports were reviewed, several recurring errors in coding were observed by comparing statements and sketches with coding. Probably the two most frequent errors in interpretation of definitions given in the Ohio Traffic Accident Procedure Manual were *angle* and *head-on* accidents. Two examples follow that show how these two errors in coding could lead to wrong conclusions.

Example 1

One concern at work zones is the potential conflict between through-traffic and construction vehicles or cars of the crew exiting work zones. Naturally, a high number of angle accidents at freeway work zones would raise suspicion that perhaps this conflict existed at a particular work zone. In fact, the data contained a significant number of angle accidents. However, the review of OH–1 forms indicated that most accidents coded as angle accidents involved cars traveling in the same direction. These accidents should have been properly coded as side-swipe accidents. A significant number of side-swipe accidents would indicate one of two problems: (*a*) an interchange within the work zone is not controlled properly or (*b*) there might be problems with the approach area to lane closure. In summary, the recurring miscoding of side-swipe accidents as angle accidents masked the clues that a certain traffic control problem might exist and gave instead the erroneous indication of another type of problem.

Example 2

One of the most controversial traffic control types at freeway work zones is the temporary TWTLO. The major concern is the potential for head-on collisions, which tend to be severe in terms of injuries. A significant number of head-on collisions in a data base would naturally raise a red flag. In the authors' experience, however, practically all accidents coded as head-on accidents were, in fact, single

TABLE 3 Distribution of Accidents by Location

Location		Study			
		Virginia (*2*)	Ohio Rural (*5*)	Kentucky (*11*)	OhioTurnpike (*13*)
Advance Zone		12.7%	15.9%	5.6%	6.5%
Taper		13.3%	22.5%	7.9%	9.2%
Work Area	Lane Closure or Buffer Area	44.7%	39.1%	54.1%	23.2%
	Construction Area		16.6%		
Ramp		0.0%	3.3%	0.0%	0.0%
Crossover		0.0%	0.0%	0.0%	34.1%
TLTWO		0.0%	0.0%	0.0%	22.2%
Others (Intersection)		29.3%	2.6%	32.4%	4.8%

TABLE 4 Contributing Factors to Construction Zone Accidents

Study	Contributing factors				
	Driver Error	Unsafe Speed	Fail to Yield	Impaired	Follow Too Close
Virginia (*2*)	Yes	No	No	Yes	No
Ohio Rural (*5*)	Yes	Yes	Yes	No	No
New Mexico (*7*)	Yes	No	No	No	Yes
Flowers (*9*)	Yes	No	No	No	No
Kentucky (*11*)	Yes	Yes	No	Yes	No
Hargroves (*12*)	Yes	No	No	No	No
Ohio Turnpike (*13*)	Yes	Yes	No	No	No

vehicle accidents. The head-on definition is assumed by officers to refer to the area of the vehicle that was damaged. In one extreme case, an object fell from a truck and hit the windshield of a car. This accident was also coded as a head-on collision. The potential for misleading the analysts by consistent and frequent coding errors is quite real.

A detailed review of all construction accident reports and an examination of the coding led to the correction of miscoded data. As shown in Table 5, the angle, head-on, parked-motor-vehicle, and other-object accident categories have a significant number of recoded accidents. Of the 810 work zone accidents at the nine sites, 124 cases (15.3 percent) were judged to have been miscoded.

To compensate for the identified coding errors, these accident reports were reanalyzed and corrected as identified. The result is shown in Table 6. Another well-recognized shortcoming of any data base derived from accident reports is the widespread problem of underreporting. In Ohio, evidence was presented by a Northeastern Ohio Trauma Study (*15*). Hospital records of 882 injuries were compared with accident reports. The findings were quite startling. Only 55 percent of the injury-causing accidents were actually

TABLE 5 Accident Distribution for Accident Types by Construction Period

Accident Type	Construction Period			
	Before	During (Original)	During (Revise)	After
Head-On	9	24	7	7
Rear-End	68	175	164	92
Backing	1	7	8	11
Side-Swipe (Meeting)	1	4	1	2
Side-Swipe (Passing)	59	115	136	50
Angle	19	65	39	65
Parked Motor Vehicle	7	10	21	11
Pedestrian	2	6	6	1
Animal	35	29	30	54
Train	0	0	0	0
Pedalcycle	0	0	0	0
Other Non-M.V.	0	0	0	0
Fixed-Object	107	221	201	130
Other-Object	13	47	106	25
Fall From or In Vehicle	1	4	0	6
Overturning	10	25	24	6
Other Non-Collision	51	78	67	50
Total	**383**	**810**	**810**	**510**

TABLE 6 Distribution of Miscoded Data by Accident Types

From\To		O[a]	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Head-On:	A	24	6	0	0	0	0	1	0	0	0	0	0	0	0	17	0	0	0
Rear-End:	B	175	0	161	1	0	4	0	8	0	0	0	0	0	0	1	0	0	0
Backing:	C	7	0	0	6	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sideswipe (Meeting):	D	4	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0
Sideswipe (Passing):	E	115	0	1	0	0	107	0	3	0	0	0	0	0	1	3	0	0	0
Angle:	F	65	0	1	0	0	23	38	1	0	0	0	0	0	1	1	0	0	0
Parked Motor Veh.:	G	10	0	0	0	0	0	0	9	0	0	0	0	0	0	1	0	0	0
Pedestrian:	H	6	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Animal:	I	29	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0	0
Train:	J	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pedalcycle:	K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Non-M.V.:	L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fixed-Object:	M	221	0	1	0	0	0	0	0	0	0	0	0	0	193	22	0	0	5
Other-Object:	N	47	0	0	0	0	0	0	0	0	1	0	0	0	0	46	0	0	0
Fall From or In Vehicle:	O	4	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	1	0
Overturning:	P	25	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	23	1
Other Non-Collision:	Q	78	0	0	0	0	0	0	0	0	0	0	0	0	5	12	0	0	61
Revised Data		810	7	164	8	1	136	39	21	6	30	0	0	0	201	106	0	24	67

[a] O stands for original data

reported. When the injury involved children under the age of 16, only 28 percent of the crashes were reported as traffic accidents.

By reviewing 18 research reports from many different countries, Hauer and Hakkert found that the problem is worldwide (*14*). They estimated that on the average, police reports miss perhaps 20 percent of the crashes that resulted in injuries requiring hospitalization. Hauer and Hakkert suggested that as much as 50 percent of the other injury crashes might go unreported. The large percentages of unreported crashes make uncertain all quantitative conclusions based on such an incomplete data base.

It would be convenient to assume that the probability of crashes going unreported at different locations and at different times is constant. In that case, statements based on the differences between two data sets would still be valid. However, there is no evidence to justify this assumption.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are organized into two sections. Each section attempts to respond to one of the two objectives of this study.

Identify the Nature and Seriousness of the Work Zone Safety Problem

In 1988, over 74,000 accidents were reported in Ohio on the Rural State System. Of these accidents, 1.72 percent were coded as work zone accidents. (The latest available data are for 1993, for which 1.8 percent of the accidents were coded as work zone accidents.) There is no baseline available by which one could judge the seriousness of the work zone safety problem, as represented by this 1.72 percent proportion. Work zone accidents show a trend that is different from the trend shown by all accidents on the Rural State System. Although all accidents increased from 1984 to 1988, work zone accidents decreased. Assuming that reconstruction and maintenance activities did not decrease during these years, one might conclude that, although the seriousness of work zone accidents cannot be judged from these numbers, at least some improvement can be claimed.

Injury accidents represent a fairly stable (approximately 34 percent of the total) number of accidents reported on the Ohio Rural State System. Injury accident percentages are consistently lower at work zones by a small margin (31 to 32 percent). In summary, in regard to the question of how serious is the work zone safety problem on the Rural State System in Ohio during the study period, the authors can only say that (*a*) work zone accidents show a trend of decreasing as a percentage of all accidents and (*b*) work zone accidents are slightly less severe than all accidents.

Regarding the nature of work zone accidents, trucks seem to present a special problem at work zones in some situations, as will be discussed later in this paper. The authors can also conclude that accidents at work zones increase more noticeably during daytime than at night. This is to be expected because congestion during peak periods is probably responsible for much of the increase in rear-end accidents.

The authors cannot conclude that work zone accidents decrease at night when compared with before periods. The authors can only conclude that work zone accidents at night decrease in proportion to all work zone accidents. At seven of the nine sites that were investigated in detail, work zone accidents at night actually increased when compared with the before period, but not as much as daytime accidents. This is significant because it might be more feasible to reduce nighttime accidents with proper delineation than to eliminate congestion (which contributes to the increase of daytime accidents).

Identify Major Cause-and-Effect Relationships of Accidents in Work Zones and Make Recommendations

By careful analysis of the information recorded on the OH–1 form by the law enforcement officers at the site, the authors have attempted to identify specific problems at the nine sites selected as case studies. The problems were different at different sites. At some of the sites, the authors were unable to identify specific problems. All sites had accidents, such as collisions with animals or vehicles catching fire, that were not related to work zone traffic control or construction activities. Discussion of the more significant problems that were identified follow.

Inadequate or Confusing Traffic Control

Case Study 2 2.5 km (7.76 mi), four-lane freeway, pavement repair, resurfacing, shoulder restoration, 1-year duration: Several drivers got into the closed area approaching an exit ramp at night. Uncovered holes in the pavement caused damage to the vehicles and injuries. The traffic control plan calls for a 30.48-m (100-ft) or greater opening at exit ramps; shorter openings required approval by the engineer. No trucks were involved in these accidents.

Traffic control at exit ramps must be reevaluated. It should be made very difficult to enter the closed area before an exit ramp and more easy to recognize the opening to the exit.

Traffic control plans called for a 30.48-m (100-ft) minimum opening at the exit ramps. This may not be sufficient. Drums or barricades are specified to be spaced at 15.24 m (50 ft) on approaching the exit openings. This spacing should be reduced, especially when errant drivers entering the closed area would face open holes in the pavement.

Case Study 8 5.6 km (3.5 mi), four-lane freeway, concrete median divider, pavement repair and resurfacing, guardrail reinstallment, median modification, bridge deck overlies, 1-year duration: The protection provided by the construction barrels appeared to be inadequate as seven accidents were reported resulting from drivers entering the closed lane and driving into holes created by pavement removal. It appears that these drivers intended to exit at the open exit ramps but for some reason entered the closed lanes before they reached the open exit ramp.

As much as possible, it should be made very difficult for drivers to enter closed areas where open holes present serious hazards. Prevention of very damaging liability cases justifies the expenditure of time and effort involved in setting up effective traffic control and temporary barricades, if needed.

Edge Drop or Soft Shoulder

Case Study 2 Edge drop or soft shoulder accidents tended to occur at night. Trucks were involved in four of the seven accidents, including one fatal accident.

Edge drops proved to be very hazardous at Case Study 2. Traffic control plans did not indicate warning signs. This situation must be properly addressed by the traffic control plans.

Traffic Slowdowns

Case Study 1 8.4 km (5.2 mi), four-lane freeway, pavement repair and resurfacing, bridge deck repair, guardrail replacement, 1-year duration: The major problem seemed to be traffic backups resulting in rear-end accidents. The problem vehicles in this situation seemed to be trucks and tractor-trailers.

Traffic signs at work zones should inform drivers of what to expect, where to expect it, and advise them what to do. The traffic control plans did not indicate that drivers approaching this work zone were advised to watch for stopped traffic or traffic slowdowns.

It would be desirable to inform drivers of slow or stopped traffic ahead *when* and *where* it is actually happening. Changeable message signs serve this function very well. Conceivably, truck drivers would also respond to such current information.

Case Study 2 The largest number of accidents were caused by traffic slowdowns. These accidents occurred during daytime, some on wet pavement. Six trucks were involved in these accidents as at-fault drivers. Two were single vehicle accidents: trucks jackknifing due to sudden breaking or running off the road trying to avoid collision with slower traffic.

The *WATCH FOR STOPPED TRAFFIC* signs seemed to be effective at other sites and should always be used when slowdowns are expected.

Lane Changing or Merging

Case Study 3 2.7 km (7.9 mi), six-lane freeway, resurfacing, 1-year duration; *Improper lane change* accidents represented the largest category, with nine accidents. With one exception, these accidents involved trucks, tractor-trailers, or campers.

It is not evident from the sketches that any weakness in the traffic control necessarily contributed to these accidents. They seemed to be caused by errant drivers. These nine accidents are a higher percentage of the work zone accidents (23 percent) than the 15 similar accidents over the same length of roadway adjacent to the work zone (18 percent).

Lane change accidents tended to occur not in the advance area nor at the taper but in the area where one of the three lanes was closed. The problem seemed to be experienced by larger vehicles. It seems that restricting larger vehicles to one of the two open lanes could reduce the problem, assuming that drivers observe the restrictions.

Guardrails

Case Study 2 Guardrails were hit in seven cases, typically in a closed lane situation. The need to provide more delineation to guardrails because of the contrast provided by the highly visible construction barrels is indicated here. Guardrails within work zones may need to be delineated.

Use of Berm as Travel Lane

Case Study 4 12.4 km (7.7 mi), six-lane freeway, resurfacing, 1-year duration: The use of berms to maintain traffic contributed to accidents in different ways: vehicles drifting off the edge lost control; disabled vehicles were parked on the berm; and operaton of ramps was complicated.

The use of the berm as a travel lane led to a variety of problems at this site. This special problem needs to be handled by the traffic control plan, and sufficient attention needs to be paid to the potential problem.

Drivers Who Have Been Drinking Alcohol

Case Study 2 Eight accidents involved drinking drivers, although no such accidents were reported outside the work area at the same site during the same time period. Three of the drinking drivers were truck drivers. Three of the accidents involved a collision with guardrails; in the other accidents, the drivers drifted into the closed area. All but one accident occurred at night.

Case Study 3 Drinking drivers are overrepresented in work zone accidents compared with drivers responsible for accidents outside work zones, and a slightly higher proportion of these accidents, resulted in injuries. All but one vehicle penetrated the work zone area.

Case Study 5 5.6 km (3.5 mi), four-lane freeway, concrete median divider, pavement repair and resurfacing, pavement widening, 20-month duration: Drinking drivers were responsible for all accidents at this site, resulting on one fatal, five injury, and two property-damage-only accidents. However, there is no indication that traffic control at the work zone contributed in any way. The concrete median barrier was involved in several of these accidents, probably contributing to the severity but at the same time preventing potentially more dangerous collisions with opposing traffic.

The problem of drinking drivers was observed at other sites as well. The fatal accident only drew more attention to this issue. This problem, however, cannot be solved by the tools available to Ohio Department of Transportation (ODOT) engineers. The recommendation is to consider identifying the level of drinking driver problems before construction at long-term projects, especially if nighttime work is considered. If the problem is potentially serious, then cooperation of law enforcement agencies might be requested.

Ways To Develop and Implement Means of Improving Work Zone Safety

The case studies described earlier involved reconstruction projects in 1984–85. Since then, significant changes have taken place. In early 1988, ODOT established Work Zone Traffic Control (WZTC) Task Groups to undertake the following tasks:

- Task 1—Develop maintenance of traffic (M/T) policies for construction work zones (CWZs);
- Task 2—Develop M/T standard construction drawings;
- Task 3—Analyze and recommend changes to existing CWZ M/T procedures, practices, and application of TC devices.

These task groups have shown significant progress in a relatively short time. Major accomplishments under Task 1 have been to initiate action that would:

- Create a WZTC engineer in each field district to monitor and control CWZ activities.
- Establish a tentative policy to reduce the speed limit by 16.1 km/hr (10 mi/hr) in construction zones on all urban and rural interstate routes and on all rural multilane highways.
- Establish Corridor Traffic Management planning teams in each district and major urbanized area to address M/T problems created during highway improvements.
- Provide design criteria or performance criteria for the design of CWZ traffic control.

Task 2 has developed new or revised standard construction drawings (SCDs) which will improve WZTC plans and lead to greater uniformity. All SCDs include designer notes to guide the designer. Significant products from Task 3 include:

- A study of TLTWO on rural freeways resulting in recommendations for changes in lane closure practice and median crossover design;
- A revised design for median crossovers at TLTWO;
- A policy on the use of changeable message signs approaching a CWZ area; and
- A study of the problems involved with implementing the use of individual pay items for CWZ, traffic control M/T items, and recommendations to specify such items on selected pilot projects.

INTERPRETATION OF ACCIDENT REPORTING FORMS

By reading the information and studying the sketch prepared by the law enforcement officer, one could often, but by no means always, form an opinion regarding the cause (or more correctly, the major causes) of an accident. During the review of the OH–1 forms, certain common characteristics emerged, as expected:

- The officers almost never volunteered information regarding the quality of traffic control (only one exception was observed).
- The written statements tended not to include statements that clearly indicated a guilty driver.
- Estimated speeds were almost always marked lower than legal speeds even when "unsafe speed" was identified as a contributing driver error.

The officers, quite properly, avoided presenting opinions on subjects that were outside their expertise (i.e., work zone traffic control) or make statements that could not be substantiated by the available evidence. The authors, however, have made an effort to interpret the information and select one of the four factors—traffic control, roadway, driver, or vehicle—as the major contributing factor. This task was made difficult by the fact that there were often secondary contributing factors, such as the combination of darkness and rain, without which the accident probably would not have happened.

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Traffic Management During Road Closure

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The overall objective of this research was to provide potential users, particularly small municipalities, with a basis for selecting the travel demand analysis package best suited for evaluating traffic management alternatives during road closures. Four travel demand analysis packages (QRS II, System II, TRANPLAN, and MINUTP) were studied and rated with respect to 14 characteristics. Of the four software packages, the two top-rated packages were used to estimate traffic in a network. The performance of the two packages was evaluated on the basis of predictive accuracy, modeling deficiency, comprehensiveness, and compatibility with other software. It was found that both packages could be used to evaluate the impact of changes in network and zonal characteristics on travel demand. However, both packages are not developed to the extent that is needed to generate all the information needed to determine the alternative traffic management strategies. Thus, it is suggested that potential users specify the primary functions for which it is to be used before investing in a software package.

The decentralization of local government functions in most large cities has led smaller entities to become more responsible for planning, designing, and managing the transportation systems. In addition to the routine tasks, such as evaluation of proposals for land development, road closures for infrastructure maintenance, changes to parking facilities or regulations, and numerous others that may affect traffic conditions, these entities are now responsible for formulating local area land-use and transportation plans. Thus, if each small municipality had its own data base and microcomputer-based analytical package, the impact on the network due to an extension of the city or a major development could be analyzed in more detail and at a comparatively smaller cost than if it were done manually.

A user survey recently conducted by the Transport Association of Canada (*1*) revealed the general consensus that the right combination of software and hardware can easily overcome many of the existing time and staff constraints faced by agencies. The survey data also show that planning models are being used for a multitude of purposes, including the examination of different scenarios, policies, and assumptions. However, the selection of the appropriate software package from several similarly priced and marketed products is not an easy task. Brochures and demo disks are often inadequate to assess the full array of underlying analytical tools or the input data, equipment, and training/educational requirements. Thus, one needs to establish certain criteria for evaluating the characteristics of each package in relation to the needs.

This article is based on a study undertaken to examine the impact of a proposed road closure on travel demand and the level of service of the road network in the city of Verdun, Montreal, Quebec. The primary objective of the study was to identify traffic management options during the period when the road would be closed for pavement reconstruction and utility upgrading. This situation, where a principal artery (Wellington Street) was closed for 4 months, was an ideal case study to better understand the pros and cons of using transportation planning software for evaluating traffic management alternatives when data and computer skills are limited.

Four travel demand analysis software (TDAS) packages—TRANPLAN (*2*), MINUTP (*3*), System II, (*4*) and QRS II (*5*)—were examined and rated with respect to 14 characteristics. From these four, the two top-rated TDAS packages (System II and QRS II) were applied to determine the optimal work-zone traffic diversion plan.

TDAS EVALUATION

The principal features of the four TDAS packages examined are summarized in Table 1. These four were evaluated on the basis of 14 criteria, some of which have been used previously by Khisty and Rahi (*6*) and the Transportation Association of Canada (TAC) (*1*). They were then ranked (10, indicating best and 0 indicating worst) with respect to each of the 14 criteria according to the degree to which they satisfied the needs. All four packages could be used in this area; however, according to the total points shown in Table 2, System II and QRS II were selected for further analysis.

STUDY AREA AND DATA COLLECTION

Verdun is a mature residential community with limited commercial and industrial activities. As shown in Figure 1, the city is bounded by the St. Lawrence River to the east and the Lachine Canal to the west and by the two cities Montreal and LaSalle to the north and south, respectively. Thus, points of access to the city are restricted to the bridges across Lachine Canal and one point to the north leading to Montreal. The two border arteries to the east and west are the main links to the southern city of LaSalle. There is also a dense central business district, which accounts for approximately 10 percent of the total land area of Verdun and contains mostly retail activity. Verdun was divided into 20 traffic zones corresponding to the census tracts, and all the external trips were considered as 10 external zones.

With the exception of traffic count data for the major arteries from May 1990, Verdun possessed no other traffic data. Therefore, the basic input data were collected from the following sources:

- Network data such as capacities, intersection types, control measures, etc., were compiled through site visits, and a 1-hr cordon count was made during one weekday afternoon peak period.
- Land use types in each zone were obtained from the city's master plan.
- The population and information on dwelling units were obtained from Statistics Canada's 1988 Census records.

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TABLE 1 Basic Features of QRS II, System II, TRANPLAN, and MINUTP

FEATURE	QRS II	SYSTEM II
Trip End Estimates	default parameters	user input trip rates
Trip Distribution	default parameters	user input friction factors
Mode Choice	need to build transit network	incomplete
Assignment	all-or-nothing in default mode	multi-path based on chosen delay/flow model
Graphics	only print screen option	presents information in many forms and CAD options
Network Performance	travel time and volume tables	travel time, volume, node/link, LOS.
Sensitivity Analysis	node and link codes change every time a change is made, thus difficult to keep track.	facilitates comparison of performance under different conditions.

FEATURE	TRANPLAN	MINUTP
Trip End Estimates	user input trip rates	user input trip rates
Trip Distribution	user input friction factors	user input friction factors
Mode Choice	splits trips between two modes.	splits trips between two modes.
Assignment	all-or-nothing, stochastic	all-or-nothing, stochastic
Graphics	presents information in many forms.	presents information in many forms.
Network Performance	many options including travel time, volume, LOS	total volume, directional volume, volume capacity ratio, congested speed
Sensitivity Analysis	accepts surveyed O-D table, and link volumes for calibration.	facilitates comparison of performance under different conditions.

- The number of retail and nonretail employees were estimated in proportion to the gross floor area of the respective activities in each zone.
- The zonal trip-generation rates were obtained from the Institute of Transportation Engineers manual on trip generation (*7*).
- Since the transit ridership figures were not available, a fixed share of 10% was used.

TRIP ASSIGNMENT

In each of its four modules (generation, distribution, mode choice, and assignment), QRS II contains default parameters based on the NCHRP Report 187 (*7*). Users have the option of using either these default parameters or other values. In the present case, all the available default values were used. For instance, it was assumed that observed volumes were unavailable, and the default function based on area size was chosen without calibrating the gravity model to the existing conditions. Likewise, the default assignment procedure was used with no adjustments to link capacities or travel time factors. Moreover, because QRS II is not geared for treating zones with land use other than residential or commercial, the zones that contained an arena and a large municipality parking facility were treated as external zones. The final results are given as observed to estimated p.m. peak volume ratio (R_k) for several selected links in Table 3.

The same zonal and network configuration used in QRS II was adopted for System II. To minimize the iterations and to determine the extent to which the distribution model parameters are transferable, the travel-time-based default friction factors from QRS II were used as the starting values for the calibration. The input parameters for trip-generation analysis were taken from the ITE manual on trip generation (*8*). The assignment was based on an exponential delay/volume function. A summary of R_k for System II is also given in Table 3.

TABLE 2 Applicability Scores of the Models—0 (Worst) to 10 (Best)

		Models			
	Criteria	TRANPLAN	MINUTP	SystemII	QRS II
1	Data required	6	6	6	10
2	Cost	4	6	10	10
3	Run time	8	8	8	10
4	Flexibility	10	8	10	4
5	Input parameters	6	6	6	10
6	User friendliness	4	4	8	10
7	Comprehensiveness of output	8	8	10	6
8	Graphics display	8	6	10	4
9	On-screen help menu	6	6	8	6
10	Reference manual	7	7	9	6
11	Hardware needs	10	10	10	10
12	Knowledge on modeling	6	6	8	10
13	Preparation time	6	4	6	10
14	Subarea analysis option	10	10	10	0
	Total	99	95	119	106

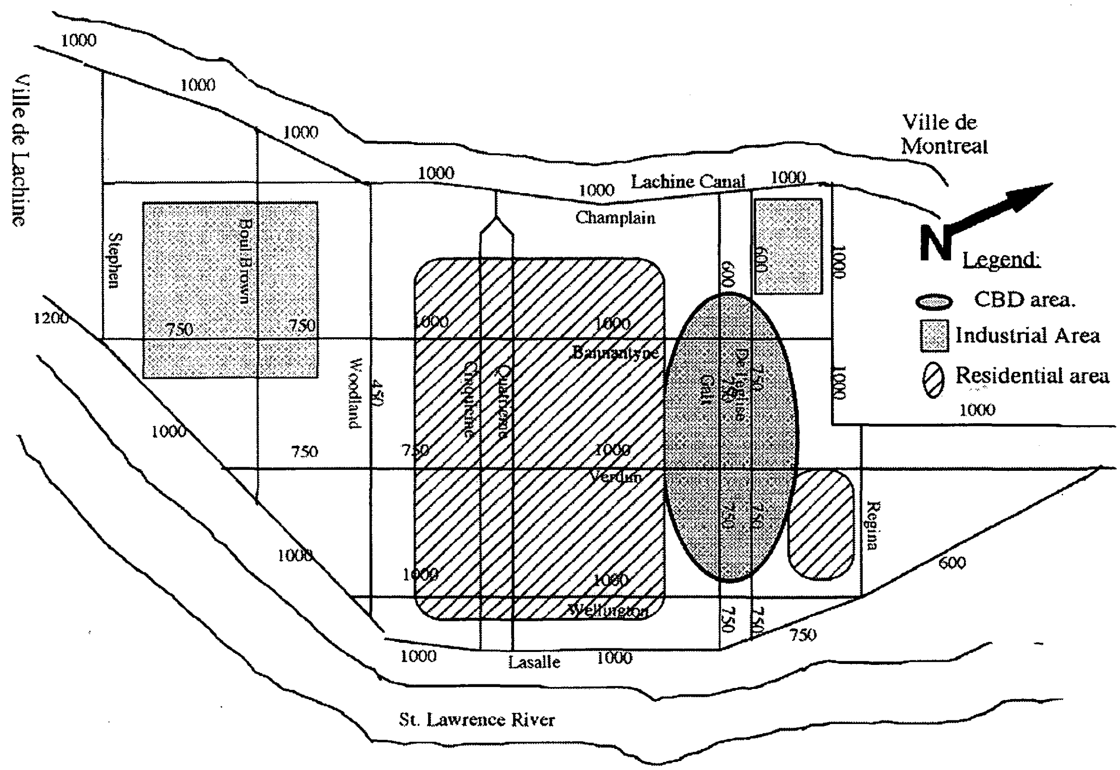

FIGURE 1 Observed p.m. peak link volumes.

TABLE 3 Ratio of Observed to Estimated Volumes (R_k) on Selected Links

LINK NAME	QRS II	SYSTEM II
Lasalle	0.90	1.56
Wellington	0.88	0.80
Verdun	0.87	1.04
Bannantyne	0.97	0.88
Champlain	0.95	0.97
Woodland	0.78	0.64
Galt	6.99	1.23
De l'eglise	2.45	1.44
Mean of R_k (MR)	1.85	1.07
Std. dev. of R_k (SD)	2.15	0.31

$R_k = O_k/E_k$

where: O_k = Observed Volume on link k,
E_k = Expected Volume on link k.

$$MR = \sum_{\text{all } k} \frac{R_k}{N}$$

$$SD = \sum \frac{(R_k - MR)^2}{(N-1)}$$

ALTERNATIVE TRAFFIC MANAGEMENT STRATEGIES

Because the objective of this exercise was to identify the traffic diversion options, it was decided to determine the various means of ensuring that traffic is reassigned according to the modeled form during the closure of Wellington Street. A discussion of the procedure adopted for each TDAS follows.

System II

There are two ways to identify the traffic diversion options. First, one could search for all origin-destination (O-D) pairs in each of the links that would experience a change in flow after the closure. Accordingly, signs could be placed at the appropriate nodes (intersections) to divert the traffic to the alternate links with the hope of achieving the modeled state. However, because System II does not have such a search procedure (select link analysis), it would have taken a considerable amount of time to perform a manual search from the trip tables. Thus, it was decided to use the second approach, which is to simply work backward from the existing conditions, that is, determine the O-D matrix for trips along the entire length of Wellington Street before closure, and reroute these trips during closure to achieve the modeled assignment without Wellington Street.

As expected, three groups of trip ends were identified as the primary users of Wellington Street: (*a*) trip ends terminating in zones bordering on Wellington Street, (*b*) trip ends originating in zones bordering on Wellington Street, and (*c*) through trips connecting to and from Boulevard LaSalle at the southern end of Wellington Street.

It was also found that most of these p.m. peak trips had origins or destinations in zones to the northwest, the north, and, to a lesser extent, the south. Thus, the system's shortest path algorithm was used to determine the optimal routes for rerouting trips between the zones identified above and five external zones: one in the north (Montreal), two in the northwest, and two in the south.

These paths (shown in Figure 2) enabled the identification of the nodes at which the detour signs should be placed. Also, because the shortest paths are the paths from the skim tree based on the appropriate delay/flow function, the detours would ideally result in the expected assignment pattern.

As mentioned earlier, the links that would experience significant changes in level of service due to these detours could be easily addressed through simple traffic management measures involving parking. For instance, field surveys of the affected links, such as Boulevard LaSalle, indicated that capacity could be increased to minimize the impact by simply changing parking regulations in the vicinity, that is, removing parking restrictions on the cross streets to permit those presently parked on Boulevard LaSalle to park on these cross streets during the peak periods.

QRS II

As for identifying points of diversion, this system also lacks an algorithm for searching the O-D matrix for a given link. Moreover, the shortest path algorithm is not geared for identifying the path between a specific O-D pair; instead, the algorithm identifies all shortest paths between a specific node and all other nodes in the network. Thus, the procedure used in conjunction with System II for selecting the detour points will involve much more tedious manual work than that of QRS II. Under the circumstances, one will be required to make educated guesses on the basis of the expected assignment given in Figure 2 about where to place the detour signs.

TDAS PERFORMANCE

Estimation Errors

The performance or accuracy of the selected models can be evaluated on the basis of either parametric or nonparametric tests as suggested by James (*9*). In the present case, three parametric tests—observed to expected volume ratio on link *k* (O_kE_k), mean ratio (MR), and percent RMSE—were used.

According to the O/E ratios in Table 3, QRS II estimation error is approximately 20 percent on most links, except the Galt and de l'eglise Streets. In terms of the mean ratio (MR), QRS II overestimates link volumes by an average of 95 percent with a standard deviation of 215 percent. The QRS II percent RMSE, on the other hand, is 39 percent.

In comparison, assignment errors of System II seem much smaller. The largest error according to O_kE_k, as shown in Table 3, is 56 percent. MR is 1.07 with a standard deviation of 0.31, and the percent RMSE value is 28. However, there are more links than with QRS II where the assigned volumes are greater than plus or minus 20 percent of the observed volumes. Most of these links carry volumes in the range of 400 to 800 vph (vehicles per hour), as shown in Figure 3.

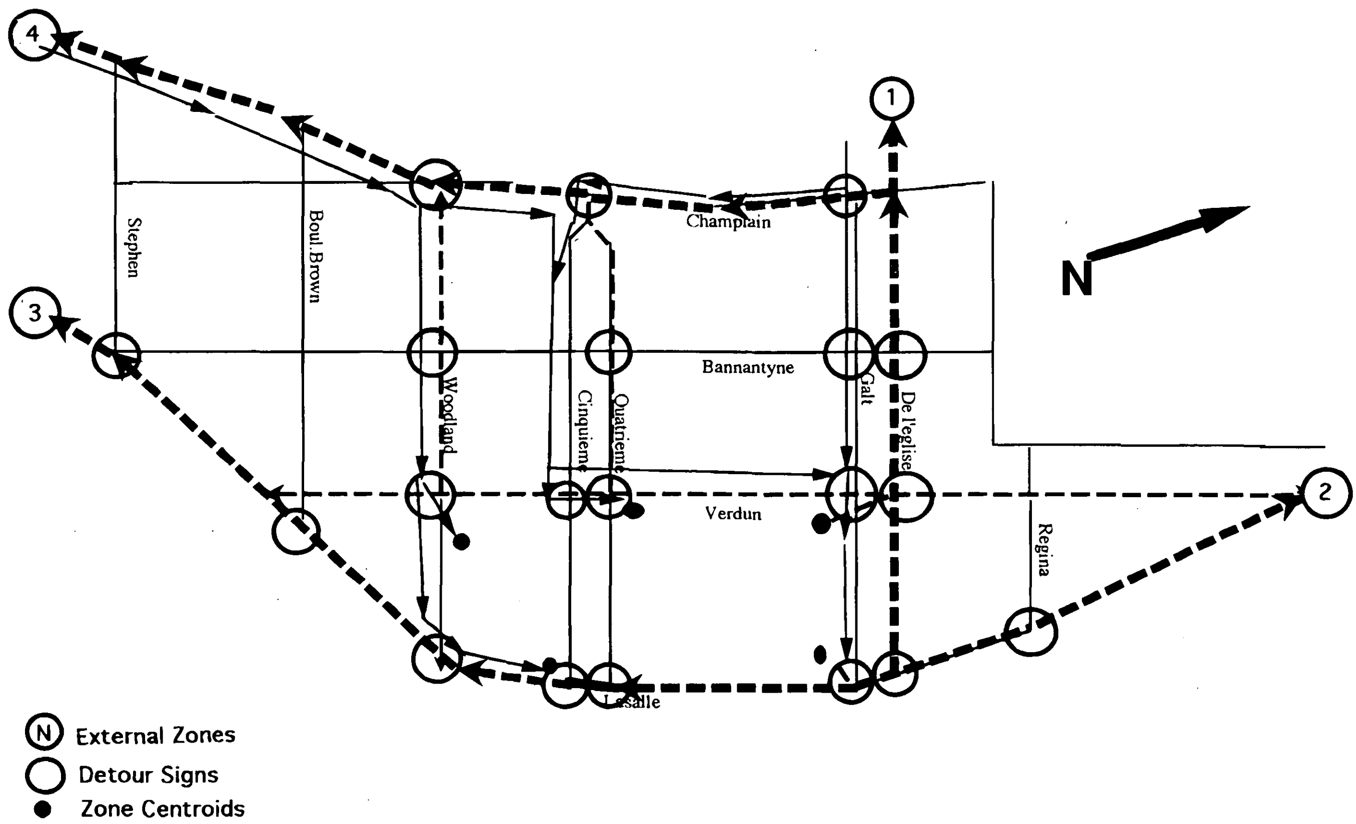

FIGURE 2 System II estimated shortest paths from selected zones.

Both packages considered here were indeed sufficient to model the travel patterns in Verdun with reasonable accuracy. From the frequency distribution in Figure 4, it is evident that differences between estimated and observed link volumes are relatively small.

Significance of Errors

A series of statistical tests was performed as shown in Table 4 to verify the significance of the differences between estimates of the two TDAS packages. It is seen from Table 4 that, with QRS II, volumes on 15 links are underestimated on the average (μ_u) by 291 vph, and the volumes are overestimated in 15 links by an average (μ_o) of 401 vph. The average μ_u and μ_o of System II were 205 and 269 vph, respectively. The *t*-values indicate that in both cases (QRS II and System II), the differences between μ_u and μ_o are significant. But, the mean differences (MDs) were not significantly different from one another at the 5 percent level.

The two packages were also compared in relation to the reassigned volumes after eliminating Wellington Street from the network. The frequency distribution of the changes in link volumes without Wellington Street is shown in Figure 5. Statistical tests were performed on two hypotheses about overall system performance. The first hypothesis was that the mean increase in traffic volume on certain links is not significantly different from the mean decrease in others after the closure. If everything else were the same, this means that the deterioration of the level of service (LOS) in some links would be offset by an improvement in the LOS in others. The second hypothesis was that the mean deviation (increases and decreases) after the reassignment with QRS II equals the mean deviation with System II reassignment. This hypothesis means that even without calibration, QRS II can produce an assignment similar to a calibrated model. It can be seen from Table 4 that both hypotheses are acceptable at the 5 percent level of significance.

COMPARISON OF PACKAGES

Despite ignoring the transit ridership and parking facilities, the ratio of observed and estimated volumes shown in Table 2 are in reasonable accordance with the observed volumes. Although the estimation errors on the two links, Galt and de l'eglise, seem unusually high, according to both Robbins (*10*) and Easa (*11*) they can be regarded as insignificant. Robbins (*10*) notes that it is common to see large discrepancies between observed and synthesized volumes, regardless of the sample size. Such errors are said to result mainly from deficiencies in modeling practices, and, until they are resolved, existing tools will have to suffice.

Each package was also found to have certain other merits and demerits. Neither system can generate all the information needed for decision making simply through pull-down menus. For instance, as in the case of finding the trips likely to be affected during road closure, the user must use trip tables to identify them.

QRS II's inability to treat all different types of land use in zones with mixed land use is a serious limitation. Despite the closeness of the observed and modeled volumes as compared with System II, this limitation makes it unsuitable for users who may need to perform site impact analyses.

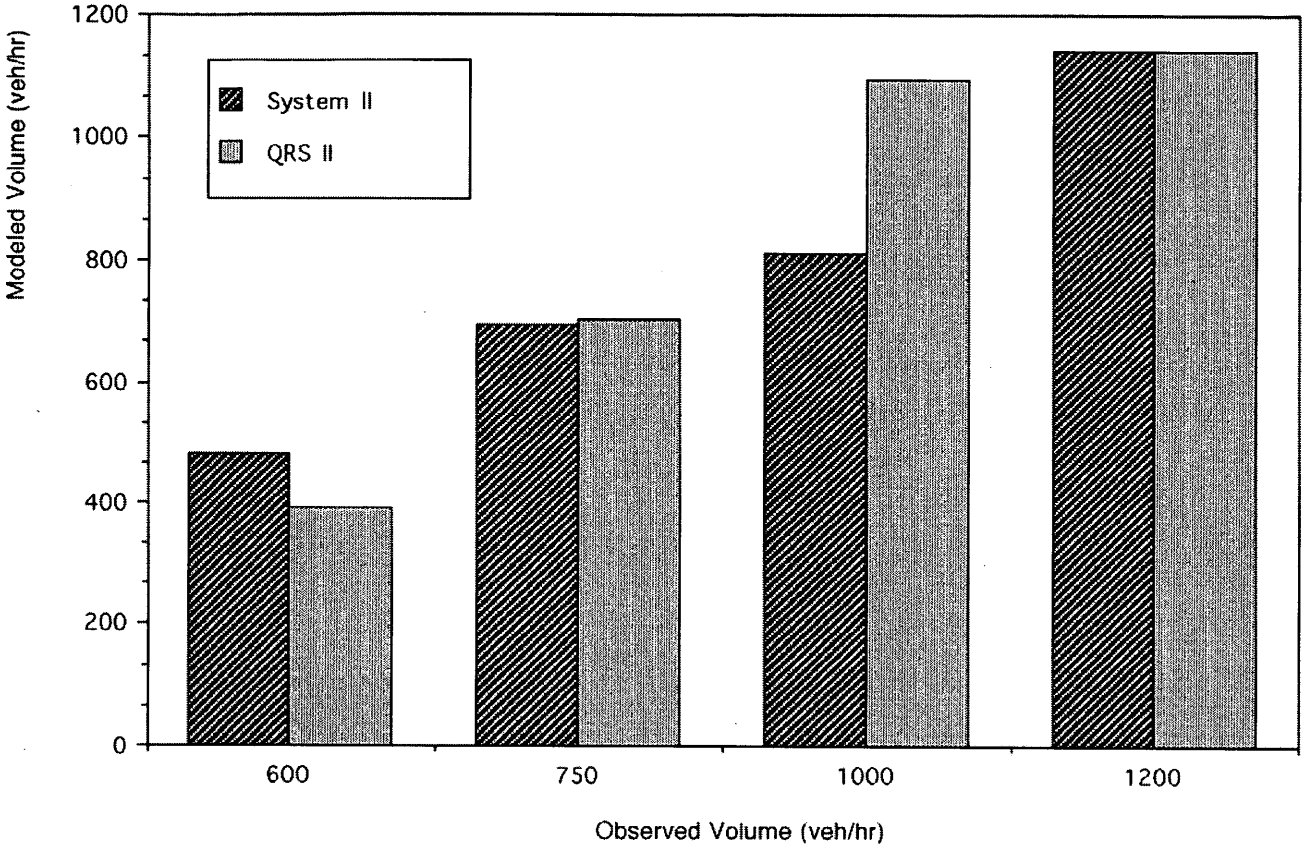

FIGURE 3 Comparison of observed and modeled link volumes.

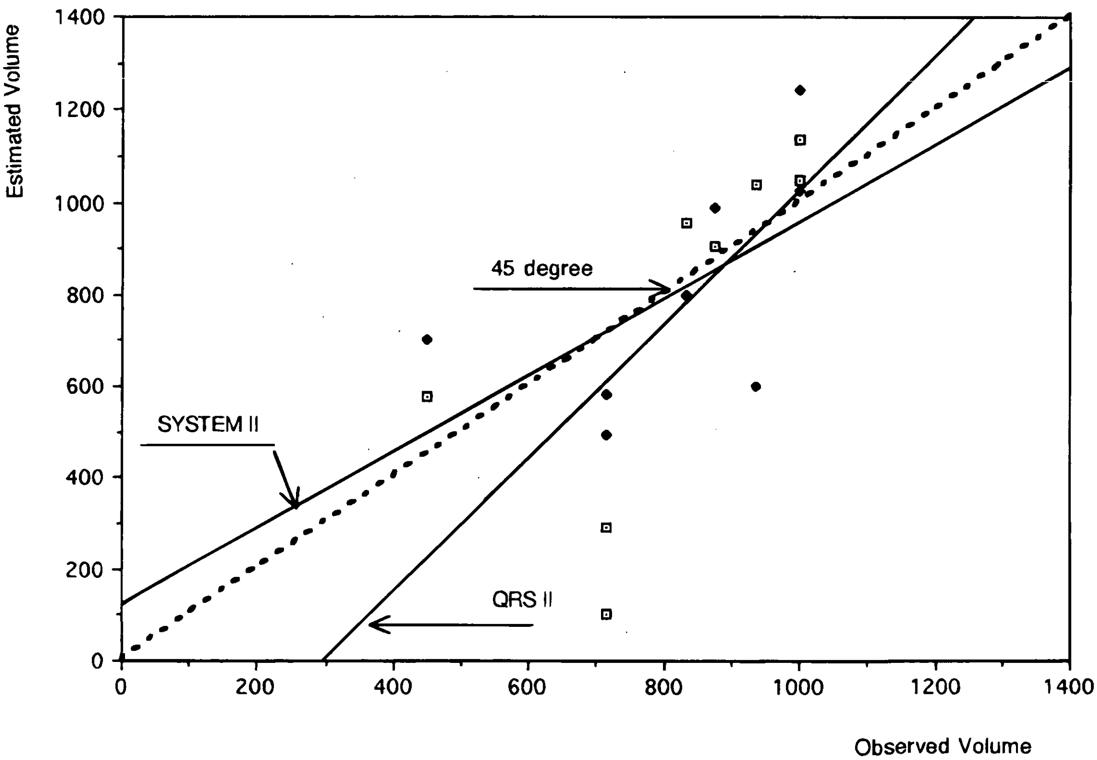

FIGURE 4 Estimation accuracy of QRS II and System II.

TABLE 4 Statistical Tests

	# of Links	MD	St. Dev.	Significance	% RMSE**
(1) QRS II					
(a) Links with $O_k<E_k$	15	-291	274		
(b) Links with $O_k>E_k$	15	401	201		
*(c) All links	30	346	339		39.28
(d) Test of MD in 1(a) and 1(b)				t =1.21	
(2) SYSTEM II					
(a) Links with $O_k<E_k$	15	-205	124		
(b) Links with $O_k>E_k$	14	269	236		
*(c) All links	30	237	267		28.15
(d) Test of MD in 2(a) and 2(b)				t = 0.80	
(3) Test of MD in 1(c) and 2(c)				z = 1.39	
(4) SYSTEM II VS. QRS II Estimated change in volume (from before to after closure)					
(a) SYSTEM II					
(i) Links with $O_k<E_k$	25	-232	335		
(ii) Links with $O_k>E_k$	16	63	78		
*(iii) All Links	49	148	344		
(iv) Test of MD in 4.a(i) and 4.a(ii)				t = 1.91	
(b) QRS II					
(i) Links with $O_k<E_k$.	34	129	173		
(ii) Links with $O_k>E_k$	13	73	75		
*(iii) All links	49	101	188		
(iv) Test of MD in 4.b(i) and 4.b(ii)				t =1.08	
(5) Test of MD in 4.a(iii) and 4.b(iii)				z = 0.02	

$$\text{Mean Difference} = \text{MD} = \sum_{\text{all k}} \frac{(O_k - E_k)}{N}$$

$$\text{* Mean Absolute Difference} = \text{MAD} = \sum_{\text{all k}} \frac{|(O_k - E_k)|}{N}$$

** Root Mean Square Error (RMSE) - observed vs. expected

Both packages are compatible with the hardware associated with IBM AT or PS–2 systems. Both QRS II and System II can process a network of the size of Verdun (49 links) on a PS–2/Z70 in approximately 20 min. However, the user needs to interact more with System II because each of the subprograms representing the four-stages of the conventional travel demand modeler modeling technique requires independent processing (i.e., needs to be run in batch mode).

QRS II's data input is via software specific templates, and output files are not transferable to other systems. Hence, additional processing, such as for calculating noise indices, will need to be performed using specially created data files. On the contrary, System II files ware directly transferable to a geographic information system (GIS) containing land use data, and the computations can be performed within the GIS. Another criticism of QRS II's output format is that the link and node identification numbers change every time the program is executed. This makes it difficult to track changes in link volumes from one run to the next.

ENVIRONMENTAL IMPACT

The impact of traffic management schemes during construction on many areas other than delays and LOS are rapidly becoming critical. Concerns about the changes in traffic-generated noise levels, air quality, and safety appear to be some of the issues that have been brought to the attention of the responsible agencies.

In this context, a limited analysis was performed of the expected changes in traffic noise using a noise prediction model by Blair and Lutwak (*12*). From this simple model, the L_{eq} at 7.5 m from the centerline of the nearest lane was computed for each link in the network using the following equations:

$$L_{eq}(\text{cars}) = 10.5 \log N + 23 + 10 \log 24/T$$

$$L_{eq}(\text{single events}) = L_{\max} + 10 \log N - 47 + 10 \log 24/T$$

$$L_{eq}(\text{composite}) = 10 \log \sum_{i=1}^{n} 10^{[L_{eq}^{(i)}/10]}$$

where

N= automobile flow during observation time,
T= observation time,
$L_{\max}$= peak noise level, and
n= different noise component.

The link noise levels before and after the closure of Wellington Street were computed to identify the links that would experience a

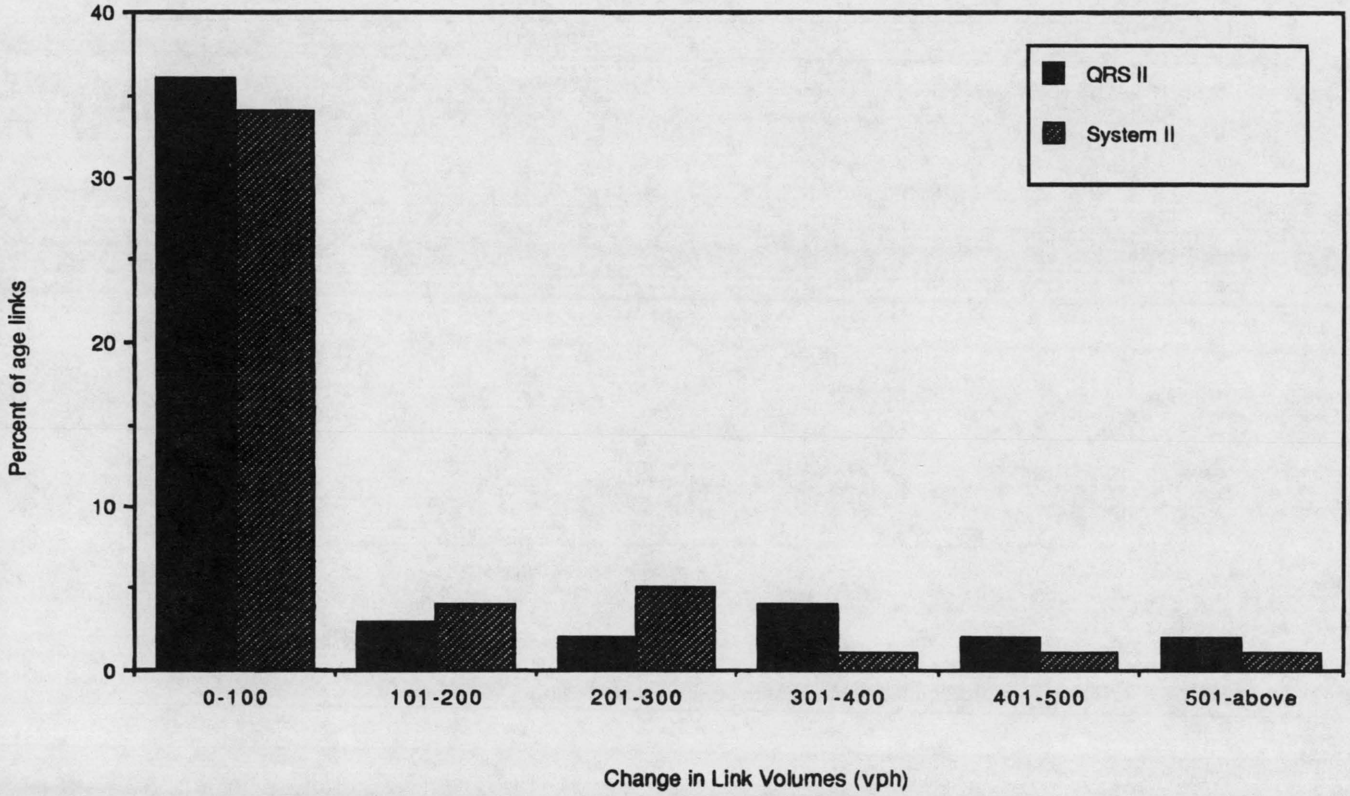

FIGURE 5 Frequency distribution of changes in expected volumes without Wellington.

change. The distribution in Figure 6 suggests that 75 percent of the links would experience less than a 5 dB increase, although, in terms of intensity, this corresponds to an increase of between 100 and 200 percent, the noise level if no link reached the 55 dBA suggested for residential zones. Thus, the detour plan shown in Figure 2 was retained as the preferred alternative.

For the purpose of examining the efficiency of the reassignment in relation to noise, a noise index (*NI*) was defined as:

$$N_{ij} = \frac{\text{change in } L_{eq} \text{ on link } (i,j)}{[\text{linear density of population on link } (i,j)]}$$

where linear density equals the average building occupancy (persons/m^2) multiplied by the total building area along link *ij* divided by twice the linear length (km) of link *ij*.

In the analysis, the noise index after closure (NI_{ija}) was computed manually for each link *ij*, and average noise index (NI_a) was estimated. Then, using NI_a as the threshold value, all links with $NI_{ija} > NI_a$ were identified and deleted from the network, and the traffic was reassigned. However, it was found that the new mean (NI'_a) was significantly larger than mean NI_a at the 5 percent level of significance. Therefore, the first detour plan given in Figure 4 was taken to be the most environmentally favorable.

CONCLUSIONS AND SUMMARY

The rate of arrival of new transportation planning software in the market indicates the growing demand for such tools. The declining price of hardware and the need to make the maximum use of limited personnel should soon entice many local authorities to adopt these tools, which are many times easier to understand and use than the preceding generation of mainframe-based packages. However, given that every software package is not necessarily designed to perform all tasks, it could mean more work than before, unless the selection is preceded by a complete review of the needs.

QRS II and System II were chosen from a sample of four popular TDAS packages. Their application to a basic traffic management problem demonstrated the need to know the systems limitations before selection. For instance, it was found that several tasks, such as finding O-D pairs of trips on a particular link, had to be performed manually. Moreover, the effects of transit services and intersection delays on trip distribution or assignment were difficult to assess. Thus, the trade-off between cost and versatility needs to be carefully considered before selecting a package.

Finally, regardless of the limitations, it became evident that these tools help users examine many detour alternatives under different scenarios. Moreover, once the area has been coded and entered, and the system models have been calibrated, updating and maintaining the data bases are minor tasks. Thus, when small local authorities assume broader roles than simply responding to the routine requests for road closures, development permits, or Transportation Systems Management (TSM) proposals from numerous sources, a fully calibrated software package will undoubtedly be a tremendous asset, particularly for testing alternatives. It is a tool that nontechnical persons can use to develop reports and other data for the analysts and decision makers.

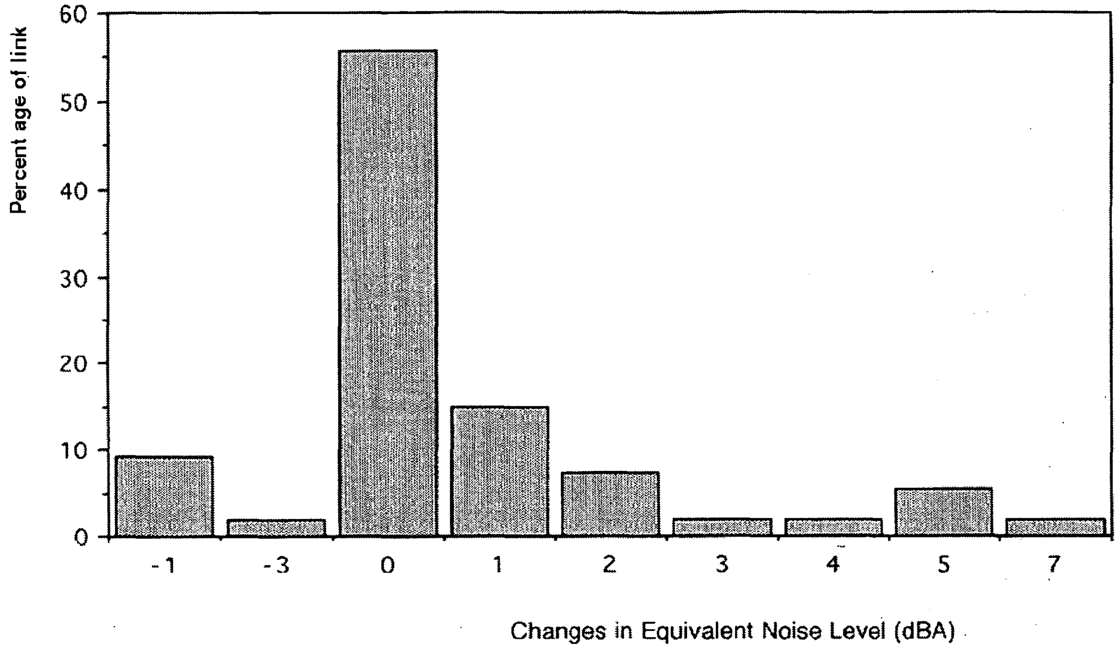

FIGURE 6 Frequency distribution of changes in noise level after closing Wellington.

ACKNOWLEDGMENTS

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Truck Drivers' Concerns in Work Zones: Travel Characteristics and Accident Experiences

RAHIM F. BENEKOHAL, EUNJAE SHIM, AND PAULO T. V. RESENDE

A study was conducted to determine truck drivers' concerns about traffic control in work zones (WZ) and to identify the locations of accidents and risky driving situations. A statewide opinion survey of 930 semitrailer drivers was conducted. The survey contained questions about driver/vehicle characteristics, assessment of WZ traffic control devices, accident and difficult driving situations, and suggestions for improving traffic flow and safety in WZ. The findings on travel characteristics and accident experiences of the truck drivers are discussed. About 90 percent of truck drivers consider traveling through WZ to be more hazardous than nonwork zone areas. About half of them want to see an advance warning sign 5 to 8 kilometers (3 to 5 mi) ahead of WZ. The drivers do not have a clear preference between one-lane closure and median crossover configurations. About two-thirds of them think the speed limit of 89 km/hr (55 mi/hr) is about right, but one-fourth believe it is too fast. Nearly half of them would exceed a speed limit of 72 km/hr (45 mi/hr), and nearly one-fifth would drive at least 8 km/hr (5 mi/hr) faster than the speed limit. About one-third said the flaggers are hard to see, and about half said that directions given by flaggers were confusing sometimes or most of the time. About three-fourths of the drivers indicated that the arrow boards were too bright. For most of the drivers, WZ signs are clear and not confusing, but 14 percent disagreed. About one-fifth of the truck drivers said some signs should be added to the work zones. A relatively small percentage of truck drivers (6.1 percent) said they had accidents in WZ. About one-third of the accidents were in the advance warning area, and about two-thirds were in the transition area. The accident experiences were significantly related to the experience of bad driving situations but not other driver/truck characteristics.

In 1992, there were 9,949 crashes in Illinois work zones: 29 were fatal and 2,422 were injury crashes (*1*). In the past several years, the number of injury and total crashes has steadily increased while the number of fatal accidents has fluctuated from year to year. The exact number of accidents per vehicle miles traveled (VMT) in work zones is not as well known for trucks as it is for cars. In 1992, over all highway types, the fatal accident rate of semitrailers in Illinois (accidents per million VMT) was 2.28, but for all other vehicles it was 1.54. The fatal accident rate of semi-trucks was 1.48 times higher than that of the other vehicles. On the other hand, the ratio for total crashes was 0.74 and for injury crashes it was 0.37. The ratios indicate that, in terms of VMT, semitrailers are underrepresented in the total and injury crashes but are overrepresented in fatal crashes. Accurate data are not readily available to compute the ratios for work zones, but it is reasonable to assume that work zone accidents would include a similar trend. Considering that the average annual miles traveled by trucks are about 10 times that of cars, reducing the frequency as well as the severity of truck accidents would improve work zone safety for all motorists.

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Accident records are very helpful in evaluating past performances, but they contain very little information about the emerging problems, those that are not reflected in the accident records yet, and problems that are not directly represented in the accident record (such as "near miss" accidents). Furthermore, the locations of the accidents in work zones are not accurately coded in most of the accident files, so an in-depth work zone accident study has not been conducted. There are a limited number of studies about the location of accidents in work zones, but these studies did not identify where the emerging problems, near-miss-type accidents, or difficult driving situations take place in work zones. The term "bad driving situation" was used to describe situations where truck drivers were exposed to a higher risk of accident such as near-miss situation, difficult driving situations, or situations that a corrective action was needed to avoid an accident. During the pretesting of the survey form, it was realized that truck drivers were using this term to describe the higher risk situations.

This study was conducted to determine the truck drivers' concerns about work zone traffic control and to identify the location of accidents and bad driving situations based on the experience and perception of truck drivers. A statewide survey of 930 semi-truck drivers was conducted. The survey contained questions about driver/vehicle characteristics, assessment of work zone traffic control devices, accident and difficult driving experiences, and suggestions for improving traffic flow and safety in the work zones.

This paper discusses travel characteristics of truck drivers and their relationship to accident experiences of the drivers. It does not include the findings of the survey pertinent to experiences of bad driving situations and their relationship to the travel characteristics.

Truck Accidents

Trucks are involved in a relatively small share of all vehicle accidents, but in a higher share of all fatal accidents. For example, in Illinois, only 16.4 percent of the tractor-trailer crashes took place in rural locations, but they accounted for 52.2 percent of the fatalities in 1992 (*1*). About 84 percent of the persons killed in tractor-trailer accidents were occupants of other types of vehicles.

Based on the VMT, overall truck accidents are underrepresented when compared with accidents of other vehicles. In 1986, the passenger-car accident rate was about 2.21 times higher than combination-truck accident rates in the United States (*2*). However, the combination-truck fatal accident rate was 1.75 times higher than the passenger-car fatal accident rate. Accident involvement rate may vary by several factors. For example, Meyers (*3*) compared truck and passenger-car accident rates on limited-access facilities. He found that the overall expressway accident rates for heavy trucks exceeded that for passenger cars by 58 percent. For the bridges and tunnels, overall accident rates for heavy trucks were four times greater than that for the average passenger car.

McGee (*4*) suggested that the key variables that influence truck safety might include truck type, truck length, truck trailer type, truck weight, driver type, driver age, and highway type. Garber and Joshua (*5*) found that the driver-related factors (such as error, speed, handicap, and alcohol) were mostly responsible for large-truck crashes: 75 percent of all large-truck crashes and 91 percent of large-truck fatal crashes on Virginia highways. Driver error was associated with over 50 percent of large-truck fatal accidents, and speeding accounted for 21 percent of these accidents.

Lyles et al. (*6*) reported that the most significant factor associated with truck accidents was the roadway class. Urban accident rates were lower than rural rates, and younger drivers were involved in more accidents than the average.

Hall and Lorenz (*7*) found that the number and rate of accidents increased during construction. The accident rate during construction increased 33 percent on the rural interstate highways in New Mexico compared with before construction.

Nemeth and Rathi (*8*) studied Ohio Turnpike work zone accident characteristics. They found that there was a high accident rate at crossovers, especially at night. Truck accidents constituted 75 percent of the total accidents at crossovers, while truck accidents at other work zone areas made up 52 percent of the total accidents, indicating that the driving task was more demanding here than at other work zones or on highways in general.

STUDY APPROACH

The overall study approach was to develop a questionnaire, conduct a state-wide survey of semi-truck drivers, perform statistical analyses to examine the relationships among responses, and interpret the findings of the study.

Survey Instrument

A survey instrument was developed in collaboration with the Illinois Department of Transportation (IDOT). The questionnaire contained over 40 questions about driver and vehicle characteristics, drivers' assessment of work zones and the traffic control devices, their accident and difficult driving experiences, and their suggestions for improving traffic flow and safety in the work zones. The main questions asked in the survey are listed in Table 1.

Pretesting

A formal pretest of the survey was conducted using about 100 truck drivers. The data collection procedures for the pretest followed, as closely as possible, those planned for the main survey to provide a

TABLE 1 Survey Items in Questionnaire

(1) Driving experience (in years)
(2) VMT during last year in U.S.
(3) VMT during last year in Illinois
(4) Driver age
(5) Type of current truck
(6) Type of current carrier
(7) Number of trucks in current carrier
(8) Preferred time of day to drive
(9) Type of permits for current truck
(10) Preferred distance of advance signs about work zones (miles)
(11) Perceived hazard of driving through work zones compared with nonwork zones
(12) Preferred type of work zones: median crossover versus one-lane closure
(13) Nine items about driving situations and work zone conditions
(14) Opinion about speed limit of 89 km/hr in work zones
(15) Actual speed in work zones with 72 km/hr speed limit
(16) Locations the driver experienced BDS in work zones
(17) Locations of accidents in work zones
(18) Visibility of flaggers
(19) Directions given by flaggers
(20) Seven items about traffic control devices
(21) Height of arrow boards
(22) Brightness of arrow boards
(23) Height of CMB
(24) Brightness of CMB
(25) Unclear or confusing signs in Illinois work zones (if any, specify)
(26) Need for more signs or messages in work zones (if any, specify)
(27) Driving in Illinois work zone(s) today
(28) Suggestions and comments

Note: 1 km = 0.6 mi.

thorough test of the survey procedures and questionnaire. The returned questionnaires were closely examined to determine if there were any unforeseen problems. Their input was used for minor revisions and clarification of the questions or responses.

Data Collection

The main surveys were conducted from 9:00 a.m. to 5:00 p.m. on weekdays in September and October of 1993. The purpose of the survey was also explained to the drivers, and they were assured that their responses would not affect their personal driving records. The survey questionnaires were handed to the truck drivers (excluding pickups) and were collected after they were completed. The data were collected mainly at truck stops and some at rest areas. The data were collected at several locations in Illinois. Approximately one out of every four drivers refused to answer the questionnaire. There was not a common characteristic among those who refused to participate; thus they would not cause a bias in this study. It seemed that these drivers were tired or were in a hurry. In general, the response rates at rest areas were lower than those at truck stops. A total of 930 truck drivers participated in the survey.

The data collection sites were selected such that near every data collection site there was at least one construction zone. Data were collected in the areas of Bloomington (I-55 and I-74), Danville (I-74), Joliet (I-55 and I-80), Springfield (I-55 and I-72), and Peoria (I-74) in Illinois. These locations were spread over Illinois and are expected to represent a good cross section of the truck drivers on the road. Almost all of the surveyed drivers (94 percent) had driven through construction zone(s) the day of the survey.

The responses were coded and checked for completeness, accuracy, and consistency. Incomplete and inconsistent questionnaires were removed from the data set. Out of 930 surveys, 834 surveys were found suitable for further data analysis.

Data Analysis

Data analysis is discussed in two sections. The first section, Travel Characteristics of Truck Drivers, discusses the frequency distribution of the responses. The second section, Accident Experience Versus Travel Characteristics, discusses the statistical analyses of accident experiences of the drivers. The analyses are conducted for the entire work zone (overall) as well as for the advance warning area (AWA), transition area (TRA), buffer space (BFS), work space (WKS), and termination area (TEA).

Different statistical tests were used, based on the distribution characteristics of the responses, for each question, as well as on the number of groups to be compared. For continuous variables, the analysis of variance (ANOVA) was applied, and for the discrete variables, comparisons were made using χ^2 goodness-of-fit tests. All statistical tests were performed, unless otherwise stated, with a 90 percent confidence level.

Statistical Analysis

The general linear model (GLM) procedure in SAS was used for ANOVA because of unbalanced situations (*9*). An unbalanced situation is when there is an unequal number of observations for different combinations of class variables, which is the case in this survey. In this situation, SAS recommends to use the GLM procedure instead of the ANOVA procedure. For continuous variables, the GLM results will indicate whether the average values for all groups are the same or whether there are at least two groups with different mean values. The authors looked at F values in the GLM output to make such judgments. If F values indicated that they were significantly different, the authors examined the results of Duncan's Multiple Range test to identify which groups are different. In the case of two groups, the t-test also can be used to determine the mean difference of two groups.

For the discrete variables, χ^2 goodness-of-fit tests were used. Drivers were grouped into two categories: those who had accident experiences in the work zones and those who did not. Each group was further divided into various travel characteristic subgroups. The test was used to determine if certain drivers were over- or underrepresented. These tests would reveal whether an unexpected number of drivers have certain characteristics.

TRAVEL CHARACTERISTICS OF TRUCK DRIVERS

The responses to various questions are summarized in Table 2 and are discussed in the following sections.

Experience and Age

The average age of the truck drivers who responded was 43, and the ages ranged from 20 to 68. Approximately two-thirds of the sample were within the range from 30 to 50 years old. Drivers 61 years and older represented 2.5 percent, and drivers under 25 represented 4.3 percent of the sample. There was a relatively strong correlation between the driver's age and his or her driving experience. Driving experience varied from 0 to 48 years with an average value of 16.1 years. About 10 percent of the drivers had 30 or more years of experience and about 8 percent of the drivers had 2 years or less of driving experience.

Miles Driven

The truck drivers were asked to indicate the total number of miles they drove last year and what portion of that was in Illinois. To increase the accuracy, only those drivers with 1 full year of driving experience were considered in the analysis. The average total kilometers driven was 180,320 (112,000 mi), and the range was from 0 to 466,900 km (0 to 290,000 mi). About 52 percent of them drove between 144,900 and 209,300 km (90,000 and 130,000 mi). About 8 percent of the sample drove less than 80,500 km (50,000 mi), and about 4 percent drove 322,000 km (200,000 mi) or more per year. Values higher than 466,900 km (290,000 mi) were deleted from the analysis because driving more than 466,900 km (290,000 mi) in 1 year appears to be unreasonable.

The drivers response to the miles driven just in Illinois indicated that the average was 40,250 km (25,000 mi) and the range was from 0 to 402,500 km (0 to 250,000 mi). About 36 percent of drivers said it was in the range of 0 to 16,100 km (0 to 10,000 mi). It was found that there is no relationship between the miles driven in the United States and those in Illinois.

TABLE 2 Frequencies of Responses to Travel Characteristics Questions

Items	Proportion			
Type of Carrier	Common (62%)	Contract (18%)	Private (12%)	Others (8%)
Driving Hours	All Hours (88%)	Daytime (10%)	Nighttime (2%)	-
Permit	No (79%)	Hazardous (15%)	Over-dimension (5%)	Combination (1%)
Advance Sign	5-8 km (47%)	2-3 km (34%)	10-16 km (14%)	Others (5%)
Hazard Assessment	More Hazard (90%)	Less Hazard (1%)	Same (8%)	Do not Know (1%)
Type of Work Zone	Median Crossover (36%)	One-Lane Closure (33%)	No Preference (29%)	No Opinion (2%)
Speed Limit of 89 km/hr	About right (62%)	Too Fast (25%)	Too Slow (9%)	No Opinion (4%)
Drive at 72 km/hr Speed Limit	74-81 km/hr (34%)	At 72 km/hr (30%)	< 72 km/hr (19%)	> 81 km/hr (17%)
Visibility of Flagger	OK (44%)	Hard to See (32%)	Very Visible (19%)	No Opinion (5%)
Direction by Flagger	Clear (46%)	Sometimes Confusing (37%)	Most Times Confusing (12%)	No Opinion (5%)
Height of Arrow Board	OK (76%)	Too High (15%)	Too low (5%)	No Opinion (4%)
Brightness of Arrow Board	Too Bright (76%)	OK (22%)	Not Bright Enough (1%)	No Opinion (1%)
Height of Changing Message Board	OK (86%)	Too Low (5%)	Too High (4%)	No Opinion (5%)
Brightness of Changing Message Board	OK (72%)	Too Bright (18%)	Not Bright Enough (7%)	No opinion (3%)
Unclear/Confusing Signs	No (86%)	Yes (14%)	-	-

Note: 1 km = 0.6 mi.

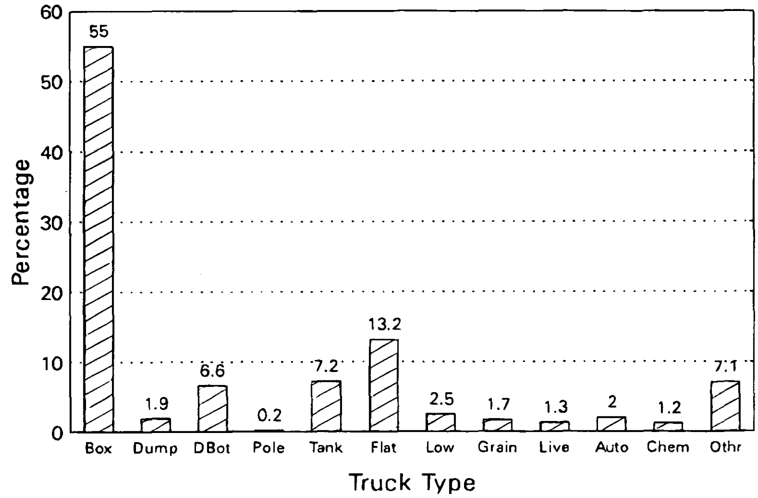
Trucks and Carrier Types

The drivers were asked to indicate what type of trucks they were driving. Figure 1 shows that a box van was the most cited (55 percent) type of truck, followed by a flatbed/platform (13 percent), tanker/hopper (7 percent), and double-bottom (7 percent). Common carrier was the largest carrier type (62 percent) that drivers worked for, followed by contract (18 percent), private (12 percent), and others (8 percent). The average number of trucks per company was approximately 930 trucks, and the range was from 1 to 25,000 trucks. The survey included drivers working for the small as well as large companies. For example, about 12 percent and 22 percent of the drivers responded that their companies have 10 or fewer and 20 or fewer trucks, respectively.

Travel Time and Load Permit

About 88 percent of the drivers answered that they had driven their trucks all hours, which is somehow expected due to the needs of their profession (i.e., schedules, nature of loads). About 10 percent of the drivers responded that they usually drive during the day, and only 2 percent usually drive at night.

Drivers were asked if they were carrying any type of permit at the survey time. About 79 percent responded that they were not holding any type of permit. Among permit types, hazardous-materials-related permits had the highest frequency (15 percent), followed by over-dimension-related permits (5 percent), and both hazardous-materials and over-dimension-related permits (1 percent).



Note: Box(box van), Dump(dump), DBot(double bottom), Pole(pole) Tank(tanker/hopper), Flat(flatbed/platform), Low(lowboy), Grain(grain) Live(livestock), Auto(auto-transport), Chem(chemical), Othr(others)

FIGURE 1 Frequency of truck type.

Hazard Assessment

Drivers were asked to compare the hazard of driving through work zones to nonwork zones. A large majority of truck drivers (90 percent) answered that work zones are more hazardous than nonwork zone areas. This is very high compared with the findings of a previous study *(10,11)* in which 54 percent of drivers (all drivers, not just truck drivers) responded that the work zones were not more hazardous. In the previous study, only 16 percent of the respondents were driving large trucks compared to this survey, which includes only the drivers of large trucks. This indicates that an educational effort to increase drivers' perception of hazard in the work zones should mainly be directed toward car drivers to increase their perception of hazard in work zones.

Truck drivers not only assess the work zones to be more hazardous, but most of them also want to know far ahead about the presence of work zones. Approximately half of the sample (47 percent) responded that work zone signs should be posted 5 to 8 km (3 to 5 mi) ahead, followed by 2 to 3 km (1 to 2 mi) ahead (34 percent), 10 to 16 km (6 to 10 mi) ahead (14 percent). Only 5 percent answered that signs should be posted less than 2 km (1 mi) or more than 16 km (10 mi) ahead.

Work Zone Layout

Drivers were given sketches of a work zone with one-lane closure and another one with a median crossover and were asked to indicate their preferred configuration. The percentage of those drivers who preferred the median crossover was only slightly higher than that of one-lane closure. About 29 percent of drivers responded that they have no preference. These responses indicate that truck drivers do not have a preferred work zone configuration.

Speed Limit

Drivers were asked about the 89 km/hr (55 mi/hr) speed limit in work zones. About two-thirds (62 percent) answered that such a speed limit is about right; 25 percent said that the 89 km/hr (55 mi/hr) speed limit is too fast; and 8 percent responded that it is too slow. It should be noted that the speed limit in Illinois interstate work zones is 89 km/hr (55 mi/hr), unless a 72 km/hr (45 mi/hr) speed limit is put into effect. When workers are present, regulatory 72 km/hr (45 mi/hr) speed limits are activated by turning on the two yellow strobe lights mounted on the speed limit signs. Drivers were asked to indicate how fast they drive in a work zone with a 72 km/hr (45-mi/hr) speed limit. The highest proportion (34 percent) was found for those driving in the range of 74 to 81 km/hr (46 to 50 mi/hr), followed by those driving at 72 km/hr (45 mi/hr) (30 percent) (see Figure 2). However, relatively high percentages were found in the ranges below 72 km/hr (45 mi/hr) (19 percent) and 82 km/hr (51 mi/hr) and above (17 percent). Thus, in a 72 km/hr (45 mi/hr) speed zone nearly half (49 percent) of the drivers would drive at or below the speed limit, and the other half would exceed it. About 17 percent of the drivers indicated that they would drive at least 8 km/hr (5 mi/hr) faster than the speed limit.

Flagger Visibility and Directions

About 63 percent of the drivers responded that the flagger visibility is either okay or they are very visible. However, 32 percent answered that flaggers are hard to see. The reasons for this could be a driver's inattention, inadequate contrast of a flagger's attire, or the position of flaggers in work zones. The reasons for the inadequate visibility indicated by one-third of the drivers should be determined and appropriate action should be taken to improve flagger visibility.

Drivers were then asked about the clarity of the direction given by flaggers in work zones. Half of truck drivers (49 per-

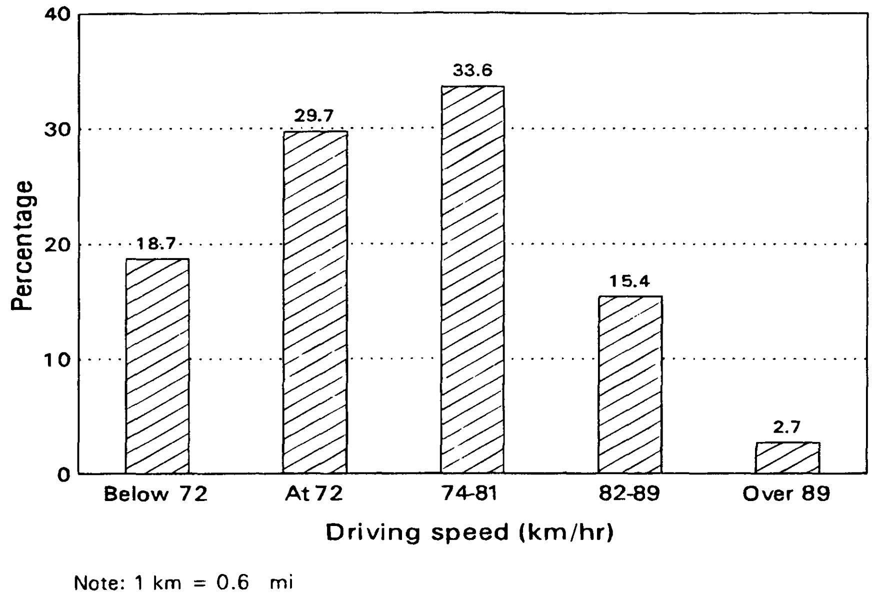


FIGURE 2 Driving speed in work zone with 72 km/hr speed limit.

cent) responded that it was confusing sometimes or most of the time; the other half (46 percent) answered that it is usually clear. Such a high proportion for the flaggers' directions to be confusing surprised the authors because the respondents are professional truck drivers and see a lot of flaggers in work zones. The clarity of the directions given by the flaggers needs to be improved. In a different survey (*10,11*), about 88 percent of the respondents (mostly car drivers) correctly identified the flagger's message from the list of responses. This does not mean that truck drivers do not understand flagger's message; it means that the direction given is not always clear and needs some improvement.

Arrow Board and Changeable Message Board

In the previous study (*10*), some truck drivers complained about brightness and height of arrow boards. In this survey, drivers were specifically asked about brightness and height of arrow board and changeable message boards (CMBs). In general, truck drivers do not have problems with the height of the arrow board, and 76 percent responded that the height is okay. However, 15 percent answered it is too high, and 5 percent replied it is too low.

Drivers seem to indicate that when the arrow boards are at their eye level, the brightness of the board bothers their eyes. About 76 percent responded that the arrow boards are too bright. This shows that truck drivers have a problem with the brightness of the arrow board. Several drivers made comments about the brightness of arrow boards. The brightness concern needs to be examined to increase the effectiveness of arrow boards and/or reduce their disturbing effects. A similar pair of questions were asked about CMBs. Contrary to arrow boards, both the height and brightness of CMBs seem to be well accepted by the truck drivers. About 86 percent and 72 percent responded that the height and the brightness are okay, respectively. Only 18 percent said that CMBs are too bright.

Confusing and Unclear Signs

Drivers were asked to indicate if they think there are any confusing or unclear signs in the work zones. They were also asked to indicate if there is a need to add any more signs to work zones. Most of the truck drivers (86 percent) responded that they did not have any confusing or unclear signs to indicate. However, 14 percent replied that there were confusing and/or unclear signs. About 6 percent, 3 percent, and 2 percent responded that there were confusing, unclear, and both confusing and unclear signs, respectively, in the work zones. The remaining 3 percent replied that there are confusing or unclear signs, but did not specify whether the signs were confusing or unclear.

Comments about confusing and unclear signs were directed toward lane closure, CMBs speed limits, exit ramps, and work zones without actual work. Drivers commented that it is unclear or confusing when a sign states that one lane is closed, but actually the other lane is closed. When a sign states that a lane is closed ahead, drivers want to know which one. Truck-only lanes changing too often also troubled drivers. Some drivers complained that CMBs didn't always work or the messages flashed too fast.

Some drivers stated that speed limit signs in work zones are unclear and confusing. Alternate 72 km/hr (45 mi/hr) and 89 km/hr (55 mi/hr) speeds in work zones also caused problems for drivers. Some drivers find that exits in construction zones are not marked clearly. Drivers found signs posted when there was no work being done confusing and unclear. Drivers also complained about signs that remain after construction is completed, when conditions have changed, and when construction has not yet begun. There were also complaints about 72 km/hr (45 mi/hr) speed zones when no workers are present.

Additional Signs

About 78 percent responded that there is no need to add signs or messages to Illinois work zones. However, 22 percent replied that some signs should be added. Drivers suggested adding signs about early merging, early notification of work zones, road conditions, construction length, and speed limits. Drivers suggested adding signs to force the car to merge immediately to prevent the last-minute merging. There were also suggestions for putting more merge signs, merge signs accompanied by law enforcement officers, and signs to make drivers aware of trucks trying to merge.

Drivers want to see more signs before the work zones, and they want to see these signs sooner. A few drivers suggested that work zone notification begin 5 to 8 km (3 to 5 mi) before the work zones. Several drivers think merge signs are placed too close to the work zones and there is not enough time to merge. Drivers would also like to see that Lane Closed Ahead signs specify which lane is closed. Some drivers want to see signs displaying the distance to the lane closure. There were also suggestions for no-passing zones when a lane is closed ahead.

Some drivers suggested adding signs for the road conditions of the temporary lane in the work zones such as width, uneven pavement, and shoulder drop-offs. There were also suggestions for notification of what type of work is being performed. Seven drivers want signs stating the length of zone before the zone, and signs within the zone stating the distance left to travel. Drivers recommended signs instructing drivers to slow down in work zones, and some proposed more speed limit signs.

ACCIDENT EXPERIENCE VERSUS TRAVEL CHARACTERISTICS

Locations of the accidents in work zones are not accurately coded in the accident files. Thus, an in-depth work zone accident study has not been possible. This study attempted to find the location of accidents by tapping the experience of truck drivers. Drivers were given a sketch of the work zone and asked to identify the locations where they have experienced accidents. The sketch was divided into five parts: advance warning area, transition area, buffer space, work space, and termination area. The drivers were also asked to indicate how many times they had experienced accidents. Thus, the number of drivers who experienced accidents and the number of accidents were determined for each part of the work zone.

Overall Experience of Accidents in Work Zones

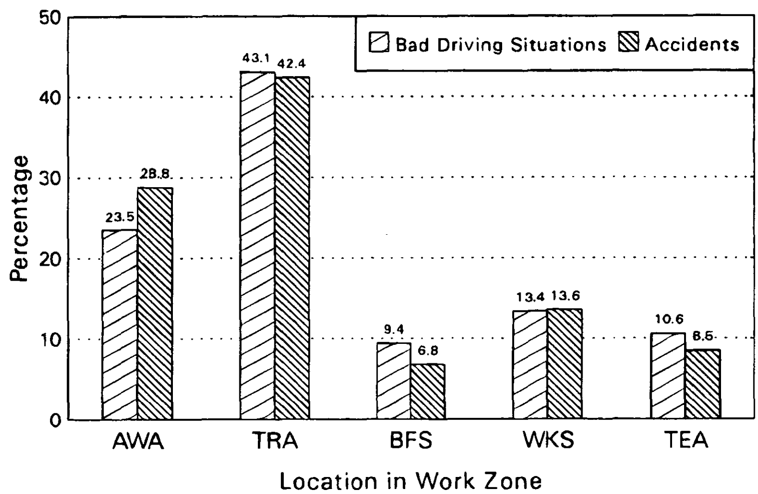
A relatively small percentage of all truck drivers (6.1 percent) said that they have had accidents in one or two locations in work zones. About 1 percent have experienced accidents in two locations, and all of them included either the AWA or the TRA. The accidents were distributed among the five areas, but were mainly in AWA (2 percent) and TRA (3 percent). In the buffer space, 0.5 percent of the respondents have had accidents; in the work space, 1 percent; and in the termination area, 0.6 percent. These numbers may seem small, but actually they are not. For instance, 5 out of every 100 drivers surveyed had accident(s) on the AWA and/or TRA. This is more than twice the number of accidents in the remaining areas of the work zones. The accident experiences support the bad driving experience of the respondents.

Considering the number of accidents, 42 percent of them happened in the TRA, and 29 percent happened in the AWA (see Figure 3). Comments and suggestions of truck drivers revealed that most of the accidents happened between passenger vehicles and trucks mainly due to lane changes and rapid speed reductions. About 14 percent happened in the WKS, 9 percent in the TEA, and only 7 percent in the BFS.

Considering the number of drivers who had accidents and the number of accidents in work zones, work zone improvement should focus on the TRA and the AWA.

Categories of Analyses

To examine the correlations between the experience of bad driving situations (BDS) and/or accidents in work zones and other truck/



Note: AWA(advanced warning area), TRA(transition area), BFS(buffer space), WKS(work space), TEA(termination area)

FIGURE 3 Frequency of bad driving situations and accidents among the number of bad driving situations and accidents.

drivers characteristics, statistical analyses were conducted in the following four categories:

1. Correlation of accidents with travel characteristics,
2. Correlation between accident experience and BDS,
3. Correlation of BDS with travel characteristics, and
4. Correlation of BDS in each work zone areas with travel characteristics.

Categories 1 and 2 are discussed in this paper.

Correlation of Accidents with Travel Characteristics

A small portion of drivers (6.1 percent) indicated that they had one or more accidents in the work zones. For the purpose of the statistical analyses, drivers were grouped into two categories; those who had experienced an accident at any point in a work zone and those who had not. Possible correlations between driver and/or vehicle characteristics and the experience of accident were examined.

ANOVA shows that none of the driving experience, age, and miles driven were related to the accident experience. The summary of χ^2 goodness-of-fit tests is given in Table 3. Detailed accident analysis for each area in the work zones was not possible because of the small number of drivers who had accidents. The χ^2 tests show that accident experience was significantly related to the experience of bad driving situations, but not other driver/truck characteristics. Some trends also emerged indicating relation, though not statistically significant, between accident experience and advance signs, a speed limit of 89 km/hr (55 mi/hr), and unclear/confusing signs. These trends can be characterized as follows: in a group of drivers who had accidents in work zones, those who wanted to know about work zones 3 km (2 mi) or less in advance were overrepresented and 5 to 8 km (3 to 5 mi) in advance were underrepresented; those who mentioned unclear or confusing signs in work zones were overrepresented, and those who think the speed limit of 89 km/hr (55 mi/hr)

TABLE 3 Results of Chi-Square Goodness-of-Fit Tests: Accidents in Work Zones Versus Travel Characteristics

Items	Degree of Freedom	χ^2-value	Prob. for $\geq \chi^2$ Value	Interpretation (With 90% Confidence Level)
type of truck	4	2.395	0.664	Not significant
type of carrier	2	0.904	0.636	Not significant
time of driving	1	0.689	0.406	Not significant
type of permit	2	0.343	0.843	Not significant
location of advance sign	3	5.286	0.152	*Not significant
hazard of work zones	1	0.414	0.520	Not significant
type of work zones	2	0.118	0.943	Not significant
speed limit of 89 km/hr	2	3.359	0.186	Not significant
speed of 72 km/hr zone	4	3.207	0.524	Not Significant
bad driving experience	1	13.097	0.000	Significant
visibility of flagger	2	2.875	0.237	Not significant
direction by flagger	2	2.134	0.344	Not significant
height of arrow board	2	0.703	0.703	Not significant
brightness of arrow board	1	0.000	1.000	Not significant
height of CMB	1	0.011	0.917	Not significant
brightness of CMB	2	3.049	0.218	Not significant
unclear/confusing sign	1	2.559	0.110	*Not significant
addition of sign/message	1	0.512	0.474	Not significant

Notes:

When χ^2 tests were not valid because of the low expected frequencies of cells, grouping of each question was performed.

When the degree of freedom is 1, continuity-adjusted χ^2 values were used.

* May indicate a strong trend although it is not significant.

1 km = 0.6 mi.

in work zones is too fast were underrepresented, and strangely those who said the speed limit is about right were overrepresented.

It should be noted that Table 3 indicates that the drivers' accident experiences were unrelated to most of the other responses. It would be an oversimplification if one concludes from Table 3 that accidents happen regardless of characteristics of drivers, vehicles, and/or geometric of work zones. This oversimplification would not be an accurate statement. Stoke and Simpson (*12*) found that new drivers are more likely to be involved in truck crashes than experienced drivers.

Some relationships between travel characteristics and accidents in work zones revealed interesting results, although the results of the χ^2 test did not indicate these to be statistically significant with a confidence level of 90 percent. It was noticed that more than the expected number of truck drivers who had accidents in work zones responded that they drive double-bottom trucks, they want to find out about work zones far ahead [e.g., 10 to 16 km (6 to 10 mi)], they drive faster than 81 km/hr (50 mi/hr) in work zones with a 72 km/hr (45 mi/hr) speed limit, they think the CMBs are too bright, and they think some signs are unclear/confusing in work zones. On the other hand, more than the expected number of truck drivers who had not had any accidents in the work zones responded that the speed limit of 89 km/hr (55 mi/hr) in work zones is too fast, they drive slower than 81 km/hr (50 mi/hr) in work zones with a 72 km/hr (45 mi/hr) speed limit, they think flagger visibility is okay, but the direction by flaggers is confusing.

In addition to this interpretation, the following may also be interesting findings: type of carrier, time of driving, type of permit, assessment of hazard, preference of a certain type of work zone, height and brightness of arrow boards, and height of CMB were unrelated to accidents in work zones.

Correlation Between Accident Experience and Bad Situations

For statistical analysis purposes, drivers were grouped into two categories: those who had BDS in work zones and those who did not. The drivers in one category were further divided into two subcategories: those who had accidents and those who did not. There was a very close relationship between the experience of bad situations and accidents in work zones. A higher than expected proportion of drivers who had experienced BDS have also had accidents in work zones. Conversely, among the drivers who had accidents in work zones, those with BDS experience were overrepresented.

The synopsis of the relationships between accidents and BDS experiences at different areas of work zones is as follows. Those who have had accidents in work zones have also experienced more bad situations in work zones. Those drivers who had experienced BDS in AWA and TRA also showed a significant correlation to accident experience. Accident experience at WKS was also related to BDS experience and was significant at an 89 percent confidence level. However, buffer space and termination areas did not show a significant relationship between accident and bad driving experience.

CONCLUSIONS AND RECOMMENDATIONS

The findings of this study are based on a survey of 930 truck drivers. Truck drivers indicated that they are aware of the hazard of driving through work zones, and 90 percent of them consider it be more hazardous than driving in nonwork zone areas. This perception is, however, low among car drivers. Truck drivers want to know far ahead about work zones and about half of them want to see a sign 5 to 8 km (3 to 5 mi) ahead. The drivers do not have a clear preference between one lane closure and median crossover configurations. About two-thirds of them think the speed limit of 89 km/hr (55 mi/hr) is about right, but one-fourth think it is too fast. Nearly half of them would exceed a speed limit of 72 km/hr (45 mi/hr), and nearly one-fifth would drive at least 8 km/hr (5 mi/hr) faster than the speed limit. Some drivers have difficulty in seeing flaggers and/or understanding the directions given by them. About one-third responded that the flaggers are hard to see, and about half replied that directions given by flaggers were confusing sometimes or most of the time.

Arrow boards seem to be too bright for most truck drivers. About three-fourths of the drivers indicated that the arrow board was too bright but that the height was okay. For a great minority of truck drivers, some signs were unclear/confusing and additional signs should be placed in the work zones. For most of the drivers, work zone signs are clear and not confusing, but 14 percent disagreed. About one-fifth of the surveyed drivers responded that some signs should be added to the work zones.

A relatively small percentage of truck drivers had accidents in the work zones. About one-third of the accidents happened in AWA and two-thirds in TRA. Efforts to improve traffic safety in work zones should mainly focus on these two locations. Accident experience significantly correlated to the experience of bad driving situations but not other driver/truck characteristics. A higher-than-expected proportion of drivers who experienced BDS also had accidents in work zones. The BDS experience is a good indicator of the problem areas in work zones.

Educational efforts should be initiated to increase driver perception of hazards in work zones. They should mainly be directed toward car drivers to increase their perception of the hazards of driving in work zones. Effectiveness of additional signs to be placed a few miles before the work zones so that drivers can get to the proper lane and avoid late lane changes should be examined. Methods of improving flagger visibility and clarity of direction given should also be explored. The brightness of arrow boards needs to be examined to improve their effectiveness and/or reduce their disturbing effects. Further studies should be conducted to improve signing lane closures, exit ramps, merging, road conditions notification, and speed limits.

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Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways

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The speed monitoring display is a traffic control device that uses radar to measure the speeds of approaching vehicles and shows these speeds to traffic on a digital display panel. It is intended to slow traffic by making drivers aware of how fast they are traveling. In addition, it is expected that its radar will also cause some drivers using radar detectors to slow down. The effectiveness of this device was evaluated at a work zone on an interstate highway in South Dakota. The speed monitoring display reduced mean speeds and excessive speeds on the approach to the work zone. Mean speeds were reduced by 6 to 8 km/hr (4 to 5 mi/hr), and the percentages of vehicle exceeding the advisory speed limit of 72 km/hr (45 mi/hr) were reduced by 20 to 40 percentage points. These speed reductions are greater than those reported for the use of radar alone.

The safety of workers and the traveling public in highway work zones is a major concern of highway agencies. Several studies (*1*) have found that the rate and severity of traffic accidents in highway work zones are significantly higher than those on normal roadway sections. Excessive speed is among the contributing circumstances most often reported for work zone accidents (*1,2*). Likewise, the accident experience in highway work zones in South Dakota has been a concern of the South Dakota Department of Transportation (SDDOT). During the 9-year period between 1983 and 1992, nearly 1,600 accidents occurred in work zones, which resulted in 18 fatalities and more than 800 injuries (*3*). Again, excessive speed was frequently cited as a contributing factor in these accidents.

In an effort to address the problem of excessive speeds in highway work zones, the SDDOT initiated a study to evaluate traffic control devices designed to reduce traffic speeds in work zones. The first task of the research was to conduct a review of the literature and current practice to identify traffic control devices with the potential to reduce speeds in work zones. In addition, the accident experience in work zones on highways in South Dakota was reviewed to identify the types of work zones that represented the most serious safety problems. Based on the findings of the review and the results of the accident data analysis, candidate traffic control devices were ranked according to their potential effectiveness, ease of implementation, advantages and disadvantages, cost, and applicability in work zones that represent the greatest safety problems in South Dakota. The traffic control devices with the highest rankings were selected by SDDOT for field testing. The speed monitoring display was among the devices selected for testing in work zones on interstate highways.

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SPEED MONITORING DISPLAY

The speed monitoring display is a device that measures and displays the speeds of approaching vehicles. The objective is to reduce traffic speeds by making drivers aware of how fast they are traveling. The speeds are measured by radar and presented to the drivers on a digital display panel. The application of the speed monitoring display found in the literature was on urban streets. Reductions in speeds of up to 32 km/hr (20 mi/hr) were observed with its use on streets in Berkeley, California (*4*). Although these observations were not substantiated statistically, they suggested that the speed monitoring display might be effective in reducing speeds in work zones.

The particular speed monitoring display evaluated in this study is shown in Figure 1. It was a portable, self-contained, solar-powered trailer unit that was fabricated by the SDDOT. The speed display panel was 508 mm (20 in.) high and 711 mm (28 in.) wide, and it had a three-digit readout with 229-mm (9-in.) high digits. The sign assembly mounted above the speed display panel included a WORK ZONE warning sign [914 mm (36 in.) by 914 mm (36 in.)], an advisory speed plate [W13–1, 610 mm (24 in.) by 610 mm (24 in.)], and a YOUR SPEED guide sign [305 mm (12 in.) by 1524 mm (60 in.)]. All of the signs in the assembly were orange with black legends. A Type I barricade panel [305 mm (12 in.) by 1524 mm (60 in.)] was mounted below the speed display panel.

STUDY SITE

The speed monitoring display was tested at a bridge-replacement work zone on westbound Interstate 90 near Sioux Falls, South Dakota. The annual average daily traffic (AADT) on Interstate 90 at this location was 9,000 vehicles per day. The work zone was on an urban section of the interstate; therefore, the normal speed limit was 88 km/hr (55 mi/hr). The right lane of the two westbound lanes was closed in advance of a median crossover. Vehicles traveling in the westbound lanes were observed during the field study. A layout of the study site is shown in Figure 2.

The traffic control plan was a typical SDDOT plan for a long-term lane closure on an interstate highway, which is consistent with the *Manual on Uniform Traffic Control Devices for Streets and Highways.* (*5*) The following sequence of traffic control devices was located on both sides of the westbound lanes:

1. ROAD CONSTRUCTION AHEAD signs about 1,434 m (4,700 ft) in advance of the lane closure taper.
2. RIGHT LANE CLOSED AHEAD signs about 671 m (2,200 ft) in advance of the lane closure taper.

FIGURE 1 Speed monitoring display.

3. RIGHT LANE CLOSED 1500 FT signs with warning lights about 534 m (1,750 ft) in advance of the lane closure taper.
4. Symbolic "lane transition reduction on the right" signs with 45 mi/hr advisory speed plates about 137 m (450 ft) in advance of the lane closure taper.

There was an advance warning arrow panel at the beginning of the 205 m (672 ft) lane closure taper. The taper was delineated by channelizing drums with warning lights spaced at approximately 15-m (50-ft) intervals and white raised pavement markers spaced at 1.5-m (5-ft) intervals. About 220 m (720 ft) beyond the end of the taper, symbolic "left reverse turn" warning signs with 30 mi/hr advisory speed plates were located on both sides of the roadway in advance of the median crossover.

Two speed monitoring displays were installed about 95 m (310 ft) in advance of the lane closure taper. The displays were positioned at the edge of the shoulder on each side of the roadway. The placement of the displays is shown in Figure 3.

Two photographs of the study site are shown in Figure 4. The photograph in Figure 4(*a*) was taken about 702 m (2,300 ft) in advance of the lane closure taper. It shows the approach to the lane closure, which was on a tangent, nearly level section of roadway. It also shows the exit ramp that was located on the approach about 183 m (600 ft) in advance of the lane closure taper. The photograph in Figure 4(*b*) was taken from the overpass at the beginning of the taper. It shows the taper and the entrance ramp located at the end of the taper.

It should be noted that the work area was not visible to traffic on the study approach. Therefore, the activity in the work area did not influence the speed of traffic on the study approach.

DATA COLLECTION

Data were collected before and after the speed monitoring displays were installed. The before study was conducted on Monday, July 12, 1993. The speed monitoring displays were installed on Tuesday, July 13, 1993. In an effort to reduce the chances of simply observ-

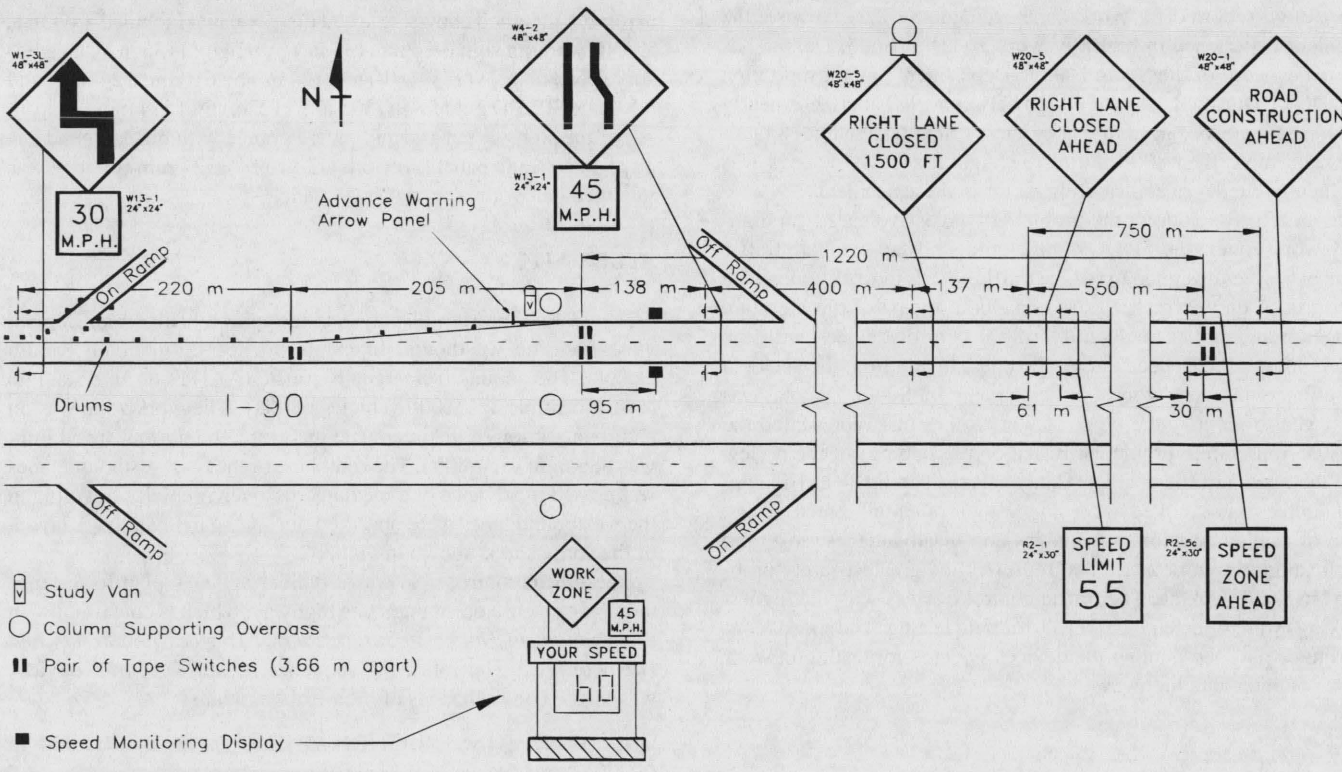


FIGURE 2 Study site plan.

FIGURE 3 Speed monitoring display installation.

ing the novelty effects of the displays, the after study was not conducted until Tuesday, July 20, 1993, about 7 days after the displays had been installed.

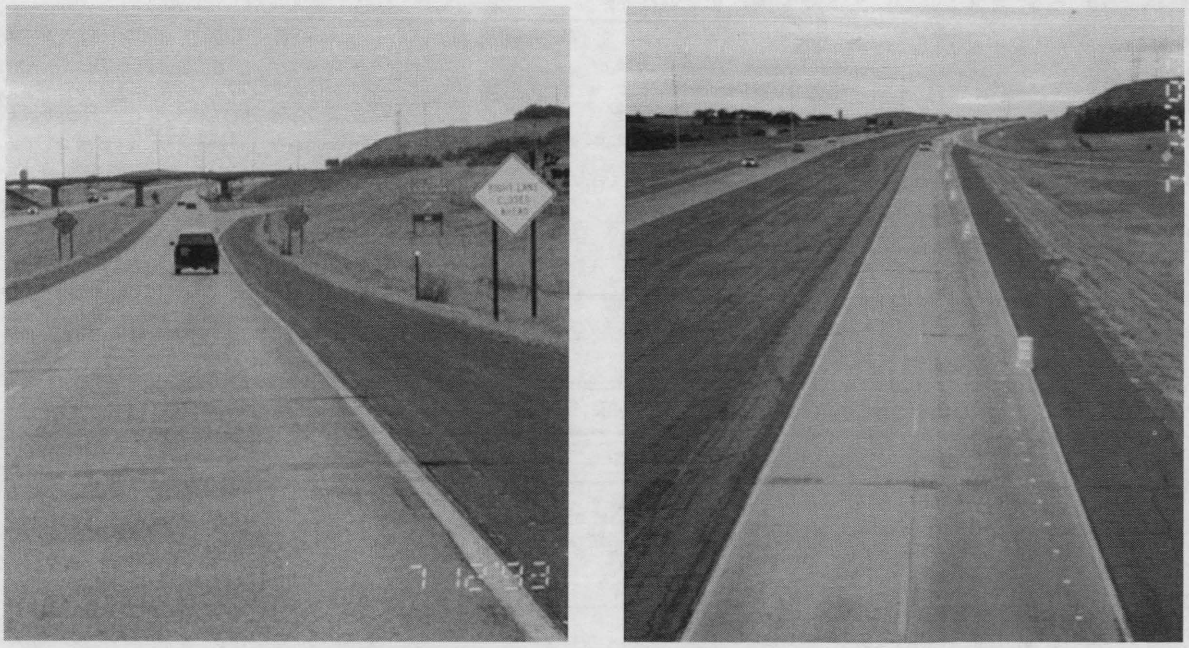
The data were collected during daylight between the hours of 9:00 a.m. and 5:00 p.m. The weather on both study days was fair to partly cloudy with no precipitation. The pavement surface was dry.

The data were collected with tape switches at three locations in advance of the work zone as shown in Figure 2. The first location (Station 1) was about 200 m (650 ft) downstream of the ROAD CONSTRUCTION AHEAD signs and 1,220 m (4,000 ft) in advance of the lane closure taper. The second location (Station 2) was at the beginning of the lane closure taper, and the third location (Station 3) was at the end of the taper. At each location, tape switches were installed in the open lanes. Two lanes were open to traffic at Stations 1 and 2, and only one lane was open to traffic at Station 3. Speed, volume, headway, and vehicle classification data were collected by the tape switches at each station.

Traffic operations on the entrance ramp and in the merge area immediately downstream of the taper were videotaped to record when entrance ramp vehicles may have influenced vehicles on the study approach. The video-camera clock was synchronized with the clock in the computer that recorded the tape switch data so that the two data sets could be coordinated during data analysis. Both the video camera and the computer were located in the study van where observers monitored their operation. The study van was parked behind a column of the crossroad overpass near the beginning of the taper as shown in Figure 5. Although a portion of the van could be seen by approaching traffic, the presence of the van was not observed to influence traffic behavior. It was parked in a "non-threatening" manner, facing away from the roadway so that it would not appear as though it was involved in speed-limit enforcement or about to enter the freeway. In addition, as can be seen in Figure 3, there was considerable visual stimuli provided by the advance warning arrow panel and the other traffic control devices on the approach, which reduced the conspicuity of the van. Also, because the same study van was located in exactly the same position during the before and after studies, its influence on traffic would be about the same in both studies. Therefore, its effect would be eliminated in the comparison of traffic speeds before and after the installation of the speed monitoring displays.

DATA ANALYSIS

The speed monitoring displays were intended to slow traffic by making drivers aware of how fast they were traveling. Therefore,



(*a*) (*b*)

FIGURE 4 Views of study site: (*a*) approach; (*b*) lane closure taper.

FIGURE 5 Location of data collection van.

the data analysis examined the difference in approach speeds before and after the displays were installed. In particular, the reductions in mean speeds and excessive speeds were examined.

The speeds used in the analysis were those of "free flowing" vehicles, which were vehicles that were not influenced by other vehicles. A vehicle was determined to be free flowing if the following conditions existed when it traveled through the study site:

- There were no vehicles on the entrance ramp downstream of the taper.
- The headway between it and the vehicle ahead was more than 4 sec.

The sample sizes observed in the before and after studies are shown in Table 1. Station 1 was the farthest from the lane closure taper. It was 1,220 m (4,000 ft) in advance of the taper. Station 2 was at the beginning of the taper, and Station 3 was at the end of the taper. The sample sizes were smaller at Station 2 than they were at Station 1 because some vehicles left the interstate on the exit ramp between Stations 1 and 2. The sample sizes were slightly smaller at Station 3, because more vehicles at this location were traveling at headways that were less than 4 sec after the two approach lanes had merged into one lane at the end of the taper. Also, in a few cases, vehicles had arrived on the downstream entrance ramp by the time free-flowing vehicles at Station 2 had arrived at Station 3.

In the before study, 83 to 86 percent of the vehicles were two-axle vehicles (e.g., passenger cars, vans, and pickup trucks), and 14 to 17 percent of them had more than two axles (e.g., passenger cars, vans, and pickup trucks with trailers, and trucks). In the after study, a slightly lower percentage of two-axle vehicles was observed. Only 81 to 84 percent of the vehicles had two axles, and 16 to 19 percent had more than two axles.

Mean Speeds

The mean speeds observed before and after the installation of the speed monitoring displays are shown in Table 2. As expected, the speed of traffic decreased as it approached the work zone in both the

TABLE 1 Sample Sizes

	Before Study			After Study		
Station[a]	Vehicles With 2 Axles	Vehicles With > 2 Axles	All Vehicles	Vehicles With 2 Axles	Vehicles With > 2 Axles	All Vehicles
1	1,820	298	2,118	1,668	312	1,980
2	1,338	261	1,599	1,197	281	1,478
3	1,285	266	1,551	1,161	267	1,428

[a]Station 1 is 1,220 m (4,000 ft) in advance of the taper.
Station 2 is at the beginning of the taper.
Station 3 is at the end of the taper.

TABLE 2 Mean Speeds (km/hr)

	Vehicles With 2 Axles		Vehicles With > 2 Axles		All Vehicles	
Station[a]	Before	After	Before	After	Before	After
1	105.6	105.5	100.2	100.2	104.8	104.7
2	98.1	92.3	93.6	85.5	97.4	91.0
3	97.3	91.3	92.3	84.4	96.5	90.0

1 km/hr = 0.62 mph.
[a] Station 1 is 1,220 m (4,000 ft) in advance of the taper.
Station 2 is at the beginning of the taper.
Station 3 is at the end of the taper.

TABLE 3 Partial Sums of Squares at Station 2

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F value	p value
Speed at Station 1	1	1,153	1,153	13.87	0.0002
Number of Axles (2, 3, 4, 5, or 6)	4	11,414	2,854	34.30	0.0001
Study Type (Before or After)	1	2,871	2,871	34.51	0.0001
Interaction of Study Type and Number of Axles	4	868	217	2.61	0.0339

TABLE 4 Partial Sums of Squares at Station 3

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F value	p value
Speed at Station 1	1	897	897	11.95	0.0006
Number of Axles (2, 3, 4, 5, or 6)	4	13,867	3,467	46.17	0.0001
Study Type (Before or After)	1	22,325	22,325	297.33	0.0001

before and after studies. In each vehicle class, the mean speeds at Station 1 were higher than those at Station 2, and the mean speeds at Station 2 were higher than those at Station 3. Also, at each station, the mean speed of vehicles with two axles was higher than that of vehicles with more than two axles in both the before and after studies.

The data in Table 2 also indicate that the speed monitoring displays did reduce the mean speeds at Stations 2 and 3. In each vehicle class, the mean speeds observed at these stations in the after study were lower than the mean speeds observed in the before study. The mean speeds of the two-axle vehicles were reduced by about 6 km/hr (4 mi/hr), and the mean speeds of the vehicles with more than two axles were reduced by about 8 km/hr (5 mi/hr).

An analysis of variance was conducted to determine the statistical significance of the differences in the before and after mean speeds at Stations 2 and 3. In the analysis, time of day and number of axles were used as blocking factors because they were expected to have influenced the vehicle speeds. In general, traffic speeds are lower during periods of higher traffic volumes, and because traffic volume varied throughout the day, time of day was used as a blocking factor in the analysis. The differences in mean speeds observed between the vehicle classes shown in Table 2 indicated that the number of axles may affect vehicle speeds and therefore should be used as a blocking factor.

Another factor that would be expected to influence a vehicle's speeds at Stations 2 and 3 was its speed at Station 1. The faster a vehicle is traveling at Station 1, the faster it would be expected to be traveling at Stations 2 and 3. However, it was not possible to accurately track vehicles over the 1,220 m (4,000 ft) between Stations 1 and 2. Therefore, the average speed at Station 1 during the same hour of the time of day when the vehicle's speeds were recorded at Stations 2 and 3 was used as a covariate to account for the possible effect of speed at Station 1.

Thus, the effects of time of day, number of axles, and speed at Station 1 were accounted for in the analysis. In addition, all two-factor interactions were considered, and those that were not significant were eliminated. The analysis was performed using the General Linear Analysis Procedure of the Statistical Analysis System. (*6*)

The partial sums of squares from the analysis of variance at Stations 2 and 3 are shown in Tables 3 and 4, respectively. These results indicate that the speed monitoring displays had a significant effect on the mean speeds at both stations because the effect of study type (before or after) was significant (p-value = 0.0001). The effects of the average speed at Station 1 during the same hour of the day and the number of axles were also significant at both stations. In addition, the effect of the interaction of study type and number of axles was significant at Station 2 (the beginning of the taper). As shown in Figure 6, this interaction indicated that vehicles with more than two axles, especially those with more than four, reduced their speeds more in response to the speed monitoring displays.

The experimental design used in this study was not balanced, because the sample sizes in the cells defined by the experimental factors were not equal and the covariate did not have the same mean value in every cell. Therefore, the best estimate of effect of the speed monitoring displays would be the least-square mean speeds, which account for differences in cell sample sizes and covariate mean values. They are the mean speeds that would be expected if the mean values of the blocking factors and the average speed at Station 1 were the same in the before and after studies. The least-square mean speeds are shown in Table 5. These data indicate that the speed monitoring displays reduced the mean speed of traffic by 7.6 km/hr (4.7 mi/hr) at Station 2 and 6.1 km/hr (3.8 mi/hr) at Station 3.

TABLE 5 Least-Square Mean Speeds (km/hr)

Station[a]	Before	After	Difference
2	95.2	87.6	-7.6
3	93.2	87.1	-6.1

1 km/hr = 0.62 mph.
[a] Station 2 is at the beginning of the taper. Station 3 is at the end of the taper.

Excessive Speeds

Previous studies(*7–9*) have found that speed reduction measures involving radar have a more pronounced effect on vehicles exceeding the speed limit. These studies have also found that truck speeds are usually reduced more than passenger car speeds, which has been attributed to the higher percentage of trucks using radar detectors.

The speed distributions at Station 1 are shown in Figure 7. At this location, 1,220 m (4,000 ft) in advance of the taper, where the speed limit was 105 km/hr (65 mi/hr), the speed distributions within each vehicle class were about the same before and after the speed monitoring displays were installed. The results of chi-square tests indicated that there was no significant difference between the distributions within each vehicle class at the 0.05 level of significance.

The percentages of vehicles exceeding the advisory speed limit of 72 km/hr (45 mi/hr) at Stations 2 and 3 are shown in Figure 8. At each station, the percentages of vehicles traveling at excessive speeds within each vehicle class were reduced after the speed monitoring displays were installed. The results of chi-square tests of these percentages within each vehicle class, at each station, indicated that these reductions were significant at the 0.05 level of significance. Comparison of the percentages between vehicle classes suggests that the reductions in excessive speeds at Stations 2 and 3 were greater for vehicles with more than two axles than they were for two-axle vehicles.

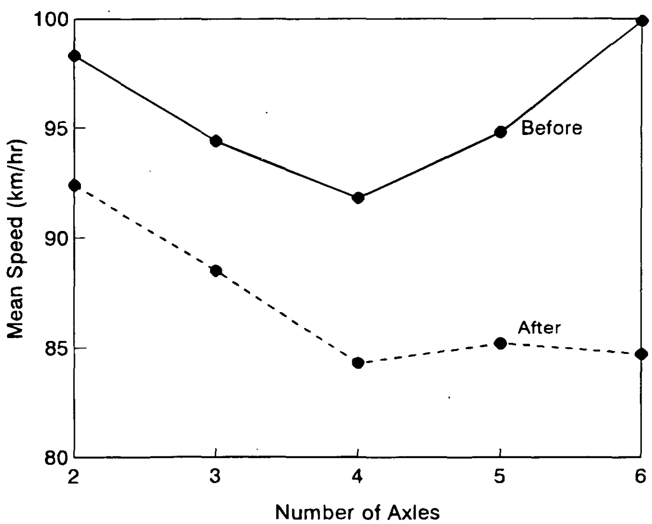


FIGURE 6 Mean speeds at Station 2.

The percentages of vehicles exceeding the speed limit by more than 16 km/hr (10 mi/hr) are shown in Table 6. At Station 1, where the speed limit was 105 km/hr (65 mi/hr), the before and after percentages were nearly the same. The results of chi-square tests indicated that there were no significant differences between the before and after percentages within each vehicle class. However, at Stations 2 and 3, the differences between the before and after percentages within each vehicle class were significant. After the speed

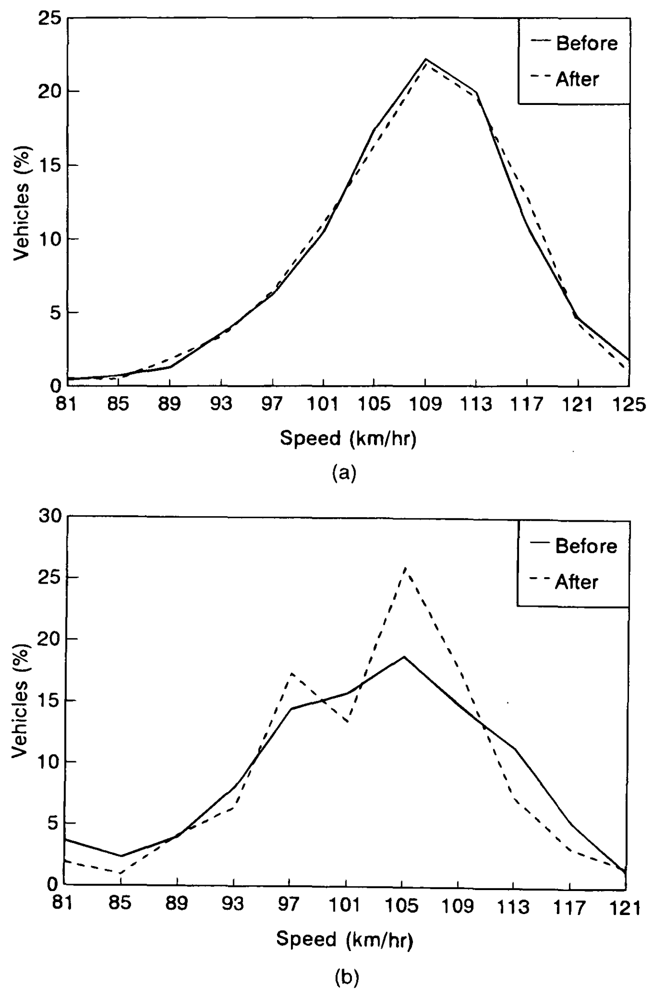


FIGURE 7 Speed distributions at Station 1: (*a*) two-axle vehicles; (*b*) vehicles with more than two axles.

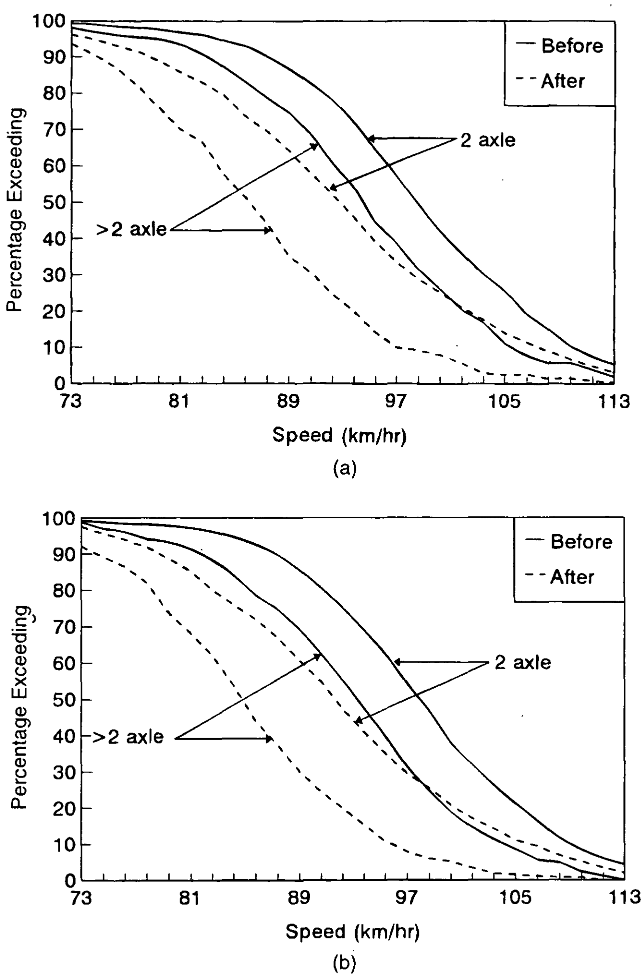


FIGURE 8 Percentage of vehicles exceeding advisory speed limit: (*a*) Station 2; (*b*) Station 3.

monitoring displays were installed, the percentages of two-axle vehicles exceeding the advisory speed limit of 72 km/hr (45 mi/hr) at Stations 2 and 3 were reduced by about 20 to 25 percentage points. The reductions in the percentages of vehicles with more than two axles were much higher. They were reduced by about 40 percentage points.

CONCLUSION

The data indicate that the speed monitoring displays with radar were effective in reducing the speed of traffic approaching the work zone. The mean speeds were about 6 to 8 km/hr (4 to 5 mi/hr) lower after the speed monitoring displays were installed. In addition, the speeds of vehicles exceeding the advisory speed limit of the work zone were reduced significantly, and the percentages of vehicles exceeding the advisory speed limit by more than 16 km/hr (10 mi/hr) were reduced by as much as 40 percentage points.

These reductions are greater than those found in previous studies of radar alone (*7–9*). In long-term work zones on interstate highways, radar alone has been found to reduce mean speeds by only about 2 to 3 km/hr (1 to 2 mi/hr), and the percentages of vehicles exceeding the speed limit by more than 16 km/hr (10 mi/hr) have been reduced by only about 10 percentage points. Therefore, the speed monitoring displays with radar seem to be more effective than radar alone.

However, it should be noted that the effectiveness of the speed monitoring displays may have been limited by the design of its sign assembly and its close proximity to other work zone traffic control devices on the study approach. The sign assembly included a WORK ZONE warning sign and a 45 mi/hr advisory speed plate in addition to the speed display panel. Thus, the sign assembly may have contained too much information for some drivers to comprehend. Also, according to SDDOT guidelines, the spacing between the speed monitoring displays and the other traffic control devices on the approach to the lane closure should have been about 180 m (600 ft). However, as shown in Figure 2, the speed monitoring displays were only 43 m (140 ft) downstream from the symbolic "lane transition reduction to the right" signs with 45 mi/hr advisory speed plates and only 95 m (310 ft) upstream from the advance warning arrow panel at the beginning of the lane closure taper. These relatively short distances may have reduced the conspicuity of the speed monitoring displays and may not have been sufficient for some drivers to comprehend the speed monitoring displays. Therefore, the SDDOT is planning further study to determine the optimum design and location of the speed monitoring displays.

ACKNOWLEDGMENT

This work was performed under the supervision of the SDDOT Technical Panel SD93–10. Members of the panel were Jim Cooper

TABLE 6 Percentage of Vehicles Exceeding Speed Limit by More Than 16 km/hr

	Vehicles With 2 Axles		Vehicles With > 2 Axles		All Vehicles	
Station[b]	Before	After	Before	After	Before	After
1	2.3	1.5	0.0	1.0	2.0	1.4
2	86.8	65.1[b]	74.7	35.2[b]	84.8	59.4[b]
3	85.5	60.7[b]	69.2	30.0[b]	82.7	55.0[b]

1 km/hr = 0.62 mph.
[a] Station 1 is 1,220 m (4,000 ft) in advance of the taper.
Station 2 is at the beginning of the taper.
Station 3 is at the end of the taper.
[b] Significantly different than the before percentage (0.05 level of significance).

of the Aberdeen Region, David Huft of the Office of Research, Jim Iverson of the South Dakota FHWA Division, Scott Jansen of the Mitchell Region, Sharon Johnson of the Pierre Region, Ron Merriman of the Division of Operations, George Sherrill of the Division of Operations, Roland Stanger of the South Dakota FHWA Division, and Dan Staton of the Rapid City Region. Special recognition is given to David Huft for his excellent coordination of the involvement of the SDDOT in the research, and Scott Jansen is recognized for his extraordinary efforts in obtaining information needed for the selection of the study sites and coordinating the schedules of the work zone projects and field studies.

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Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar

NICHOLAS J. GARBER AND SURBHI T. PATEL

Studies have shown that most drivers do not slow down in response to the standard regulatory or advisory speed signs that are customarily used to regulate speeds at temporary traffic control zones (work zones). This study evaluated the effectiveness of the Changeable Message Sign (CMS) with a radar unit in reducing speeds at work zones. Four CMS messages designed to warn drivers that their speed exceeded the maximum safe speed were tested at seven work zones on two interstate highways in Virginia. Speed and volume data for the whole population traveling through the sites were collected with automatic traffic counters. To assess the effect of the CMS with radar (on high-speed drivers in particular), vehicles that were traveling above a selected threshold speed triggered the radar-activated display and were videotaped as they passed through the work zones. The data obtained from the videotapes were used to obtain speed characteristics of these speeding drivers as they traversed these study sites. Statistical tests were then conducted using these speed characteristics to determine whether significant reduction in speed accompanied the use of CMS. The results indicate that the CMS with radar significantly reduced the speeds of speeding drivers. The messages used were rated according to their level of effectiveness in the following order: (1) YOU ARE SPEEDING SLOW DOWN, (2) HIGH SPEED SLOW DOWN, (3) REDUCE SPEED IN WORK ZONE, and (4) EXCESSIVE SPEED SLOW DOWN.

With over 90 percent of the national interstate highway network infrastructure completed, emphasis is now being placed on the rehabilitation and widening of existing highways rather than the construction of new ones. Thus, there are more and more temporary traffic control zones (work zones) on U.S. highways. The number of accidents and fatalities in work zones increased significantly as spending on highway construction grew during the 1980s, most of which was for rehabilitation work along heavily traveled roadways (1–3). In 1991, 680 persons died in construction/maintenance zones, and work zone fatal crashes represented approximately 3.75 percent of all fatal crashes on interstates, freeways, or expressways in the United States (3).

Many studies have identified excessive vehicle speeds in these zones as a major contributing factor in crashes (4–7). It has been shown that the static or passive methods endorsed in the *Manual on Uniform Control Devices* (MUTCD) do not in most cases influence drivers to respond to the posted speed limit or maximum advisory speed signs at these zones (*8*). Thus, many attempts have been made to develop additional techniques to control speeds at work zones, (9).

In this project, the Changeable Message Sign (CMS) integrated with radar was used to influence drivers speeding in the work zone to reduce their speed. The radar, attached directly to the CMS, was used to determine the actual speeds of individual vehicles in the traffic stream. Upon detecting a speed higher than a present threshold limit, the CMS was programmed to display a preselected warning message to the driver.

To evaluate the effectiveness of the CMS with radar, an investigative study to test its operation was conducted. In the past, the CMS has been successfully used in an informational and advisory capacity. However, in this new role, the sign represents an excellent application of Intelligent Vehicle Highway System (IVHS) technology as it provides credible, real-time information based on the determination of actual vehicle speeds as the vehicles enter the work zone. In this study, four messages were used, and each influenced speeding drivers to significantly reduce their speed in the work zone.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the effectiveness of the CMS with radar effective means of influencing drivers to reduce their speed work zones, especially those traveling at speeds much higher than the posted speed limit. The project was designed to study four different messages in several different environments and to determine their effects on speed profiles as described by characteristics such as average speeds, 85th percentile speeds, and speed variance.

The scope of the study was limited to temporary traffic control zones (work zones) on interstate highways in Virginia. Only those zones that called for speed reduction were selected for the project, and the zones were studied only by daylight and under dry weather conditions. In addition, the work zones chosen also had to meet certain criteria regarding length, the amount of traffic on the roadway, and the provisions for the safety of the data collection team.

The specific objectives of the study were to

1. Determine the speed characteristics of work zones on different types of highways using standard signing as specified in the MUTCD (10),
2. Determine the speed characteristics of the same work zones using both the standard MUTCD signing and the CMS,
3. Compare the results from Objectives 1 and 2 and assess the overall effect of CMS on the speed characteristics and speed profiles of the work zone areas,
4. Determine the effect of CMS on individual driver behavior, particularly high-speed drivers, as opposed to the whole population, and
5. Determine to what extent and under what traffic conditions this technique will be most effective.

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DATA COLLECTION

Identifying Suitable Work Zone Sites

Initially, information on anticipated maintenance and reconstruction activities throughout the state of Virginia was requested from resident engineers by distributing a survey letter. The survey requested information on the project location and a description of specific characteristics of the work zone, for example, day or night operation, the number of lanes to be closed, and the length of the work zone. If the work zone appeared to be feasible during this preliminary evaluation, then a site visit was warranted, and it was submitted for the final selection process.

For the site to be suitable for data collection, the work zone had to meet the following qualifications:

- The length of the work zone had to be at least 457.2 m (1,500 ft) or more to allow drivers who wished to vary their speed along the study area to do so.
- As congested flow usually predominates on highways with high annual average daily traffic (AADT), the estimated free flow traffic on the highway in question had to be at least 30 percent of the total traffic. This condition allowed for the monitoring of the individual speeds of a sufficient number of vehicles being driven at the drivers' desired speed.
- The work zone had to be able to safely accommodate the CMS equipment and researchers without interfering with construction vehicles and workers or obstructing the traffic flow.

Seven sites were selected for data collection throughout the course of the project (Table 1). The normal speed limits shown in Table 1 are the posted speed limits on these roads under normal conditions (i.e., when no work is being performed on the roads). Only regulatory signs were used for the posted speed limits at all study sites. Figure 1 shows an example of a typical work zone study area.

Speed and Volume Data: Automatic Traffic Counts

The first step entailed laying down the pneumatic tubes and automatic traffic counters (StreeterAmet 141A traffic counters) to collect the speed and volume data for all vehicles traveling through the work zone. These data were collected continuously, day and night, during the course of the data collection period to provide the data for all the vehicles without the CMS and also with the CMS during actual videotaping and sign display.

The tubes were set down at the following three locations within the temporary traffic control zone (work zone):

- At the advance warning area, just before the beginning of the transition area (station 1),
- At approximately the midpoint of the activity area (station 2), and
- Just before the end of the work zone (station 3).

These three locations were chosen because (a) at the entrance to the transition area, vehicle speeds are usually those preferred by the drivers; (b) in the middle of the activity area, vehicle speeds may be influenced by the speed control effort; and (c) at the end of the work zone drivers may choose to regain their speed, believing that they have passed the monitored area.

Data Collection with CMS

Placement of CMS

The CMS was placed a short distance behind the first set of tubes (at the beginning of the taper if vehicles were channelized into a single lane) to detect vehicle speeds as they entered the work zone. The

TABLE 1 Work Zone Study Sites

ROUTE NUMBER	NEAREST CITY OR TOWN	COUNTY	1991 AADT	NUMBER OF LANES	NUMBER OF LANES OPEN TO TRAFFIC	NORMAL SPEED LIMIT	POSTED SPEED LIMIT	TYPE OF WORK ZONE	DATES OF STUDY
81 South	Lexington	Rockbridge	24,000	2	1	105 km/hr	88.5 km/hr	Rockslide Damage Control	8/18-8/21/92 8/25-8/26/92
64 East	Covington	Alleghany	8,400	2	1	105 km/hr	88.5 km/hr	Bridge Deck Repair	9/14-9/16/92
64 East	Short Pump	Henrico	25,000	2	2	105 km/hr	88.5 km/hr	Construction of Additional Lane	10/26-10/29/92
81 North	Bristol	Washington	33,000	2	2	105 km/hr	88.5 km/hr	Bridge Reconstruction	5/24-5/27/93
81 North	Abingdon	Washington	24,000	2	1	105 km/hr	72.4 km/hr	Bridge Reconstruction & Complete New Interchange Construction	7/12-7/14/93
81 South	Abingdon	Washington	24,000	2	1	105 km/hr	88.5 km/hr		8/23-8/26/93
64 East	Shadwell	Albemarle	21,000	2	1	105 km/hr	88.5 km/hr	Concrete Joint Repair	11/1-11/3/93

1 km = 0.6 mi.

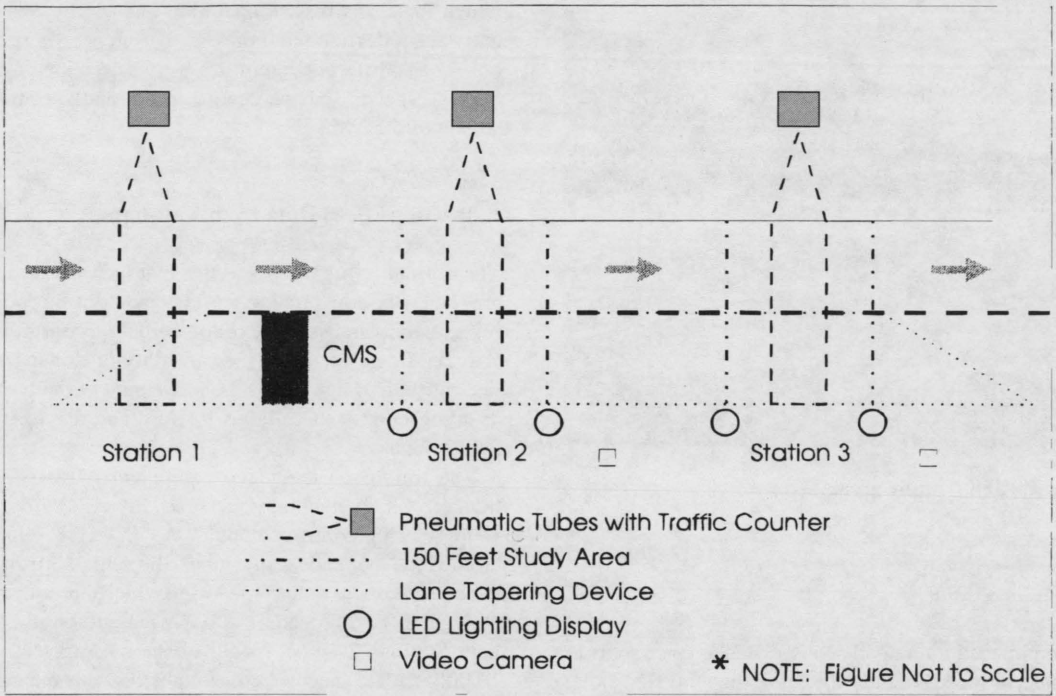

FIGURE 1 Example of typical work zone study area—two-lane highway tapered to one lane.

CMS that was used in this project was specially designed for the study. It used the standard message display board (CMS–T300, American Signal Company). The radar unit attached to the side was a special feature (Figure 2). This radar (TRACKER TDW–10 Wide Beam Vehicle Detector) was connected to the central processing unit that controls the functions of the message display. If the radar was activated and it detected a speed higher than a preset threshold speed, the message display could be programmed to flash a particular message instantaneously.

The radar, attached directly to the side of the message display (Figure 2), was positioned to align with vehicles as they entered the work zone at a range of 91.4 m to 182.9 m (300 to 600 ft). Generally, the main objective was to direct the radar to a point where only *one* vehicle's speed would be detected by the radar. The purpose of this particular arrangement was twofold. First, when the radar detected a speeding vehicle, an observer was able to identify that particular vehicle, take note of its key characteristics (color of vehicle, vehicle type) and relay this descriptive information over the walkie talkie to the crew activating the video cameras. At the same time, the driver of the vehicle would be in the range to see the message as it came up on the display and then be able to act accordingly, if he or she so desired.

Marking the Study Areas

At the second and third locations (near Stations 2 and 3, where the counters were placed), additional tubes were set down marking a distance of 45.7 m (150 ft). These tubes designated a section of known distance to calculate the speeds of those vehicles for which the message was activated. The cameras provided the means to determine the vehicles' travel times across the sections as their movements were recorded on film. The speeds of the vehicles at these two locations in the work zone were calculated by time and distance.

To enhance the visibility of the tubes, during the extraction of the data from the video tapes, an air-pressure-activated lighting device, which consisted of a light-emitting diode (LED) display, was constructed. The lighting device was attached to each of the two tubes marking the entrance and exit of the 45.7-m (150-ft) sections (Figure 2). The light was activated when the tire exerted pressure on the tubes, giving a clear indication of when each vehicle's front wheels entered and exited the study area. The light did not in any way distract or endanger drivers as it was placed off the traveled way and faced the opposite direction of travel. A typical study area is shown in Figure 3.

FIGURE 2 Changeable message sign with radar unit.

FIGURE 3 Typical 150-ft study area.

Placement of the Video Cameras

Two cameras were placed a relatively long distance apart so as to capture any changes in speeds of the vehicles as they traveled along the roadway. With the strategic placement of the cameras, driver behavior, as well as the effectiveness of the speed control device, was studied. As the speeding vehicle entered the work zone, its progress was monitored by two camera operators.

In addition to videotaping, the second camera operator was also required to manually record data on each speeding vehicle's description using a predesignated form. Information regarding the type, color, and size, as well as the make of the vehicle, was marked on the data collection sheet to help identify each speeding vehicle on the videotapes during the data reduction process.

Data Recording with CMS

Each time a speeding vehicle triggered the automated speed display, the observer at the CMS identified the vehicle and relayed the descriptive information to Stations 2 and 3 so the progress of that specific vehicle could be monitored through the work zone by videotaping its movement.

The following four messages were tested at each site:

- EXCESSIVE SPEED SLOW DOWN,
- HIGH SPEED SLOW DOWN,
- REDUCE SPEED IN WORK ZONE, and
- YOU ARE SPEEDING SLOW DOWN.

Compiling Speed and Volume Data from Traffic Counters

Using the StreeterAmet T240, the speed and volume data were extracted from the traffic counters on a daily basis. Using the data from the automatic counters as well as the speed data obtained from the videotapes, a detailed analysis was carried out for (*a*) the period during work activities but before the installation of the CMS, (*b*) the period during which the CMS was in operation with the video cameras and data collection team present, and (*c*) the period during which the CMS was in operation but without the video cameras and data collection team present. Differences in speed characteristics for the different conditions were determined by comparing the average speed, 85th percentile speed, and speed variance downstream of the CMS.

Extracting Speed Data from Videotapes

The normal ½-in. videocassettes that were used in the video cameras had to be converted to professional ¾-in. tapes as the ¾-in. editing system was used to extract the data from the videotapes. The ¾-in. editing system has the capability of slowing frames down to one-thirtieth of a second. The movement of the frames is managed by a jog control that allows forward and reverse frame-by-frame adjustments.

The timing on the video equipment is recorded on a control tracker, which maintains accuracy to $\pm 2/30$ sec (two frames). Using the jog control to obtain the times the vehicle's front tires crossed the first and second tubes, the vehicle's travel time between the two tubes was determined from which the vehicle's velocity was computed. This procedure was carried out for all of the vehicles at both Stations 2 and 3 for all of the messages at each site. Over 10,000 vehicle speeds were computed in this manner.

ANALYSIS

Calculation of Average and Percentile Speeds

Camera Data

Having computed all of the speeds at Stations 2 and 3, the average and 85th percentile speeds of those vehicles exceeding the threshold speed were computed at each station for each message using all of the data.

The camera data were then divided to assess the effect of the messages on high-speed drivers in particular. The speed data at Station 1 were sorted into two categories: 95 to 103 km/hr and $\geq$104 km/hr (59 to 64 mi/hr and $\geq$65 mi/hr). The corresponding speeds at Stations 2 and 3 for each vehicle were also sorted along with Station 1. Average speeds for the two speed categories were then calculated at each station for each message. The main purpose for this division was to observe the behavior of the two different groups of speeding vehicles as they traveled through the work zone.

Traffic Counters Data

Three separate sets of data were extracted from the traffic counters. The first set represented the speeds of vehicles when only the standard MUTCD traffic control signs were in place, including the regulatory speed signs, without the use of the CMS. This condition represented the base condition for analysis, and under this condition, only the regulated speed signs informed drivers of the speed limit at the work zone. The second and third sets were obtained for the times when the CMS was in place, in addition to the standard MUTCD traffic control signs including the regulatory speed signs, with and without the data collection team present.

The average and 85th percentile speeds, the speed variance, and the pace were calculated at each station and for each message.

Significance Testing

The statistical techniques used to test the significance of the speed reductions achieved with the CMS included the *odds ratio, the analysis of variance* (ANOVA), and the *t*-test. The odds ratios were used to determine the odds of exceeding the speed limit in the work zone under the various conditions prescribed in the study, for example, the use of the four different messages on the CMS. The effectiveness of the CMS was measured by the decrease in the odds for speeding when using the CMS as compared with the odds for speeding when not using the CMS. ANOVA was used with the whole population data to determine whether there were significant reductions in average and 85th percentile speeds, as well as speed variances, as a result of using the CMS. In addition, ANOVA was also used with the camera data to determine if there was a significant difference in speeds when using any of the four messages on the CMS. And finally, the *t*-test was used with the camera data to test whether the drivers of the high-speeding vehicles were significantly reducing their speed as they traversed the three stations through the work zone. (Due to space constraints, only the results of the ANOVA tests are presented.)

Analysis of Variance

Camera Data

ANOVA was conducted with the speed data obtained from the videotapes (data on speeding drivers only) to determine whether there were significant differences between the four messages with regard to average and 85th percentile speeds of the speeding drivers within the work zone. Using the data from all test sites, the following null hypotheses (1–10) were tested:

1. The average speeds at Station 2 are the same for all four messages on the CMS.
2. The 85th percentile speeds at Station 2 are the same for all four messages on the CMS.

These null hypotheses were also tested using the data obtained at Station 3.

Whole Population Data

Initially, ANOVA tests were conducted to determine whether there were significant differences in the speed data obtained when the data collection team was present at the study sites and the speed data obtained when the team was not present. If there were no significant differences in the two sets of data, then it would be reasonable to assume that the presence of the data collection team when recording the camera data did not bias the results.

The tests compared the two conditions for average speeds, 85th percentile speeds, and speed variances at Stations 2 and 3 using the whole population data. The following set of null hypotheses was developed [these were repeated for Station 3 speeds and for each of the other two speed characteristics (i.e., 85th percentile speeds and speed variance)]:

3. The average speeds at Station 2 with the data collection team present are the same as the average speeds without the data collection team present for the message EXCESSIVE SPEED SLOW DOWN.
4. The average speeds at Station 2 with the data collection team present are the same as the average speeds without the data collection team present for the message HIGH SPEED SLOW DOWN.
5. The average speeds at Station 2 with the data collection team present are the same as the average speeds without the data collection team present for the message REDUCE SPEED IN WORK ZONE.
6. The average speeds at Station 2 with the data collection team present are the same as the average speeds without the data collection team present for the message YOU ARE SPEEDING SLOW DOWN.

The whole population data obtained from the automatic counters were also used to evaluate the effect of the CMS on three particular characteristics of the speed profiles through the work zone: the average speeds, 85th percentile speeds, and the speed variances.

The next four null hypotheses pertain to the average speeds that were calculated at Station 2. It should be noted that the 85th percentile speeds, the speed variances, and the percentages of vehicles speeding in each category were all tested in a similar manner. In addition, all of the speed characteristics were evaluated at Station 3 as well.

7. The average speeds at Station 2 using the CMS displaying the message EXCESSIVE SPEED SLOW DOWN are the same as when using standard MUTCD signing only.
8. The average speeds at Station 2 using the CMS displaying the message HIGH SPEED SLOW DOWN are the same as when using standard MUTCD signing only.
9. The average speeds at Station 2 using the CMS displaying the message REDUCE SPEED IN WORK ZONE are the same as when using standard MUTCD signing only.
10. The average speeds at Station 2 using the CMS displaying the message YOU ARE SPEEDING SLOW DOWN are the same as when using standard MUTCD signing only.

RESULTS

Tables 2 through 4 contain the statistics for the camera data, which include the average speeds and 85th percentile speeds in Tables 2 and 3, respectively. Table 4 provides the average speeds that were determined at each station when Station 1 speeds were divided into two categories: 94.9 to 103 km/hr and ≥103 km/hr (59 to 64 mi/hr and ≥65 mi/hr). Table 4 shows the benefits of using the CMS to reduce speed variance. The notable trend in this table can best be described with an example: For the speeds at I-81 South at Buffalo Gap for the message EXCESSIVE SPEED SLOW DOWN, the difference in average speeds at Station 1 for the two speed categories was approximately 9 km/hr (5.6 mi/hr, i.e., 66.6 to 61.0 mi/hr). By Station 2, this difference reduced to approximately 5.4 km/hr (3.4 mi/hr, i.e., 54.3 to 50.9 mi/hr). And finally, by Station 3, the difference in average speeds for the two high-speeding groups dropped to 1.1 km/hr (0.7 mi/hr, i.e., 50.8 to 50.1 mi/hr). The average speeds for all of the messages at all of the sites showed a similar trend in driver behavior, although to slightly different degrees. The fact that all of the high-speeding vehicles tend to converge to a similar speed by the time they

TABLE 2 Average Speeds (km/hr) Calculated Using Camera Data

	EXCESSIVE SPEED SLOW DOWN			HIGH SPEED SLOW DOWN			REDUCE SPEED IN WORK ZONE			YOU ARE SPEEDING SLOW DOWN			SLOW DOWN NOW		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
81 South Buff. Gap	99.77	83.12	80.90	99.73	82.01	75.71	98.97	85.92	78.24	100.5	82.30	73.43		Not	
64 East Covington	100.1	75.34	69.31	101.3	77.97	70.65	100.4	80.17	73.70	101.4	77.21	66.16		Tested	
64 East Short Pump[1]	99.04	--	78.07	99.92	--	80.46	100.1	--	80.08	99.52	--	79.13		At	
81 North Bristol[2]	98.58	83.11	80.34	98.46	82.16	81.24	99.18	84.91	83.80	98.41	80.69	79.76		These	
81 North Abingdon[2]	89.82	61.64	--	89.21	63.13	55.62	90.83	68.75	67.03	88.39	62.25	59.11		Sites	
81 South Abingdon	99.44	71.81	73.45	99.07	75.69	75.95	99.23	72.86	73.93	99.20	71.87	74.87	99.23	72.03	73.93
64 East Shadwell	101.2	94.29	94.24	100.9	89.86	85.94	101.6	93.24	94.21	102.4	88.66	85.52	101.7	90.73	89.49

1 km=0.6 mi.

[1] Two lanes open.

[2] Reduced to 72.4 km/hr.

-- Indicates that speeds were incalculable because a problem was encountered with the videotapes and travel times were unavailable.

TABLE 3 85th Percentile Speeds (km/hr) Calculated Using Camera Data

	EXCESSIVE SPEED SLOW DOWN			HIGH SPEED SLOW DOWN			REDUCE SPEED IN WORK ZONE			YOU ARE SPEEDING SLOW DOWN			SLOW DOWN NOW		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
81 South Buff. Gap	104.6	93.16	89.78	106.2	91.44	86.63	103.0	94.95	88.18	106.2	95.95	85.13		Not	
64 East Covington	104.6	86.63	80.95	107.8	86.63	83.68	106.2	91.44	83.68	107.8 3	88.18	79.65		Tested	
64 East Short Pump[1]	103.0	--	88.18	104.6	--	88.18	104.6	--	88.18	103.0	--	88.18		At	
81 North Bristol[2]	103.0	93.17	89.79	101.4	93.17	89.79	103.0	94.95	93.17	103.0	91.44	88.18		These	
81 North Abingdon[2]	96.56	71.57	--	96.56	72.61	63.31	98.17	78.37	74.82	94.95	70.54	67.64		Sites	
81 South Abingdon	104.6	82.86	83.94	103.0	85.83	85.36	104.6	82.86	82.56	103.0	82.86	85:36	103.0	82.86	83.94
64 East Shadwell	104.6	98.75	100.8	104.6	93.16	91.44	104.6	98.75	100.8	106.2	96.82	91.44	106.2	94.95	94.95

1 km=0.6 mi.

[1] Two lanes open.

[2] Reduced to 72.4 km/hr.

-- Indicates that speeds were incalculable because a problem was encountered with the videotapes and travel times were unavailable.

TABLE 4 Average Speeds (km/hr) Calculated Using Camera Data (According to Two Categories of Speeds)

	Speed Category	EXCESSIVE SPEED SLOW DOWN			HIGH SPEED SLOW DOWN			REDUCE SPEED IN WORK ZONE			YOU ARE SPEEDING SLOW DOWN			SLOW DOWN NOW		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
81 South	95-103	98.2	81.9	80.6	97.8	79.9	74.5	97.5	85.3	78.1	98.3	80.4	69.7		Not	
Buff. Gap	≥ 104	107.2	87.4	81.8	107.3	88.8	80.3	107.3	89.8	79.2	107.6	88.7	77.7			
64 East	95-103	98.2	74.4	68.2	98.3	77.9	70.3	98.0	78.1	71.9	98.8	76.6	65.5		Tested	
Covington	≥ 104	107.1	79.0	73.5	108.6	78.2	71.5	107.1	86.3	78.2	108.6	79.7	68.1			
64 East	95-103	97.8	--	77.7	98.3	--	80.1	98.5	--	79.7	98.2	--	78.4		At	
Short Pump[1]	≥ 104	106.9	--	84.7	107.2	--	80.1	107.1	--	82.1	107.3	--	83.2			
81 North	95-103	97.5	82.6	79.7	97.5	82.1	81.1	98.3	84.3	83.2	97.4	82.1	78.9		These	
Bristol[2]	≥ 104	107.2	87.1	87.1	107.1	83.7	83.2	107.2	90.4	90.4	106.2	79.8	82.4			
81 North	79-87	83.8	60.7	--	84.0	61.6	54.9	84.2	66.3	65.3	83.0	62.0	58.4		Sites	
Abingdon[2]	≥ 88	94.8	62.4	--	93.8	64.4	56.3	95.4	70.5	68.1	94.6	62.6	60.0			
81 South	95-103	98.0	71.3	72.9	98.2	74.8	75.3	97.8	72.7	73.9	98.0	71.9	74.8	98.0	71.3	73.5
Abingdon	≥ 104	106.9	74.2	76.6	106.2	82.6	81.4	106.8	73.7	73.9	106.4	71.8	75.3	107.1	76.6	76.6
64 East	95-103	99.1	93.8	93.8	98.5	88.4	85.8	99.3	91.6	92.7	99.5	88.5	85.3	99.1	89.3	88.5
Shadwell	≥ 104	107.5	95.8	95.4	107.5	94.1	88.0	107.8	97.8	98.5	106.7	89.0	85.8	106.7	93.5	91.6

1 km = 0.6 mi.

[1] Two lanes open.

[2] Reduced to 72.4 km/hr.

-- Indicates that speeds were incalculable because a problem was encountered with the videotapes and travel times were unavailable.

reach Station 3 suggests that the CMS had a positive impact on reducing speed variance.

Figures 4 and 5 show the average and 85th percentile speeds calculated for the high-speeding vehicles (using the camera data) at the work zone on I-81 South at Buffalo Gap. This site was chosen to illustrate some of the trends that were observed at nearly all of the sites. The graphs in Figure 4 show that vehicle speeds reduced at Stations 2 and 3 for all of the messages that were used on the CMS. In addition, the messages HIGH SPEED SLOW DOWN and YOU ARE SPEEDING SLOW DOWN appear to have had a greater impact on vehicle speeds than the other two messages. Figure 5, which illustrates the 85th percentile speeds at this site, confirms this finding.

As shown in Figure 5, the 85th percentile speeds did decrease for all of the messages; however, the two messages mentioned previously were more effective in that they reduced these speeds to values that were *at or below the posted speed limit.*

ANOVA Results

Before these results are presented, it should be noted that the data for the work zone at I-81 North in Abingdon could not be used in the analysis, as this was the only study site where the normal speed limit of 104.6 km/hr (65 mi/hr) was reduced to 72.4 km/hr (45 mi/hr), and these data could not be compared with the data for the remaining sites as they were all reduced from 104.6 km/hr to 88.5 km/hr (65 to 55 mi/hr).

Camera Data

The average and 85th percentile speeds at Stations 2 and 3 were tested, and no significant difference was found between any of the messages with regard to these statistics. Based on the results of all of the tests, which indicated that there was no significant difference at $\alpha = .05$ among the average and 85th percentile speeds for the four different messages, Null Hypotheses 1 and 2 were not rejected for both Station 2 and station 3 speed comparisons.

Whole Population Data

In the first set of tests, ANOVA was used to determine whether there were significant differences in the data obtained when the data collection team was present and not present at the work zone. At a significance level of $\alpha = .05$, it was found that there was no difference in the average speeds, 85th percentile speeds, and speed variances at either Station 2 or 3 under the two different conditions. In light of these results, the presence of the data collection team was not considered a bias in favor of the CMS when judging its effectiveness. Null Hypotheses 3 through 6 were therefore not rejected for each of the speed characteristics at both Stations 2 and 3.

The results of the ANOVA conducted to assess the effect of each message on speeds as compared with speeds when not using the CMS indicate that the messages YOU ARE SPEEDING SLOW DOWN and HIGH SPEED SLOW DOWN are the most effective

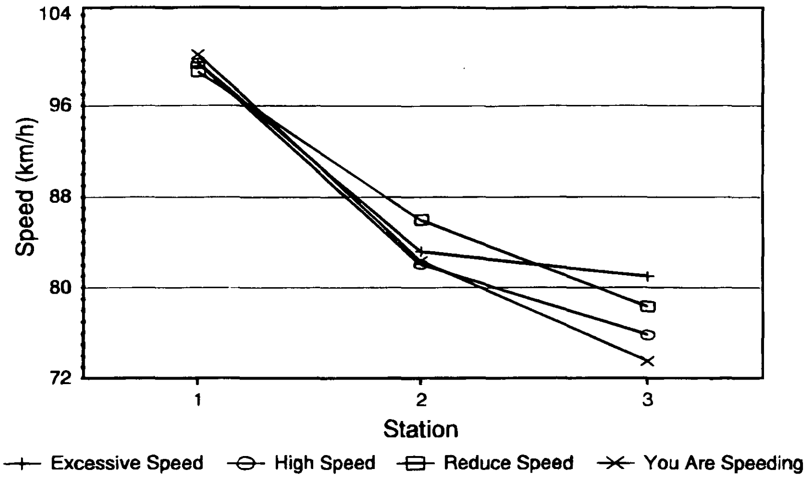

FIGURE 4 Average speeds calculated from camera data for I-81, South Buffalo Gap (threshold speed limit = 93.3 km/hr; posted speed limit = 88.5 km/hr; 1 km = 0.6 mi).

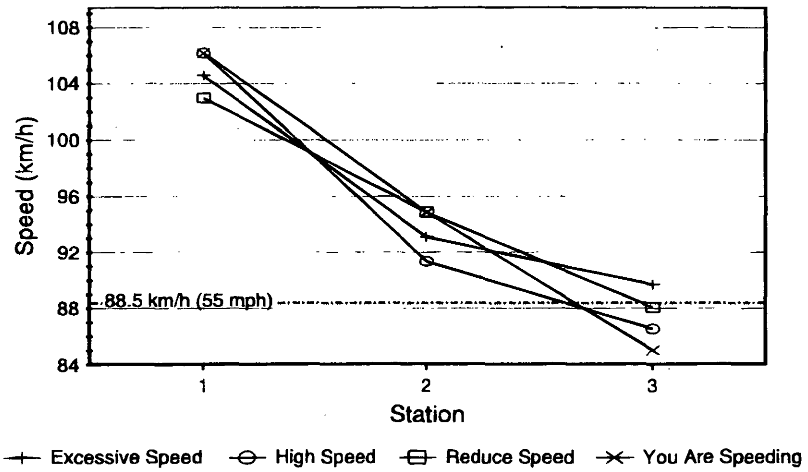

FIGURE 5 85th percentile speeds calculated from camera data for I-81, South Buffalo Gap (threshold speed limit = 93.3 km/hr; posted speed limit = 88.5 km/hr; 1 km = 0.6 mi).

of the four messages. They both show a significant reduction in average speeds at Stations 2 and 3 with the use of the CMS. Null Hypotheses 8 and 10 were therefore rejected for average speeds at both Stations 2 and 3.

Each of the remaining two messages had significant differences at one station only. For the message EXCESSIVE SPEED SLOW DOWN, there was a significant difference in average speeds at Station 3, and for REDUCE SPEED IN WORK ZONE, the significant difference in speed was at Station 2. These results might indicate that drivers are not responding to the messages in a consistent manner. In other words, the messages may not be as influential or forceful as the first two messages or make as strong an impression on all drivers as desired. For example, in using the message REDUCE SPEED IN WORK ZONE, there is a significant reduction in average speeds between Stations 1 and 2, but speeds rise again before the end of the work zone. This occurrence suggests that the message may not have had a lasting impression on drivers as they traveled through the work zone. Based on these results, Null Hypothesis 7 for average speeds was rejected only at Station 3, and Null Hypothesis 9 for average speeds was rejected only at Station 2.

The results also show that all of the messages are effective in reducing the 85th percentile speeds of vehicles traveling through the work zone. When compared with the 85th percentile speeds for the control condition without the CMS, all of the differences were found to be significant at $\alpha = .05$. Thus, Null Hypotheses 7 through 10 were rejected for 85th percentile speeds.

For comparisons of speed variance between no CMS and the four messages, EXCESSIVE SPEED SLOW DOWN was the only message that did not have significant differences in variance at Stations 2 and 3. Thus, Null Hypothesis 7 was not rejected for speed variance at both stations. When all of the results thus far are considered together, this message appears to be the least effective of the group. The remaining three messages were effective in significantly reducing speed variance when compared with conditions when the CMS was not in use. Thus, Null Hypotheses 8 through 10 were rejected for speed variance at both Stations 2 and 3.

The results of the comparisons of the percentage of vehicles speeding by any amount confirm the trends that were illustrated in the earlier results. All of the messages were effective in reducing the total number of speeding vehicles. Null Hypotheses 7 through 10 were therefore rejected for the percentage of vehicles speeding by any amount at both Stations 2 and 3.

CONCLUSIONS

The following conclusions are made based on the literature search and the results of the analyses.

- The changeable message sign with a radar unit is a dynamic speed control measure that is more effective than the static MUTCD signs in altering driver behavior in work zones. The use of personalized messages to the high-speed drivers makes these drivers more inclined to reduce vehicle speeds in these zones.
- Upon testing the CMS at seven sites on interstate highways in the state of Virginia, it was found that the CMS is an effective means of reducing vehicle speeds and speed variance, thereby increasing safety in work zones.
- When directly compared, it was found that there were no significant differences between the four messages with regard to their effect on high-speed vehicles as well as the whole population.

RECOMMENDATIONS

The CMS with radar unit is recommended as an effective speed control device to be used in work zones on interstate highways. In addition to reducing speeds, it is also effective in reducing speed variance, which could result in overall safer conditions in the work zone.

The following guidelines are suggested for using the CMS:

- The threshold speed should be set at approximately 3 mi/hr over the posted speed limit to warn drivers that they are exceeding the safe speed in the area.
- The CMS should be placed just before the beginning of the transition area, unobstructed by other signs so that it may be easily read and obtain drivers' full attention.
- When there is a taper and traffic is funneled into a single lane, it is suggested that the CMS be placed so the radar will detect only one vehicle at a time and the display be seen clearly by that one vehicle. If more than one lane of traffic is allowed through the activity area, the CMS should be placed so that drivers on both lanes can easily see the display board.
- The message **YOU ARE SPEEDING SLOW DOWN** is recommended for the display as it obtained the best response from the driving public. **HIGH SPEED SLOW DOWN** may also be used and will obtain virtually the same results.
- This study determined that the CMS is effective in work zones for short term applications, up to 1 week at a time. To assess its effectiveness for longer periods, it is recommended that a similar study be carried out to determine its effectiveness in long-term applications.

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