MULTI-OBJECTIVE OPTIMIZATION OF INTERSECTION AND ROADWAY ACCESS DESIGN

John T. Taber
Principal Investigator,
Utah Transportation Center
Utah State University

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DISCLAIMER

ABSTRACT

Poor site design of driveway access and intersection points is a major cause of accidents and traffic congestion. The reasons such poor designs are permitted to occur often can be attributed to lack of concern before major growth occurs in adjacent development and traffic volumes; developer and political pressure, especially where there is a lack of consistent design regulations; a lack of knowledge of design criteria; and focusing on only one of several measures of effectiveness.

This research developed a methodology to optimize roadway access intersection design using an expert system to guide design in accordance with published criteria, a graphical multi-criteria evaluation system, which revealed marginal impacts of changing design parameters across three objective functions (delay, safety, and cost); and intelligent techniques, which suggested design parameter changes and found optimal solutions.

Access intersection designs, exhibiting different roadway characteristics, were analyzed at three sites. Optimal designs were developed by the decision support system by changing several design parameters — lanes, turn lanes, control devices, signal timing/phasing, and intersection spacing. For each case, the trade-off between the different objective functions were shown.

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EXECUTIVE SUMMARY

This research developed a methodology to optimize roadway access intersection design using an expert system to guide design in accordance with published criteria; a graphical multi-criteria evaluation system, which revealed marginal impacts of changing design parameters across three objective functions — delay, safety, and cost; and intelligent techniques, which suggested design parameter changes and found optimal solutions.

Access intersection designs, exhibiting different roadway characteristics, were analyzed at three sites. Optimal designs were developed by the decision support system by changing several design parameters such as lanes, turn lanes, control devices, signal timing/phasing, and intersection spacing. For each case, the trade-off between the different objective functions were shown. Most importantly, in each case, more optimal results were generated by the methodology rather than by human manual methods.

In summary, the research work conducted in this project for optimization of intersection design resulted in the following findings:

(1) A high-level architecture has been established that supports a wide variety of evaluation models and provides a great deal of flexibility to incorporate new models that may be developed in the future.

(2) The expert system component of the model highlighted design exceptions that might otherwise be overlooked in a conventional manual design or review analysis.

(3) A computerized approach allows for fast, integrated comparisons between different design alternatives. It was found that evaluation of 32 design alternatives was approximately 1 second. Thus, the system can evaluate more than 25,000 alternatives in about the same time as manually evaluating one alternative.

(4) The multi-objective analysis incorporates quantifiable trade-offs of safety risk and cost, generally treated only as qualitative measures. This permits a more thorough analysis and justification where geometric improvements are required, but may not affect delay.

(5) Intelligent optimization methods generate a wide range of alternative designs, avoiding limitations that might be caused by an preconditioned biases.

(6) The high sensitivity of the objective weighting parameters resulted in a high level of uncertainty around the calculated “z” value. Thus, interpretation of optimal solutions should consider other designs that have a “z” value close to the optimal solution. The system’s display of each solution makes this possible.

(7) The use of goal programming techniques with the A* search technique resulted in a reduced, manageable set of optimal solutions, even though the complete set of valid solutions was quite large.

The test case studies have shown that optimization of access intersections can provide for increased benefits from conventional manual design or review analysis. The research has shown that the optimization process can adhere to and even promote the four main principles of access design: limit access points, separate conflict points, remove turns from thru traffic, and promote signal progression.

CHAPTER 1

INTRODUCTION

Managing the increasing traffic congestion and safety issues that occur in growing areas is one of the most pressing worldwide issues. Congestion and accidents often occur because of conflicting traffic maneuvers at roadway intersections where design and operation are comprised of a complex set of parameters, which include number of traffic lanes, number and length of turning lanes, spacing between access or intersection points, and traffic control devices. Congestion and safety issues often are the result of inadequate design of the access and intersection points, which often are established in the early stages of adjacent roadway development when such inadequate designs are not noticeable or given much importance. Poor site intersection designs also can be attributed to developer and political pressure, especially where there is a lack of consistent design regulations, a lack of knowledge of design criteria, and the focus is only on one of several measures of effectiveness. Poor site design of driveway access and intersection points is a major cause of accidents and traffic congestion.

Much of the current highway system is rural. More than 70 percent of the non-interstate highway mileage on the proposed National Highway System (NHS) currently does not have any access control (Gorman, 1993). More than 56 percent of the mileage is only two-lane and likely to require capacity improvements to handle growing traffic volumes. As land develops along these roadways, there is a demand for ingress to and egress from the highway, which, in virtually all cases, occurs at surface intersections.

When traffic volumes are low on the main roadway or adjacent land development is sparse, access intersections do not pose much of a problem and the need for adherence to design criteria is less apparent. However, as traffic volumes or land development increases, access intersections play an increasing role in the safety or capacity of the main roadway (see Figure 1.1). In addition, when adjacent land parcels

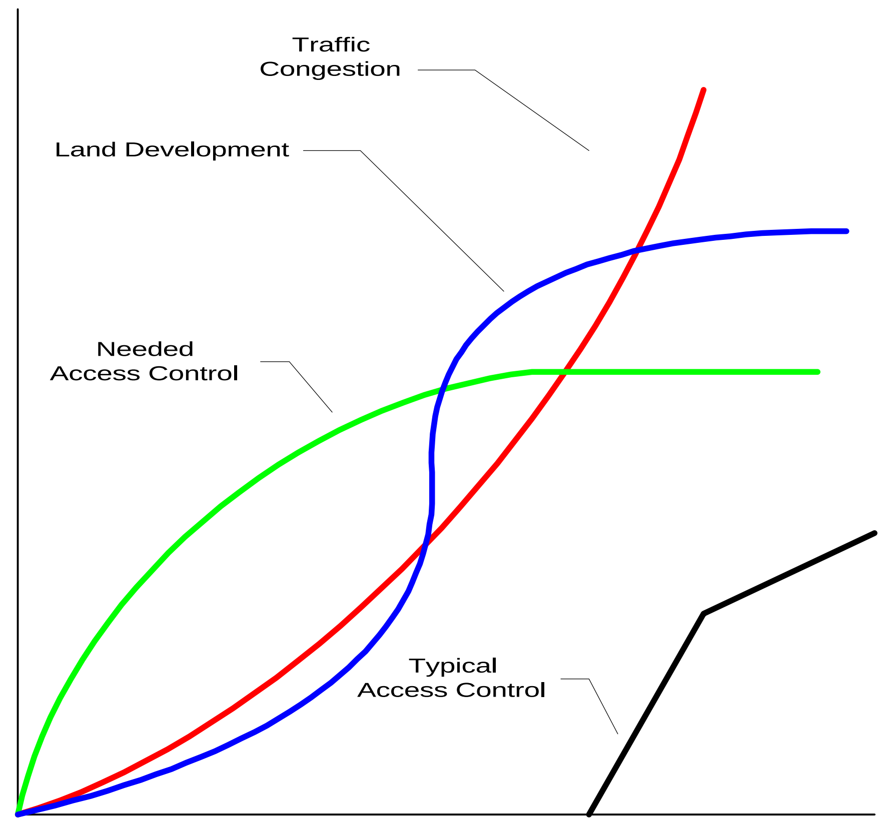


Figure 1.1 Relationship of development, traffic congestion, and remedial highway measures.

develop and access proliferates, highways often become multi-functional, serving both high-speed long-distance traffic and local access-oriented traffic. This leads to traffic safety conflicts, traffic congestion, and delay.

Traditionally, most decisions for approval and design of highway access points and intersections are based on locally available criteria and analysis tools that are limited in terms of evaluating site-specific measures of effectiveness. The trade-off between measures such as motorist time delay, safety, air pollution, and cost are evaluated subjectively, if at all. Even though the costs of not selecting the optimal design may be extremely high, the current process all too readily accepts designs based on judgments by one or two individuals.

If performed, existing methods of site or driveway access review generally are limited in scope. This practice has several principal limitations:

- There often is an over-reliance on experience rather than documented criteria because published information is scattered and may be unknown, not easily accessible or retrievable.
- Because of the many design parameters involved, most current procedures may not find the optimal design for the specific site location. Even a simple four-way signalized intersection can have nearly unlimited (i.e., over 10^{15}) acceptable alternative designs.

The penalty for accepting sub-optimal designs can be great. Accumulated motorist delay may be enormous, safety may be compromised, congestion and air quality may be worsened, and construction and maintenance costs may be increased.

The overall goal of this research is to develop an efficient methodology for designing optimal access intersections and incorporating multi-objective evaluation techniques to examine the trade-off between delay, risk, and cost. The process includes a rules-based expert system — heuristic rules based on published criteria in applicable manuals and research reports; the evaluation of three objective functions: average vehicle delay, intersection accident risk, and intersection construction costs; and intelligent processes to assess the objective functions and the remaining search space of valid alternatives and to what degree design parameters should be altered and reevaluated. To demonstrate this approach to improving design, several example case studies of actual roadway access points were tested and results have been shown.

CHAPTER 2

BACKGROUND

While research on the proposed intersection and roadway access design model has been conducted in the fields of expert systems for roadway intersections, geometric design criteria for access management, intersection evaluation models, and artificial intelligence techniques for design problems, this combination of techniques to optimize intersection design has not been thoroughly addressed.

Much of the highway research has focused on criteria contained in three nationally-accepted publications: “A Policy on Geometric Design” (American Association of State Highway and Transportation Officials, 1994); the 1994 “Highway Capacity Manual” (Transportation Research Board, 1994); and the “Manual of Uniform Traffic Control Devices” (Federal Highway Administration, 1990). The publications correspond to the areas of highway design, capacity analysis, and traffic operations including pavement signs and markings. Since each publication has a different focus and is published by different sources, some criteria assumptions differ between manuals, leading to possible design confusion.

Expert Systems in Intersection Design

Expert systems can be defined as the application of computerized rules or knowledge to develop decisions or advice about a particular function or process. In essence, they replace or enhance the human “checking” or experienced thought process.

Much of the research work regarding the application of expert systems in the design of roadway intersections has concentrated on using heuristic rules based on deterministic equations, interviews with experienced traffic engineers, and procedures and criteria from the AASHTO Green Book (American Association of State Highway and Transportation Officials, 1994), HCM (Transportation Research Board 1994), and MUTCD (Federal Highway Administration, 1990) reference manuals.

Expert systems for signalized intersections have received much attention due to the complexity in optimizing traffic signal phasing and timing. Research by Zozaya-Gorostiza and Hendrickson (1987); Linkenheld, Benekohal, and Garrett (1992); Pattnaik, Rajeev, and Mukundan (1991); and Chang (1987) all have illustrated rule-based systems.

Rule-based systems also have been developed for analyzing geometric configurations at intersections. Morris and Potgeiter (1990), Bryson and Stone (1987), and Chang (1989) have used rule-bases for this analysis.

To correctly examine intersection design options, it also is necessary to evaluate and assess traffic operations. Ritchie (1990); Gupta, Maslanka, and Spring (1992); Chang and Huarng (1993); Bielli et al. (1991); and Elahi, Radwan, and Goul (1991) have proposed knowledge-based systems with most of the systems developed as prototypes, primarily tailored for freeway and arterial routing.

Several knowledge-based systems have been developed for safety or risk evaluation (Seneviratne, 1990 ; Gal-Tzur, Mahalel, and Prashker, 1993). Other transportation expert systems (Tyler, 1991) demonstrate the use of probabilistic decision analysis.

Verification of rule-based traffic engineering systems also has been addressed in previous research. Radwan et al. (1989) addressed expert system verification procedures in a static testing environment and proposed seven verification activities:

(1) Critique of literature

(2) Paper-based methodology check

(3) Heuristic approach analysis

(4) Formalize component program logic

(5) Test examples

(6) Test to literature base

(7) Problem domain conformance testing

Other procedures and recommendations suggested by the authors included assembling a diverse project review team; using simulation programs for additional testing; and during the formalization stage, performing a complete paper-based solution for the proposed tests. Demetsky (1992) also examined verification and validation procedures of rule-based traffic engineering systems, including the use of a rule-base shell to correct input errors and a second knowledge engineer, or computer scientist, to check structure for logic errors, and a problem-solving workshop.

Access Management Design Criteria

Driveway access is not regulated along much of the highway mileage with more than 70 percent of the non-interstate mileage that carries 40-45 percent of vehicular traffic having no formal access control (Gorman, 1993). During the last 10 years there has been a renewed research effort in restricting roadway and driveway access along highways, including the following roadway design elements: driveway separation, corner clearances, median openings, signal spacing, turn movement restrictions, right-of-way purchases, land use zoning, interior site design as related to access, and improved intersection geometry. States actively pursuing access management programs include Colorado, Florida, Oregon, New Jersey, and Wisconsin. Colorado (Demosthenes, 1993) has regulated access for more than 12 years. Access control is based on a roadway classification hierarchy that follows the functional purpose of the roadways, and ranges from interstate highways to local collectors. Florida (Frawley, 1993) regulates highway access by functional classification using seven levels with subdivisions by area and median type, and existence of frontage roads. Legislation for access management in New Jersey (Jennings, 1993; New Jersey Department of Transportation, 1992) specifies permitted access levels for each highway functional classification, with specific access requests guided by the access level.

Another form of an access control technique, “corridor preservation,” has been undertaken by the State of Delaware (Federal Highway Administration, 1993a). It attempts to maintain the traffic-carrying capacity and the safety of a highway corridor by a combination of land use planning, access restrictions, and right-of-way purchases for additional future capacity.

Research has found that access management techniques significantly reduce accidents and increase capacity along highway corridors. Demosthenes (1994) has calculated a 50-65 percent accident reduction on roadways with access control versus similar roadways with unmanaged access. Levinson and Kopeke (1993) have found that each commercial driveway adds 0.1 to 0.5 accidents per year with a one percent reduction in capacity. In addition, they found a 30-44 percent reduction in accidents following implementation of access management techniques. Sokolow (1993) has found that access control can produce a 43 percent increase in capacity in traffic levels on four-lane arterial highways at level of service "D" and an 88 percent increase in speed.

Research in access management techniques by Levinson and Kopeke (1992) and Stover(1993) included the establishment of design criteria regarding access intersections and intersection control. Walker (1993) examined design of intersections. Design criteria for driveway access intersections has been assembled in several publications (Gluck et al., 1995; Federal Highway Administration, 1993b). Other research in design criteria for turning operations was performed by Failmezger (1963) and Asante, Ardekani, and Williams (1993).

Evaluation Methods for Access Intersections

Highway access intersections can be measured using several measures of effectiveness such as vehicle delay, safety, capital cost, and air quality impacts. Specific techniques of measurement have been extensively researched, but not effectively combined.

The 1994 Highway Capacity Manual (Transportation Research Board, 1994) provides deterministic procedures for determining highway capacities, including special procedures for signalized and unsignalized intersections. The signalized intersection capacity procedures calculate average delays per vehicle by movement. The popularity of this evaluation measure has encouraged recent research efforts to develop calculations for average vehicle delay for unsignalized intersections, including work by Kikuchi and Chakroborty (1991); Kikuchi, Chakroborty, and Vukadinovic (1993); Kyte (1990); Kyte, Lall, and Mahfood (1992); and Rozic (1992).

Safety at intersections often is measured with historical traffic accident records by identifying existing intersections having a high number of incidents and developing accident rates, usually based on traffic volume. This methodology has several important drawbacks for analysis of existing or proposed access points: accidents occur infrequently and can be the result of a large combination of variables; it may be difficult to locate an intersection having similar characteristics with enough prior accidents to have statistically significant findings; and prior research has shown that historical accident analysis can be a poor predictor of future accidents (Glauz and Migletz, 1980).

Using traffic conflicts as a surrogate for traffic safety first gained widespread popularity in 1968 with research presented by Perkins (1968), followed with work by Baker (1972); Hayward (1972); Allen, Shin, and Cooper (1978); Glauz and Migletz (1980); Schuckel, Picha, and Parham (1997); Pietrzyk and Weerasuriya (1997); and Kaub (1996).

Other work that examined the variability of conflict analysis included Glennon et al. (1977); studies conducted by the Federal Highway Administration, State of Ohio, State of Washington, Transportation Road Research Laboratory, and City of Toronto; Zegeer and Deen (1978); (Yauch and Parsonson, 1978); and Hauer (1978).

Models based on the “risk opportunity” of total vehicle exposure in the intersection area and the number of conflict opportunities with other vehicles have been developed by Council et al. (1983), and Ha and Berg (1995). Fazio and Rouphail (1990) used the Intras microsimulation model as an alternative to performing extensive field data analysis.

Other Research in Intersections

Cost effectiveness for prioritizing intersection improvements was analyzed by Witkowski (1992a) and Witkowski (1992b) using a cost-effectiveness ratio of delay savings versus improvement cost.

The use of integrated models for driveway access is beginning to occur in research. Malek et al. (1996) developed a model combining a knowledge-based system with a traffic simulation model. Chung and Goulias (1996) developed a system integrating a regional planning model with a traffic simulation model. Long and Gan (1997) have developed a model for driveway corner clearances.

Evaluating Multiple Measures of Effectiveness

Three key measures of effectiveness in intersection design — delay, risk, and cost — have widely varying units of measure and, usually, conflicting relationships. Virtually all transportation intersection analysis and site impact reviews are quantitatively-based solely on vehicle delay, with possibly subjective commentary on safety and cost considerations. Attempts to measure safety and delay in terms of cost or cost benefit have been performed (Transportation Research Board, 1990; Witkowski, 1992a).

Evaluating multiple criteria in public projects by using goal programming was proposed by McKenna (1980) and Taha (1992). Other examples of multi-criteria decision making that used surrogate worth trade-offs were shown by Chankong and Haimes (1983); Chankong et al. (1980); and Haimes and Hall (1974). Feng, Liu, and Burns (1996) demonstrated the use of Pareto optimization for time-cost trade-offs in construction scheduling.

Optimization Techniques for Access Intersection Design

The application of expert systems and machine intelligence in engineering design can be described as developing in stages. Stage I systems dealt with creating simple rule-based systems that allow faster computations, encourage consistency, and reduce errors and omissions. Stage II refers to the use of mathematical optimization techniques with deterministic models that solve complex problems. Stage III systems are extending models that include machine intelligence to handle complex tasks and find optimal solutions.

Expert systems rely upon the inclusion of heuristic rules usually required by interviews with experienced professionals. This is a resource-intensive and time-consuming process.

> Traditional methods of manual knowledge acquisition are insufficient to deal with complex engineering problems. Progress in using decision support tools has been delayed in part due to the difficulties of knowledge acquisition. The solution to this problem is automated knowledge acquisition based on the use of learning systems. (Arciszewski et al., 1994, p. 286)

Kirkpatrick, Gelatt, and Vecchi (1983), demonstrated why heuristic-based systems can lead to suboptimal designs. If the system uses a divide-and-conquer solution approach, the optimum solution found for the subproblem may not form the optimal solution when the subproblems are patched back together. If the system instead uses iterative improvement, which is the procedure most often used in the traffic design process, it is likely to find a local optimum, rather than finding the ultimate global optimum solution. Even if the iterative process is replicated several times with random starting configurations, as in a simulation model, it is still uncertain that a global optimum solution is reached.

Another approach to knowledge acquisition systems is the use of case-based design, which uses satisfactory components from previous designs. Case-based systems (Maher and Balachandran, 1994) can be described by relation, function, behavior, and structure attributes, which are similar to the object-oriented approach to expert systems.

Highway intersections are complex entities, particularly intersections with signalized control. Thus, various models have been developed to optimize intersection traffic operations, including Passer-II (Malakapalli and Messer, 1993), Maxband-86 (Gartner and Hou, 1992), Passer-IV (Chaudhary and Messer, 1993) (and Transyt-7F (Cohen, 1983) for signalized intersections. Although not optimization models, several highway simulation models — Corsim (Federal Highway Administration, 1997), Intras, and Freevue (Hellinger and Shortreed, 1992) — have been developed that produce extensive evaluation measures for users to apply trial and error techniques to find optimal designs.

The current traffic control optimization models rely on human operation, which can easily induce error and non-optimal solutions. Stage III expert systems use machine intelligence to allow review checks to ensure optimal designs. Arciszewski et al. (1994) pointed out the increasing problem of misuse of software tools:

> The problem of selecting the proper type of wind bracing is particularly important when inexperienced designers use software tools for design and optimization; their lack of experience may lead to feasible designs that could be significantly improved through simple changes in configuration. (Arciszewski et al., 1994, p. 287)

To avoid the human bias, use data-driven or hypothesis-driven constructive induction, which creates new attributes based on applying operators to relationships found in the data (Arciszewski et al., 1994).

Beginning in the mid-1980's, early attempts at machine intelligent systems Stage II designs, found their way into the field of traffic engineering problems. Neural network systems have been proposed, primarily for data evaluation, such as pavement management, image processing, traffic flow prediction, driver behavior, and traffic operations as described by Lyons and Hunt (1992) and Faghri and Hua (1992).

The application of genetic algorithms to traffic signal timing was explored by Foy, Benekohal, and Goldberg (1992), Hadi and Wallace (1993), and Hadi and Wallace (1994).

Another stage II type machine intelligent process is simulated annealing, which seeks global solutions for combinatorial optimization problems and has been successfully demonstrated by Kirkpatrick, Gelatt, and Vecchi (1983). Applications for traffic signal timing have been demonstrated by Hadi and Wallace (1994), and Flann, Taber, and Grenney (1994).

CHAPTER 3

MODEL FORMULATION

Optimization of access intersection design involves computerizing many steps of the design process that are traditionally performed manually, including formation of initial design, generation of design alternatives, review of design feasibility, operational analysis of design, evaluation of alternatives, and acceptance of the best solution. Because of the large amount of design criteria and the many design alternatives that should be analyzed to ensure an optimized design, an efficient and time-responsive process requires the system to be computerized. A decision support system has been developed to accommodate the design process. The system has been structured to replicate each major component of the design process (see Figure 3.1). Much like the current manual process, the system first examines an initial design, which can simply be existing conditions, for adherence to design criteria. Criteria exceptions can be modified using manual adjustments or by allowing the system to use an intelligent design parameter swapping model.

Valid designs are tested by appropriate simulation models with results output to a graphical response function model that both graphs and performs multi-criteria analysis. Assuming that a design evaluation result is not accepted as optimum, results are sent to the swapping model to generate another alternative. The process continues until an optimum solution is reached or the complete set of valid alternatives is searched.

Initial Design

The access management decision support system requires an initial design to be placed in the system, which many times should be the existing roadway network or a proposed site access. A goal of

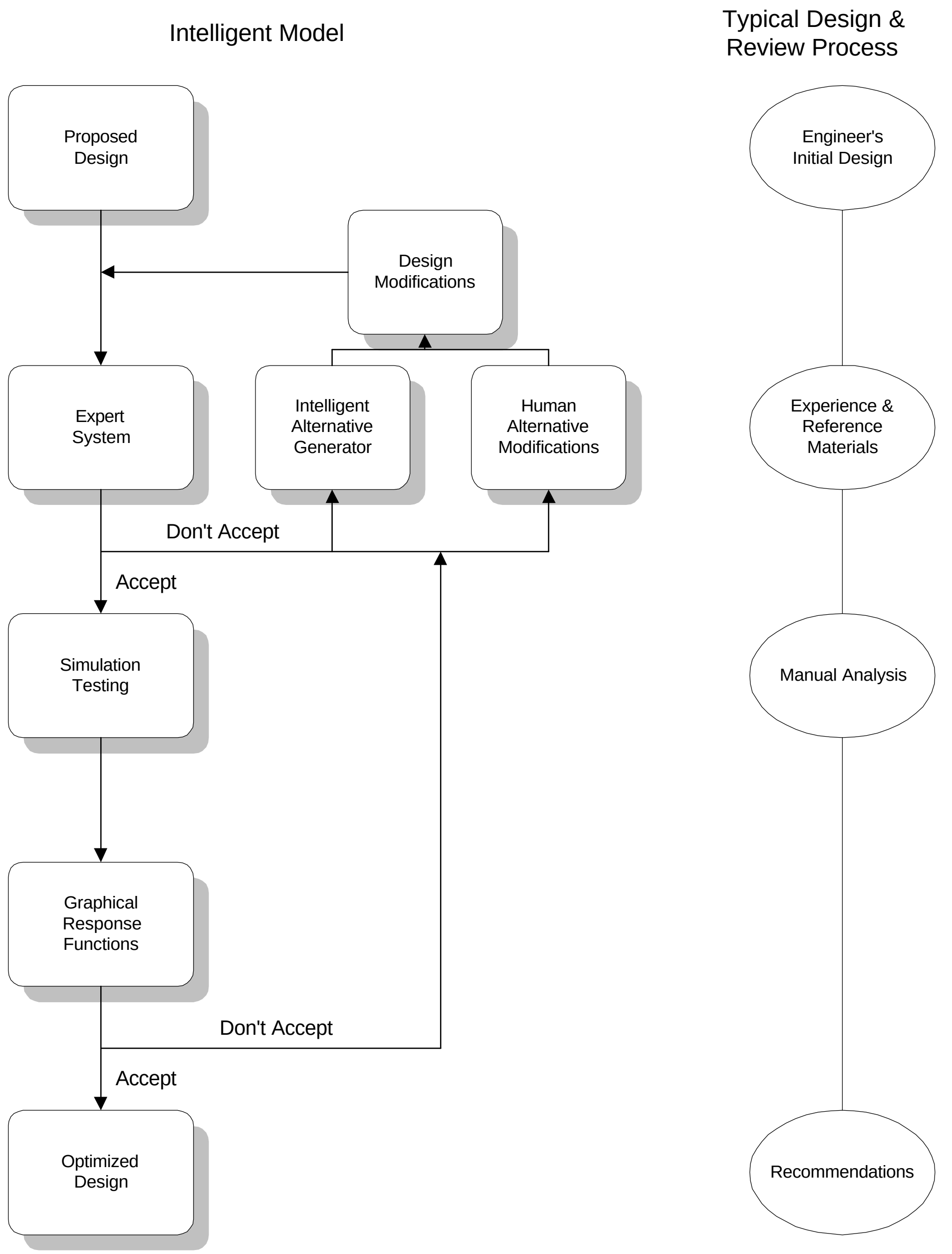
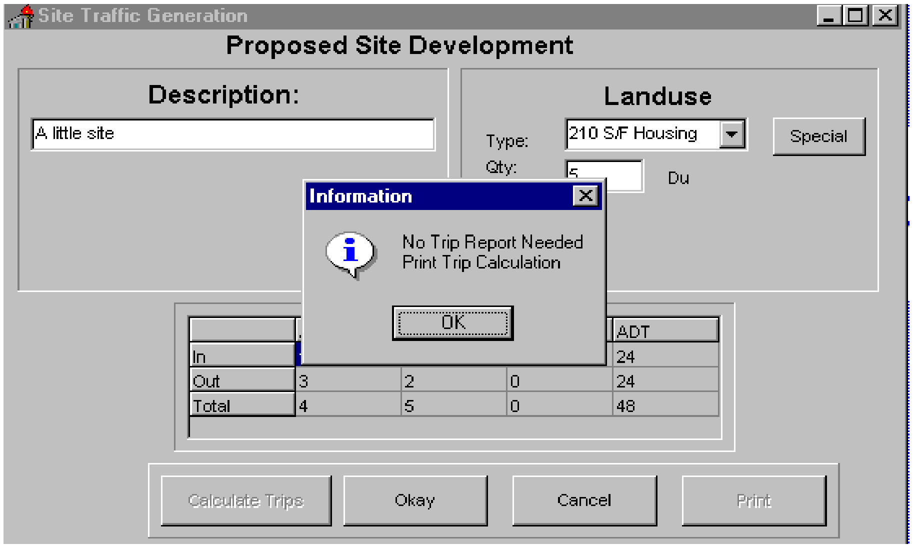


Figure 3.1 Proposed design process vs. traditional process

this research was to experiment with new computer technology to enhance user-friendliness and improve or lessen the data input process, which can be quite laborious. The decision support system was constructed to provide an easy-to-use modern windows graphical user interface, using two advanced software techniques — "wizard" templates and intelligent "smart forms" screen display — in accordance to selections made by the user.

For new design cases, the system begins with a series of templates of the most common access designs. This process of using preset templates is an application of using "software wizards." It is a common procedure in many commercial software packages, but currently not used in any traffic engineering software packages. The "wizard" creates an initial valid design alternative using preset default values. A smart form was developed to check for a minimum number of trips to require an access study (see Figure 3.2).



Description: A little site

Landuse

Type: 210 S/F Housing

Qty: 5 Du

Information

No Trip Report Needed
Print Trip Calculation

				ADT
In				24
Out	3	2	0	24
Total	4	5	0	48

Figure 3.2 Smart Forms

Review of Design Feasibility (expert system rule-based module)

Current design review practice relies heavily on a manual review, typically performed by an individual engineer. This process results in an over-reliance on the "experience" of a single individual rather than documented criteria, and can result in unsatisfactory designs being approved if the individual is not highly experienced in traffic design criteria or unaware of the many various design guidelines. Often, published design criteria information is scattered among publications and not always easily accessible or retrievable.

To minimize the opportunity for invalid design alternatives being accepted, the decision support system includes an expert system and knowledge rule base to evaluate alternative design values according to design criteria contained in the rule base. The rule-based decision-support module is based on using a forward-chaining procedural approach with a knowledge database of if-then rules constructed from an exhaustive search of reference manuals, publications, and surveys of experienced traffic engineers. The knowledge rule base contains reference information for each rule, which specifies the publication and location for the design criteria the rule is based on.

The knowledge base constructed in this research includes criteria specified by the Utah Department of Transportation (Utah Department of Transportation, 1994a). In conditions where no generally accepted criteria are available, design criteria for one jurisdiction will be selected and noted in the reference. Knowledge-base rules are formatted in an if-then construct using data fields for each subject, operator, and value. This allows rules to be kept in an object file for easy additions, deletions, and modification.

The expert system permits the option for an interactive approach, which allows manual design changes to immediately be checked against the rule base with on-screen exception reporting. Options for acceptance and exception reporting to a database are included, along with on-screen and printed output reporting.   If the tested access design fails to meet a criterion item with a “Stop” indication, the design alternative is considered an invalid design and is not considered in the optimization process.

Another important component in this research demonstrates the use of multi-media technology's assistance in the design process. To assist the user in correcting or modifying an access intersection design, several reference tools are built into the exception reporting dialogs. A reference button activates a windows help file that has been constructed to contain excerpts from prominent publications on access management and allows the user to read the context of the design criteria used in the rule. Capability also is provided for video and audio clips to more clearly illustrate important criteria. A link to the metric/English roadway design calculator, Hypercalc, also is provided to assist in evaluating the design relative to the criteria.

Operational Analysis of Design

It is important to establish a relevant and efficient system that measures the effectiveness of roadway access designs. Traffic engineering decisions often are made on the basis of only one of several categories of measures — delay, safety, environmental, or cost. This is partly due to a lack of good engineering tools that examine the trade-offs between the different measures. A traditional method of evaluating traffic operations is to analyze "measures of effectiveness" (MOE). Commonly-used measures usually include vehicle delay, vehicles stopped, stopped vehicle queue lengths, and average speed. Other important measures, such as safety and roadway construction costs, usually are applied in a more qualitative rather than quantitative manner due to the current lack of standard ways of measuring them.

For this research effort, three measures of effectiveness were represented as traditional measures used throughout the traffic engineering profession. The measures used were total average vehicle delay along the study corridor, which is the weighted average of average vehicle delay along each link; accident risk by level of severity; and construction cost of added geometric improvements. Although air quality measurement can be an important measure of effectiveness, it was found in discussions with state Transportation Department representatives that if the study location was in an area of U.S. Department of

Environmental Protection Agency (EPA) designated “attainment” status, then air quality would not generally be an issue that most officials would consider, while if the area was designated “non-attainment,” then the applicable air quality measure would simply be a binary accept/reject decision. Thus, for purposes of this research, air quality was not included as a decision variable.

A set of simulation models has been developed to generate the specified measures of effectiveness and is described more fully below.

Vehicle Delay

Vehicle travel delay can result along uninterrupted roadway sections, primarily due to speed differentials where passing is not possible or where geometric restrictions create a lower operational capacity, and from interrupted flow due to traffic control devices. Since this research is focused on access intersection design, vehicle delay only is considered in the vicinity of intersections and includes the associated delay due to conflicting turning movements, traffic control devices, and acceleration and deceleration.

The methodology to calculate delay at each intersection type is derived from commonly used deterministic procedures in the 1994 “Highway Capacity Manual” (Transportation Research Board, 1994, Webster and Cobbe, 1966) and the Australian “Guide to Traffic Engineering Practice” (Austroads, 1991, Troutbeck, 1992). The procedures are based on regression analysis of surveyed intersections. They calculated vehicle delay and queuing for each directional movement.

Traffic Accident Risk

Traffic safety is a major issue in the design of roadway access, yet it is usually dealt with in a subjective, non-quantitative manner, based on the engineer’s judgment or adherence to typical design criteria. Hauer (1988) illustrated that traffic engineers “have neither faced up nor lived up” to the responsibility of traffic safety. As Hauer argued, there is a wide lack, but strong need, to relate roadway design to projected traffic safety. Since traffic safety impacts of roadway access design can be measured by determining the risk of accidents, this research has formulated and included a risk analysis model. Although many of the risk components require additional research beyond the scope of this study, the model provides a relative indication of the projected safety risk of various design alternatives.

According to Blockley (1992), determination of engineering risk must consist of likelihood, consequences, and context. Likelihood is the measure of probability that an accident will occur. Consequences are the tangible impacts should an accident occur. Context is how society values the likelihood or consequences of accidents. Even with a high incidence of one of these elements, without the other two, the risk is still insignificant. For example, even if the likelihood of an accident is high, if the consequences are negligible or if people just do not care or value it highly, the risk is not great. Risk assessment has been used successfully to evaluate designs and expenditures in other fields, such as water dams, and assessment can follow procedures set out by Bowles, Anderson, and Glover (1996).

The determination of accident likelihood is highly complex and is not well understood. While it is attractive to measure accident likelihood based on historical information, previous discussion has shown that predictions are not usually that statistically significant because of the random nature of reported accidents. While conflict opportunities seem to be a better determination of likelihood, it is unfortunate that pure conflict opportunity measures for certain movements will dominate other movements and will unlikely be in proportion to risk. For example, as developed by Council et al. (1983), head-on collision opportunities will be the product of the total traffic on the main thru street, which can be a large number, but the actual likelihood of cross-over collisions is quite low compared to angle collisions where conflict opportunities may be lower. Council et al. (1983) have tried to address this concern with a conflict type specific weighting factor. This is similar to using propensity as a factor in determining likelihood, as explained later in this chapter.

This research has used the conflict analysis approach and merged it with a comprehensive risk management model. Using the three elements of risk analysis — likelihood, consequences, and context — a combined risk analysis equation can be formulated:

$$\text{Total Risk} = \text{Likelihood} * \text{Severity} * W_{(\text{Context})}$$

where:

$$\text{Likelihood} = \Sigma\,(\text{Conflict Opportunities} * \text{Propensity} * \text{Accident Rate})$$

The likelihood of risk occurring at intersections can be developed by identifying all conflicting movements and multiplying them by the propensity of each conflicting movement to be an accident. A four-leg intersection has a total of 40 possible conflict points. Closely-spaced intersections in functional boundaries have additional conflict points (see Figure 3.3).

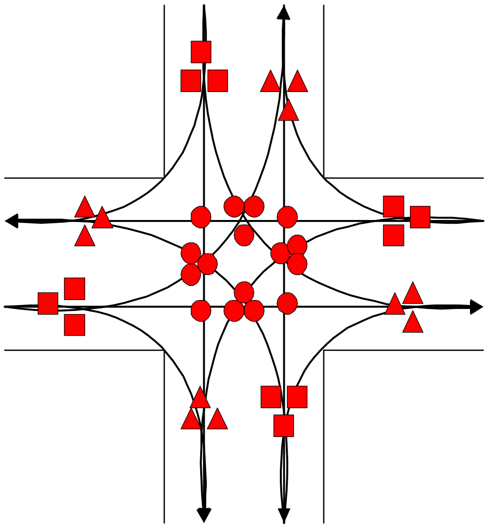


Figure 3.3 Intersection Conflicts

While conflict opportunity equations were developed by Council et al. (1983) for various types of movements, intersection control, and conflict types, research by others indicates the most predominate conflicts are limited to several basic types. Zegeer and Deen (1978) found that three types of conflicts — traffic backup, slow for left-turn, and slow for right-turn, which are all mostly rear-end types — accounted for 80 percent of all conflicts (measured intersections were signalized). Accident record and conflict analysis by Glauz and Migletz (1980) indicate that the predominate types of intersection accidents are opposing left-turns and cross-traffic, or side-angle types. A review of accident records by Council et al. (1983) showed major types of accidents to be predominately angle, cross-traffic, rear-end, pedestrian, and single vehicle to fixed object. Baker (1972) narrowed the conflict types to weave, left-turn head-on, cross-traffic, and rear-end. Although pedestrian conflicts were not included in this research, the high liability exposure makes this category important in an overall risk calculation where pedestrian movements are allowed or frequently occur. Based on the research studies discussed above, rear-end and side-angle conflicts are the most prevalent types of intersection collisions, and thus both types have been measured in this research and selected as representing the safety of an intersection.

Determination of conflict opportunities is based on equations developed by Council et al. (1983) and Ha and Berg (1995), for both rear-end and side-angle conflicts. Side-angle conflicts in roundabouts occur where entering vehicles collide with vehicles traveling in the roundabout or, in the case of multi-lane roundabouts, vehicles cross paths when entering or exiting. Estimation of potential side-angle conflicts in roundabouts is complex and for purposes of this research has been assumed to reflect the same characteristics of an uncontrolled approach of a two-way stop-controlled intersection.

To determine the likelihood of traffic accident risk, the number of conflicts must be multiplied by their respective accident rates. As previously discussed, prior research has not shown reliable accident rates based on conflict analysis. Rates have been developed (Ha and Berg, 1995) for side-angle and rear-end conflicts based on several field studies of 0.054 accidents/conflict for left-turn side-angle conflicts and 0.00049 accidents/conflict for rear-end conflicts. Glauz and Migletz (1980) found a rate of 0.021 accidents/conflict based on actual measure conflict avoidance maneuvers, which should be less — meaning the rate is higher — than potential conflict opportunities. In calculating conflicting traffic volumes, the decision support system also checks not to double count movements.

Based on a typical intersection volume of 16,850 vehicles/day and an accident rate of 0.0003 accidents/conflict, a typical intersection would yield approximately six accidents per year. This compares favorably to regional rates of 0-20 accidents per year and average intersection accident rates of 2.69/million vehicles (Plass and Berg, 1986). However, it is again noted that these rates only provide a relative measure and require additional research beyond the scope of this project.

An important element in the calculation of overall risk is the consequence of accidents. Consequences of traffic accidents can be measured in terms of severity. Although heavy traffic, conflicts, and erratic maneuvers can be stressful and increase driver workload, people just do not seem to be overly concerned until a physical accident occurs (see explanation of context). Zegeer and Deen (1978) listed seven levels of traffic event severity: traffic flow, routine conflicts, moderate conflicts and erratic maneuvers, severe conflicts and near-miss accidents, minor collisions, property damage accidents, injury accidents, and fatal accidents. Currently, accident reporting is categorized into several levels of severity with three of the major groupings being property damage, injury, and fatality. For purposes of this research, three categories have been maintained and are expressed as levels 1-3 with level 1 being the most severe.

While there are other factors that can affect severity (i.e., wearing seat belts, etc), the collision magnitude traditionally has been assumed to be a good surrogate of severity. Most technical collision analysis is based on kinetic energy calculations (mass multiplied by velocity squared), for example: KE(fatality) > KE(injury) > KE(property). While some analyses (i.e., Ha and Berg, 1995) have assumed values for collision speed and vehicle mass, this approach correctly requires traveling speed and mass distributions of colliding vehicles, something that statistically is difficult to determine. Instead, for purposes of this research, percentages of severity have been determined, by accident type (rear-end, side-angle). It was estimated that severity levels for rear-end accidents are approximately 70 percent property damage, 25 percent injury, and 5 percent fatal. Side-angle collisions have rates of approximately 50 percent property damage, 45 percent injury, and 5 percent fatal (Utah Department of Transportation, 1997).

Finally, the context of the risk must be considered. Although non-accident conflicts and erratic maneuvers can be stressful and increase driver workload, people do not appear to be overly concerned until a physical accident occurs. Since all vehicle accidents involve human beings — unmanned vehicles do not travel around yet! — and virtually all people travel on roadways, it can be assumed that accidents are viewed as important to the overall public and a high value can be placed on the risk of accident. It should be noted that certain traffic accident events involving children and bus accidents seem to have a higher impact value on the public. A measurement of this impact, via surveys, is beyond the scope of this research.

Capital Cost

The cost of an intersection based on a given design is often a limiting factor in terms of minimizing vehicle delay and maximizing safety. Intersection construction costs can range from several thousand dollars for simple restriping to millions of dollars for overpasses; thus, methodology to minimize cost is critical to efficient design.

For purposes of this research, only capital design and construction costs are considered. Although some designs can affect operating costs (i.e., median islands affect snowplowing costs), it has been assumed that capital costs are the predominate factor in decision making. In the decision support system, average capital improvement costs are accrued when certain design parameters are changed to add physical facilities to the system such as additional lanes, signal control devices, turning lanes, or channelization. Costs are determined by simply multiplying the occurrences of each design parameter times predetermined average unit costs. Average unit costs have been obtained from local engineering estimates and are expressed in 1996 dollars (see Table 3.1). Costs are added for each intersection and can be measured for each access intersection as well as a system total.

Evaluation of Alternatives (Multi-Criteria Decision Analysis)

There are many popular approaches to performing multi-criteria decision-making analysis. Approaches most applicable to this research include: scaling, which involves the translation of each criteria to a common denominator unit of measure; weighting, which applies importance weights to each criteria; decision rules, essentially a weighting method; exclusionary screening, which excludes alternatives if one of the criteria fails pre-established boundary conditions; concordance, whether weighted results exceed pre-established thresholds; goal programming, which uses initial weights to find a solution set, and then moves in the solution set to achieve pre-established goals; compromise Programming, which seeks to minimize distance to the ideal point between criteria; surrogate worth trade-offs, which measures secondary trade-off's worth, to a primary objective for each alternative; and computer graphical techniques, displaying the visual trade-offs between solutions.

Table 3.1 Unit Improvement Costs

Improvement Type	Cost ($)
Right-turn Lane	$ 45,000
Left-turn Lane	40,000
Thru Lane	75,000
Signalization	100,000
Signal Phasing Changes	25,000
Restriping	5,000

A combination of several of the above techniques — scaling, weighting, graphical analysis, and goal programming — appears to offer the best approach for conducting trade-off analysis. In the traffic engineering profession, decision-making tends to use boundaries or thresholds rather than firm values. While measurements of delay can be firm, decisions usually are based on minimum levels of service. For the most part, safety decisions rely on overall levels. For example the potential for several accidents might be tolerated, but the potential for multiple accidents or any fatalities might not be tolerated. This implies that using thresholds appears to offer the best means of evaluating multiple criteria for traffic engineering designs, leading to the applicability of goal programming. The objective function can be expressed as:

$$\text{Min } Z = \Sigma\,(Dw_d s_d p_d g_d + Sw_s s_s p_s g_s + Cw_c s_c p_c g_c)$$

where:

D = delay

S = safety risk

C = cost

w = parameter importance weight

s = parameter scaling factor

p = penalty factor for exceeding goal

g = distance from goal

This formulation produces a trade-off analysis by seeking to minimize the distance from the established goals for each measure of effectiveness.

The measures used in this research have a wide range of values (i.e., delay time, which can range from 0 to 100+ seconds per vehicle; safety, which can range from 0 to 1000+ conflicts per day; and cost, which can range from 0 to over $1,000,000). Thus, scaling factors have been developed to compare all measures on a single scale of 0-100. The default scale factors are as follows:

Table 3.2 Scaling Factors

Measure	Scale Factor
Delay	1.00
Cost	0.10
Safety Risk	0.06

Weighting factors also are assigned to the three measures of effectiveness used in the trade-off analysis. The default weights used are subjective and represent the importance that each measure has to the public. The weights can be changed easily by the user of the computer program. The default weighting values are:

Table 3.3 Weighting Factors

Delay	0.60
Risk 1	0.10
Risk 2	0.10
Risk 3	0.10
Cost	0.10

Goals and their respective penalties should reflect society's acceptance of the measures of effectiveness, or objective functions. For this research, penalties have been assumed to be a three-step function representing society's tolerance of slightly exceeding the safety goal, but intolerance at some higher level of exceeding the goal. The first step reflects any penalty for being less than or equal to the goal. Since the goal for each objective function in this research is zero, the penalty for being less than or equal to is zero. The second step in the penalty function reflects values between the goal and the acceptable limit. The third step drastically penalizes any solutions that are beyond an acceptable limit.

It is reasonable to assume goals for average vehicle delay to correspond to levels of service, as established in the 1994 HCM (Transportation Research Board, 1994). Service levels A-C are generally accepted as desirable, “D” is tolerated, but levels “E-F” generally are not acceptable. Obviously, zero delay would be ideal; thus, the target goal for delay was established as zero, with a slight penalty for delay up to the “D-E” boundary — 40 seconds for signalized intersections, 30 seconds for stop-controlled intersections. Goals for safety risk are not well established and would depend on local preferences. For this research, estimates were made of maximum levels where public outrage would be expected. Goals for cost amounts also are a local condition; however, estimates were made of maximum levels where developers would be outraged or that development would occur. For example, hypothetical goals could be 25 seconds or less of delay (LOS=C), less than five injury accidents per year, and construction cost of less than $250,000.

Generation of Design Alternatives (Intelligent Parameter Swapping)

The number of theoretical combinations of design parameters in a highway corridor is well beyond the scope of this research. For example, a simple intersection can have more than 10^{15} possible design element combinations (Flann, Taber, and Grenney, 1994). To evaluate design combinations in such a large search space, an intelligent search agent module was developed. The structure of the intelligent module is based on the criteria of an ideal rational agent, which is defined as having the ability to take necessary actions to maximize its performance measure using its precept sequence and built in knowledge (Russell and Norvig, 1995).

For this research, the intelligent search agent evaluates changes in three key design parameters: lane configuration, access intersection spacing, and control device type. Furthermore, since the spacing parameter has infinite incremental intervals, the intelligent module increments distance between access intersections is 15 m.

The intelligent agent module developed for this research is based on the A* Search procedure, which combines an evaluation function with a heuristic function. Heuristic rules, based on typical traffic engineering judgment, rank the alternative designs to create search paths not to be exceedingly restrictive, but to discourage random designs that are impractical from engineering practice. The running speed of the model (including the various simulation models) restricts the number of design alternatives that can be practically evaluated (i.e., less than about 10,000 evaluations on a typical personal computer).

Table 3.4 Change Operators for Intelligent Parameter Swapping
(1) Change to Signal
(2) Change to NS Stop
(3) Change to EW Stop
(4) Change to All-Way Stop
(5) Change to Roundabout
(6) Move access 15 m. upstream
(7) Move access 15 m. downstream
(8) Move access to nearest opposite T intersection
(9) Add NB left-turn lane
(10) Add NB left-thru lane
(11) Add NB left-thru-right lane
(12) Add NB thru lane
(13) Add NB thru-right lane
(14) Add NB right-turn lane
(15) Add EB left-turn lane
(16) Add EB left-thru lane
(17) Add EB left-thru-right lane
(18) Add EB thru lane
(19) Add EB thru-right lane

(20) Add EB right-turn lane
(21) Add SB left-turn lane
(22) Add SB left-thru lane
(23) Add SB left-thru-right lane
(24) Add SB thru lane
(25) Add SB thru-right lane
(26) Add SB right-turn lane
(27) Add WB left-turn lane
(28) Add WB left-thru lane
(29) Add WB left-thru-right lane
(30) Add WB thru lane
(31) Add WB thru-right lane
(32) Add WB right-turn lane
(33) Remove NB left-turn lane
(34) Remove NB left-thru lane
(35) Remove NB left-thru-right lane
(36) Remove NB thru lane
(37) Remove NB thru-right lane
(38) Remove NB right-turn lane
(39) Remove EB left-turn lane
(40) Remove EB left-thru lane
(41) Remove EB left-thru-right lane
(42) Remove EB thru lane
(43) Remove EB thru-right lane
(44) Remove EB right-turn lane
(45) Remove SB left-turn lane
(46) Remove SB left-thru lane
(47) Remove SB left-thru-right lane
(48) Remove SB thru lane

(49) Remove SB thru-right lane
(50) Remove SB right-turn lane
(51) Remove WB left-turn lane
(52) Remove WB left-thru lane
(53) Remove WB left-thru-right lane
(54) Remove WB thru lane
(55) Remove WB thru-right lane
(56) Remove WB right-turn lane

There are several techniques for generating parameter changes and alternative designs, such as genetic algorithms and simulated annealing. As previously mentioned, due to practical running speeds, this research uses parameter swaps guided by heuristic rules. The objective function used in the process is the z value calculated by the goal programming methodology.

Stopping criterion has been developed for the intelligent alternative design generator. The user also is permitted to intervene from visual analysis of the graphical response function. For the intelligent generator, it has been proposed (Flann, Taber, and Grenney, 1994; Kirkpatrick, Gelatt, and Vecchi, 1983) that an appropriate stopping criterion is when is no improvement in the objective function following 50 iterations of alternative designs. Because of the additional intelligent rules and wider intervals in parameter swaps, this research has used a more limited stopping interval of three alternatives having no improvement, with improvement measured as a 0.10 difference interval around the value of the calculated objective function (“z”) value.

CHAPTER 4

MODEL EXPERIMENT AND TESTING

Verification and Validation Testing

A complex decision support system requires verification and validation tests to be conducted. Verification is the process of assuring that algorithms and computer code is working correctly and producing the results intended. Validation is the process of assessing how well the model replicates its intended real-life situations.

The process of verification for the decision support system developed in this research consisted of several steps. First, a base case intersection was selected. Keeping the traffic turning volumes constant, a three-dimensional block design was constructed, comparing the measures of effectiveness (delay, risk, and cost) of the base design case for each type of control device (n-s stop, e-w stop, signal, and roundabout), intersection configuration (four-leg and three-leg), and four approach lane configurations (lt-th-rt, lt+th-rt, lt-th+th-rt, and lt+th+rt). Some combinations were not possible, for example, roundabouts only have the equivalent of right-turn lanes. For each valid combination, the model results for delay, risk, and cost were compared to manual calculations using the appropriate procedure as described in the previous chapter. This involved testing an intersection for measures of delay, risk, and cost. Comparisons indicated the model closely replicated hand calculations.

Validation tests compared results from the decision support system to results from field testing to ensure realistic conclusions from model runs. Individual tests for delay, and risk (since costs are a direct, simple calculation, it was not deemed necessary to validate to field results) on each type of lane configuration and control device then were compared between the field results and the decision support system.

For delay, it was assumed that results from the 1994 HCM (Transportation Research Board, 1994) procedures were representative of field measurements, since the procedures are based on extensive field measurements and are the de facto standard used throughout the industry. Results of the tests are shown in Table 4.1.

Table 4.1 Validation results for delay

Control	Approach	HCM	Model
Signal	NB	12.8	11.5
	EB	5.8	6.8
	SB	14.1	12.3
	WB	5.5	5.5
	Total	7.0	7.2
NS Stop	NB	210.0	419.4
	EB	0.34	0.39
	SB	591	1090.4
	WB	1.12	1.18
	Total	67.3	126.5
EW Stop	NB	1.1	2.4
	EB	248	138.3
	SB	1.1	2.4
	WB	21.0	17.8
	Total	123.0	62.1
All Stop	NB	3.6	3.7

Results of the comparison show general agreement with larger differences under over-saturated conditions. It is important to note that some differences were expected due to simplifying assumptions. Results of the comparison indicate several issues: (1) Where oversaturated conditions — vehicle arrivals exceed capacity — existed, slight differences in calculated capacity levels have a large effect on delay due to the sharp exponential delay curve. (2) The Highway Capacity Software, the official computerized version of the HCM, was unable to calculate several of the oversaturated conditions; thus, EB and WB thru volumes were reduced. The decision support system was able to calculate the oversaturated conditions, although the HCM states that values in this range may be unreliable.

An analysis of accident records for 10 Utah intersections over a three-year period was compared to the safety risk analysis results developed by the decision support system. A summary of the accident records is shown in Table 4.2. Results of the accident record analysis show the severity relationships (see Table 4.3).

Table 4.2. Summary of Accident Records for Various Utah Intersections

Intersection	Control	Type	Severity	No.(93-95)	Rate/Vol
1	UnControl	RE	PDO	3	0.0001
			INJ	0	
			FAT	0	
		SA	PDO	0	0.0001
			INJ	2	
			FAT	0	
2	UnControl	RE	PDO	1	0.0001
			INJ	0	
			FAT	0	
		SA	PDO	0	
			INJ	1	0.0001
			FAT	0	
3	UnControl	RE	PDO	0	0.0000
			INJ	0	
			FAT	0	
		SA	PDO	0	
			INJ	1	0.0001
			FAT	0	
4	Stop	RE	PDO	5	0.0001
			INJ	0	
			FAT	0	
		SA	PDO	7	0.0005
			INJ	11	

Intersection	Control	Type	Severity	No.(93-95)	Rate/Vol
			FAT	1	
5	UnControl	RE	PDO	13	0.0004
			INJ	3	
			FAT	0	
		SA	PDO	4	0.0003
			INJ	9	
			FAT	0	
6	Stop	RE	PDO	10	0.0011
			INJ	2	
			FAT	0	
		SA	PDO	0	0.0000
			INJ	0	
			FAT	0	
7	Signal	RE	PDO	14	0.0003
			INJ	12	
			FAT	0	
		SA	PDO	26	0.0005
			INJ	14	
			FAT	0	
8	Signal	RE	PDO	1	0.0001
			INJ	3	
			FAT	0	
		SA	PDO	2	0.0001
			INJ	1	
			FAT	0	
9	Signal	RE	PDO	7	0.0001
			INJ	4	
			FAT	0	
		SA	PDO	4	0.0001
			INJ	1	
			FAT	0	
10	Signal	RE	PDO	42	0.0004

Intersection	Control	Type	Severity	No.(93-95)	Rate/Vol
			INJ	30	
			FAT	0	
		SA	PDO	35	0.0004
			INJ	25	
			FAT	0	
11	Signal	RE	PDO	12	0.0002
			INJ	2	
			FAT	0	
		SA	PDO	19	0.0004
			INJ	17	
			FAT	0	
12	Signal	RE	PDO	2	0.0001
			INJ	0	
			FAT	0	
		SA	PDO	2	0.0001
			INJ	1	
			FAT	0	

Table 4.3. Severity of Accidents

Control	RE rate	SA rate	RE severity percentage			SA severity percentage		
			PDO	INJ.	FAT.	PDO	INJ.	FAT.
UnControl	0.0003	0.0002	85%	15%	0%	24%	76%	0%
Stop	0.0005	0.0005	87%	13%	0%	37%	58%	5%
Signal	0.0003	0.0003	60%	40%	0%	60%	40%	0%

Several issues are identified: (1) Fatal accidents at intersections of major and minor arterials are extremely low and since there was only one occurrence in the study sample, the severity percentage for fatalities can be assumed as a very low number below the significant digits. (2) “Busier” intersections appear to have a higher accident rate. Additional study beyond the scope of this research project should be conducted to develop the relationship between “busyness” and accident rates. (3) Accident rates appear relatively constant between control devices although accident severity lessens with stop and signal control.

Sensitivity of Goal Programming Weights and Penalties

The goal programming approach used to assess the multiple objective criteria — delay, risk in three levels, and cost — employs weighting and penalty factors for each objective. Because the values for the weights and penalties are not clearly established throughout the profession, an assessment of the weighting and penalty parameter inputs was desirable. By using a base intersection design case and holding traffic and control device type constant, a sensitivity analysis was performed. A three-dimensional block design was constructed to compare results between the five objective functions (delay, levels of risk [3], and cost) with six increments of weighting factors (0.0, 0.20, 0.40, 0.60, 0.80, 1.00), and varying levels of penalty factors. Default values for weights and penalties are shown in Table 4.4. Results of the various combinations were plotted (see Figures 4.1, 4.2, 4.3) to examine the significance of the parameter values. Results are also shown in Table 4.5.

Table 4.4. Default weights and penalties

	Delay	Risk-1	Risk-2	Risk-3	Cost
Wt.	0.40	0.10	0.15	0.15	0.20
Goal	0.00	0.00	0.00	0.00	0.00
Penalty	1.00	1.00	1.00	1.00	1.00
1st Target	25.0 (15.0)	5.0	1.0	0.25	500
1st Penalty	2.0	2.0	2.0	2.0	2.0

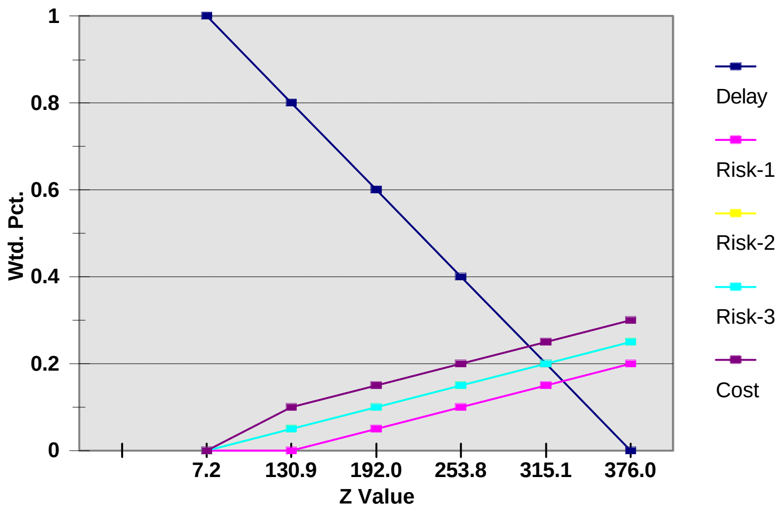


Figure 4.1 Sensitivity of Objective Weights - Varying Delay

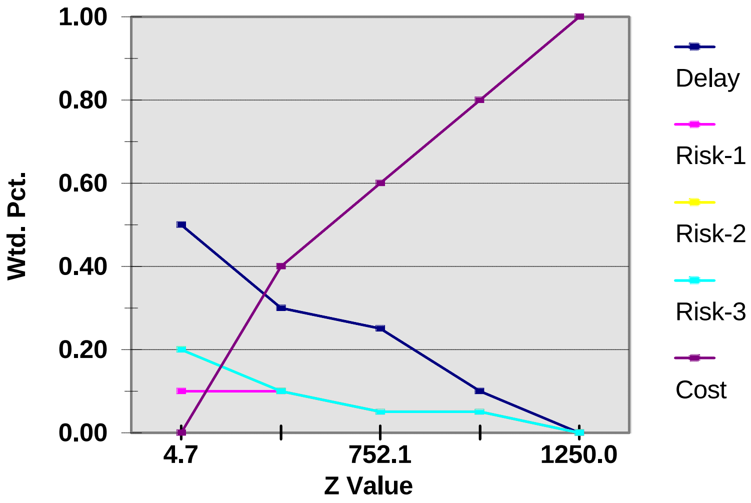


Figure 4.2 Sensitivity of Objective Weights - Varying Cost

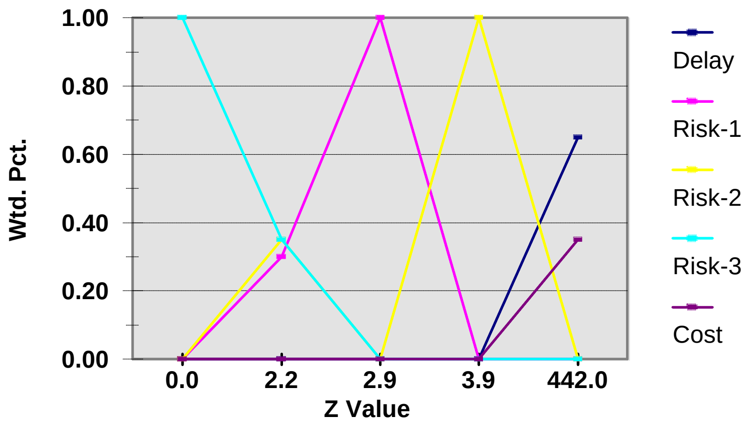


Figure 4.3 Sensitivity of Objective Weights - Varying Risk.

The sensitivity plots shown indicate that the effects of changing the parameter values depend on several factors, but can have significant impacts on the overall “z” value. Not surprisingly, the larger the percentage weight factor, the larger impact it has on the “z” value. However, the magnitude of the actual objective function value can have significant impact, thus scaling might be necessary before applying the weighting factors.

Table 4.5 Sensitivity by objective function weights

Delay	Risk-1	Risk-2	Risk-3	Cost	Z
0.40	0.10	0.15	0.15	0.20	253.8
0.00	0.20	0.25	0.25	0.30	376.0
0.20	0.15	0.20	0.20	0.25	315.1
0.60	0.05	0.10	0.10	0.15	192.0
0.80	0.00	0.05	0.05	0.10	130.9
1.00	0.00	0.00	0.00	0.00	7.2
0.50	0.10	0.20	0.20	0.00	4.7
0.30	0.10	0.10	0.10	0.40	502.8
0.25	0.05	0.05	0.05	0.60	752.1
0.10	0.05	0.05	0.05	0.80	1000.9
0.00	0.00	0.00	0.00	1.00	1250.0
0.65	0.00	0.00	0.00	0.35	442.0
0.00	0.30	0.35	0.35	0.00	2.2
0.00	0.00	0.00	1.00	0.00	0.0
0.00	0.00	1.00	0.00	0.00	3.9
0.00	1.00	0.00	0.00	0.00	2.9

CHAPTER 5

ANALYSIS OF RESULTS

To examine the application of multiple measures of effectiveness in site access intersection planning and design, several actual access intersection locations were tested using the decision support system. The model results were compared to actual design decisions. Three case study examples are discussed in the following paragraphs.

Case Study Example #1

The first case study example is a typical corner development site at the intersection of two formerly high-speed rural minor arterial two-/three-lane highways that are undergoing transition into busy suburban highways with strong roadside development pressure. The roadways have average daily traffic volumes (ADT) of approximately 5,000 vehicles per day. Existing land use adjacent to the intersection consisted of only one small convenience store on the northeast corner and a small grocery-based shopping center on the southwest corner. Development of a small professional complex on the southeast corner was granted access onto both roadways (see Figure 5.1), although adjustments were made from the original proposal. The decision support system model was used to test alternative designs for the access driveways beginning with the originally proposed access points, which included a two-lane driveway (9.2 m wide) along the west arterial, approximately 91 m center-center from the intersection of the two arterials and directly across from a driveway access to the grocery shopping plaza, and another 9.2 m-wide driveway access along the north arterial, approximately 83 m from the existing intersection of the two arterials (see Figure 5.2). On-site throat distance, which allows for queuing, was approximately 30 m for both access drives.

Figure 5.1 Case Study #1

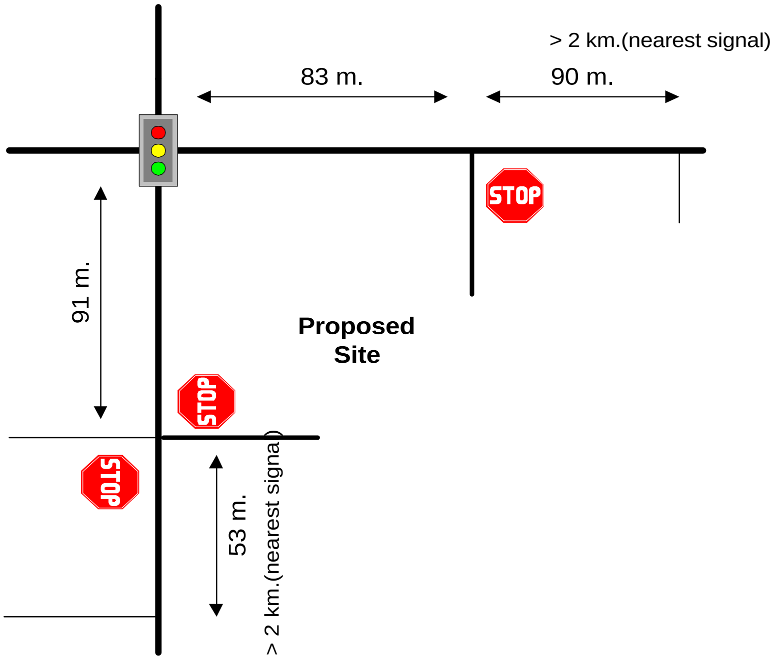


Figure 5.2 Case Study #1 - Geometric Layout

The decision support system was applied to test alternative designs for the proposed development and access driveways. Site traffic volumes were based on 13,000 square feet, or 1,200 square meters, of professional office space and 4,000 square feet, or 370 square meters, of a drive-in bank. Resulting intersection turning volumes are shown in Figure 5.3. Each access driveway was treated as a separate mid-block access intersection design for purposes of running through the decision support system.

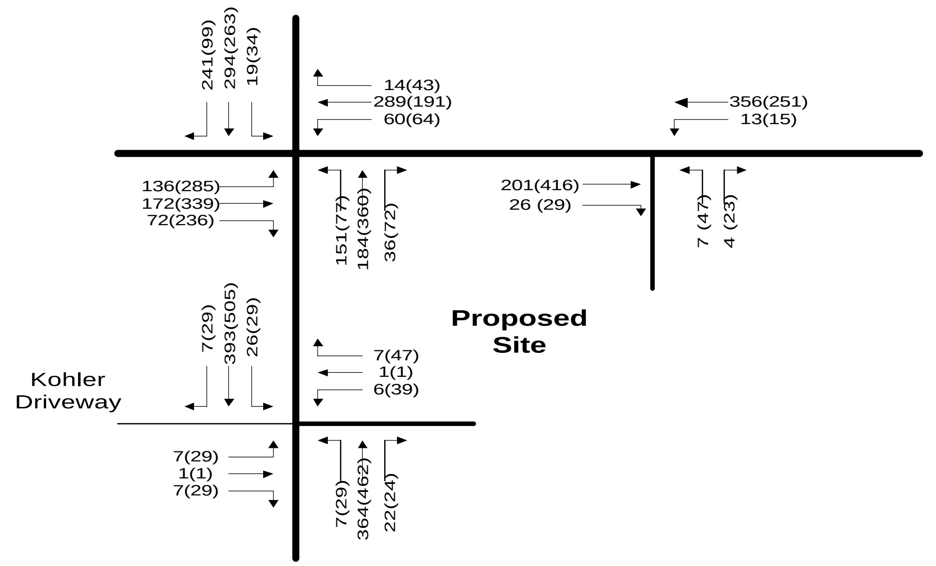


Figure 5.3 Case Study #1 - Intersection Turning Volumes [am(pm).]

For the north side access driveway, the expert system component immediately indicated that upstream and downstream corner clearances should be increased to meet suggested design criteria, even though minimum UDOT criteria were satisfied. A detailed listing of design criteria tests and exceptions is shown in Appendix H. Running the optimization routine for this access point did not result in any changes (base design is considered optimal). To examine the effects that other control device types could have on the various measures of effectiveness, a series of tests was run, varying control device but holding traffic volumes and intersection geometrics constant. Results are shown in Table 5.1. The base design of stop control on the driveway approach is shown to have optimum values in every category.

Table 5.1 Case Study #1 North Access

Control	Delay	Risk-1	Risk-2	Risk-3	Cost	Wtd. Z
Base - NB Stop	0.9	0.45	0.32	0.001	426	85.7
Roundabout	14.4	4.42	0.68	0.005	725	296.3

While the three-way stop control alternative is similar in the overall weighted “z” value, the risk of potential property damage accidents is much higher due to the additional stopping maneuvers required on the arterial roadway.

The west side access driveway also had corner clearance considerations and the expert system revealed that while the design met the UDOT criteria, it was not in agreement to other nationally based criteria.

Running the optimization routine again resulted in no change from the base design since most values were in acceptable ranges. However, the delay to the driveways was much higher than at the north access driveway. According to levels in the 1994 “Highway Capacity Manual,” the side driveways would experience levels of service in the “D” range. As such, the weighted “z” score is higher than for the north access intersection. A major issue with the actual development was the potential increase in traffic along the west arterial, which was projected to increase to approximately 20,000 ADT.

To test the impact of this projected increase, the intersection turn volumes were adjusted to reflect thru volumes along the west arterial of 1000 in the south direction and 800 in the north direction. With these additional volumes, the base intersection design showed a poor overall level of service and failing levels on the driveway approaches, based on delay. To examine other effects, the optimizer was run again. The optimizer found that a signal was more desirable from the standpoint of the heuristics — based on traditional engineering knowledge and meeting traditional peak hour warrant criteria used to determine installation of signals — even though the overall weighted “z” score increased (see Table 5.2). Although installation of traffic signals usually is thought to reduce accident potential, it can be seen

Table 5.2 Case Study #1c West Access

Control	Delay	Risk-1	Risk-2	Risk-3	Cost	Wtd. Z
Base - NB Stop	25.66	0.52	0.38	0.001	621	269.0
Signal	5.01	2.81	1.87	0.005	745	300.9

that based on recent accident rates, the signal alternative actually would increase the accident potential, even in the injury category. These trade-offs illustrate how the decision support system offers additional information over traditional approaches to intersection analysis.

The actual engineering review of the site, conducted in the traditional, mostly manual method, also concluded that the access point on SR-92 should be located further from the main intersection. This resulted in a revised proposed location about 120 m from the main intersection. In addition, each access drive would include a separate left-turn exiting lane. This design was considered acceptable with projected p.m. peak hour levels of service of “C” and “D,” respectively, for the SR-92 and SR-74 access points.

Case Study Example #2

The second case study example is a driveway access to a major office complex, located on a five-lane minor arterial suburban highway. The driveway forms a stop-controlled T-intersection with the arterial. The arterial has outside shoulders of approximately 1 m width and a center turn lane that serves as a de facto left-turn lane at each intersection. The driveway has a single lane in, but two lanes out for a total width of approximately 9.7 m with no taper or flare. The intersection layout is shown in Figure 5.4. The nearest upstream corner is approximately 61 m while the nearest downstream corner is approximately 91 m in distance.

The site consists of a major office building approximately 350,000 square feet in size. Estimated arterial and driveway intersection turning volumes are shown in Figure 5.5.

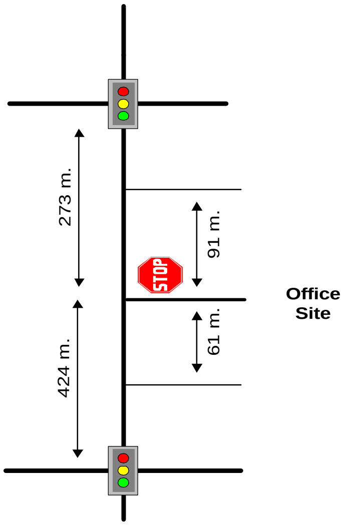


Figure 5.4 Case Study #2 Geometric Layout

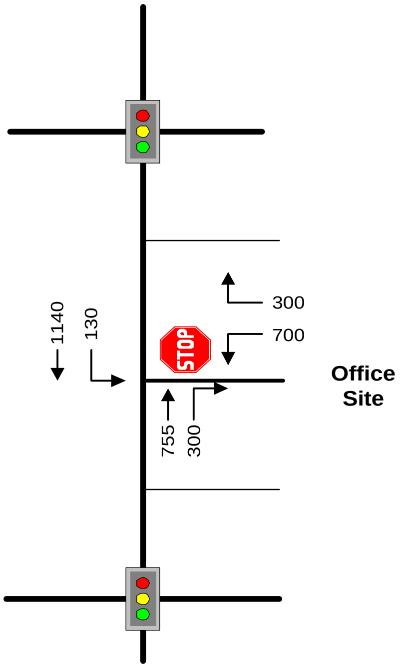


Figure 5.5 Case Study #2 - Intersection Turning Volumes

When the decision support system was run, the expert system immediately revealed that the site access intersection conflicts with the upstream driveway due to right-turn overlap. Since the upstream intersection also is a driveway to the same site, one of the driveways should be relocated. Another site driveway located downstream also was highlighted as a warning message and requires an additional 15 m of separation. The expert system also found that there should be a right-turn deceleration lane from the arterial roadway into the site. In addition, the expert system found that the site driveway should have two left-turn lanes (see complete listing of findings in Appendix).

Evaluation of the existing intersection using the estimated turning volumes listed above shows a failing delay level of service with high accident risk potential. The decision support system optimizer was run to evaluate any geometric changes required for the intersection. The optimizer found that several changes should be considered (see Table 5.3). The intersection base design that currently exists shows a high level of deficiency with a high level of delay and safety risk potential. By applying the heuristic rules, the optimizer was able to develop a design that improved measures of effectiveness and met state design criteria.

Table 5.3 Case Study #2

Control	Delay	Risk-1	Risk-2	Risk-3	Cost	Wtd. Z
Base - NB Stop	10,586.	8.59	2.96	0.012	426	9999
Signal	79.55	6.32	4.22	0.012	500	9999
SB LT	74.50	6.32	4.22	0.012	590	9999
WB TH	23.90	6.25	4.17	0.012	665	278.06
WB RT	15.59	6.19	4.13	0.012	710	292.71
Manual Run						
WB RT +Signal	19.0	6.22	4.14	0.010	595	248.1

This case study also points out that the heuristic rule order can be a significant factor in determining the optimal result. Another run of the model was made adding only a westbound right-turn lane as suggested by the expert system, and changing to a signalized control. This design alternative ranked better in all measures of effectiveness and had the lowest weighted "z" score. This indicates a non-ordered parameter swapping technique can produce more optimal results.

Case Study Example #3

The third case study example involves a minor public street intersecting with a major, high-speed two-lane rural highway. A high school is located at the northeast corner of the intersection and has access to the minor street, approximately 500 feet from the highway (see Figure 5.6). The highway has approximately 1-m safety shoulders in both directions and a right-turn deceleration lane of approximately 60 m in length. The minor public street is approximately 15 m in width with a de facto left- and right-turn lane based on available pavement width. The intersection is stop controlled and forms a T-intersection. Estimated intersection turning volumes are shown in Figure 5.7. During the morning, there is a heavy traffic movement turning left from the arterial onto the street, which includes approximately an 8 percent movement of school buses. During the mid-afternoon period, this movement reverses itself. To evaluate the design of this existing intersection, the decision support system was run. The expert system immediately showed the need for a left-turn lane on the major arterial highway (a detailed listing of checks to design criteria is shown in the Appendix).

Optimization runs (see Table 5.4) indicated that the addition of a left-turn lane would be advisable, but the benefit trade-off was not clearly shown. Although delay and accident risk declined slightly, the cost went up, thus resulting in an overall higher weighted "z" score. This result indicates that a closer examination of the potential accident risks might be necessary to correctly evaluate the effects of geometrics on traffic safety risk.

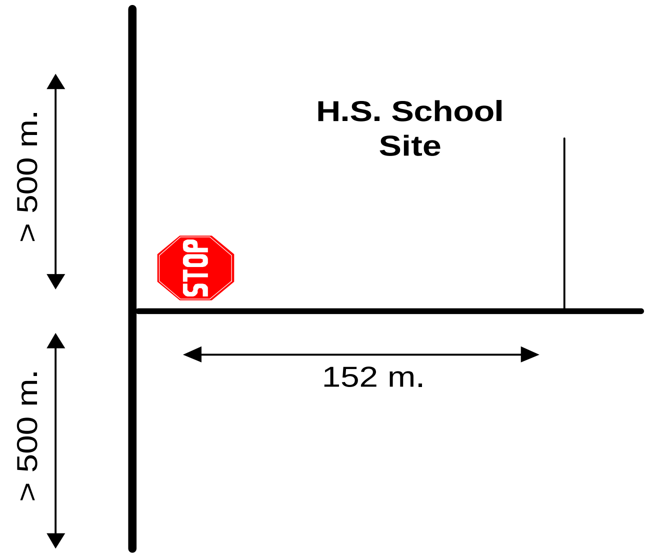


Figure 5.6 Case Study #3 Geometric Layout

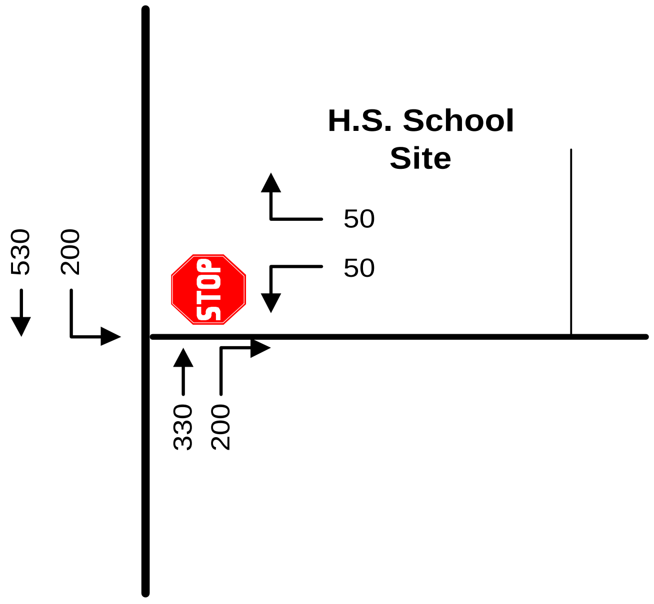


Figure 5.7 Case Study #3 Intersection Turning Volumes

Table 5.4 Case Study #3

Control	Delay	Risk-1	Risk-2	Risk-3	Cost	Wtd. Z
Base - SB Stop	2.04	1.336	0.527	0.002	281	57.2
EB LT	1.88	1.331	0.526	0.002	321	65.2

CHAPTER 6

CONCLUSIONS

This research examined several new approaches to intersection design and analysis. New methods included finding optimal designs; using multi-criteria analysis examining the trade-offs between delay, safety risk, and cost; and applying computerized intelligent methods.

The research work conducted in this project resulted in the following findings:

1. A high-level architecture has been established that supports a wide variety of evaluation models and provides a great deal of flexibility to incorporate new models that may be developed in the future.
2. The expert system component of the model highlighted design exceptions that might otherwise be overlooked in a conventional manual design or review analysis.
3. A computerized approach allows for fast, integrated comparisons between different design alternatives. It was found that evaluation of 32 design alternatives was approximately 1 second. Thus, the system can evaluate more than 25,000 alternatives in about the same time as manually evaluating one alternative.
4. The multi-objective analysis incorporates quantifiable trade-offs of safety risk and cost, generally treated only as qualitative measures. This permits a more thorough analysis and justification where geometric improvements are required but may not affect delay.
5. Intelligent optimization methods generate a wide range of alternative designs, avoiding limitations that might be caused by preconditioned biases.
6. The high sensitivity of the objective weighting parameters resulted in a high level of uncertainty around the calculated “z” value. Thus, interpretation of optimal solutions should consider other designs that have a “z” value close to the optimal solution. The

system's display of each solution makes this possible.

7. The use of goal programming techniques in combination with the A* search technique resulted in a reduced, manageable set of optimal solutions, even though the complete set of valid solutions was quite large.

The test case studies have shown that optimization of access intersections can provide for increased benefits from conventional manual design or review analysis. The research has shown that the optimization process can adhere to and even promote the four main principles of access design: limit access points, separate conflict points, remove turns from thru traffic, and promote signal progression.

This research has been exploratory in nature, resulting in a working prototype of the decision support system and an architecture that can be easily expanded as new evaluation methods are developed. Further research work is encouraged in several areas:

1. Evaluation components must be developed in more detail to provide additional levels of measurement, to better reflect specific geometric designs such as channelized lane medians and turn bays.
2. Guidelines must be further developed regarding weighting parameters and trade-offs between the different objective functions. While there will always be a need to permit some specific localized preferences on weighting parameters, a national consensus of weighting guidelines will assist in many designs.
3. A determination of more specific parameter values, and accident-to-conflict ratios, especially related to intersection geometrics, is important to better define levels of risk.
4. There exists a strong need for consensus in the professional traffic engineering community for adaptation of consistent factors, such as heavy vehicle effects, to apply to all types of traffic operation models.

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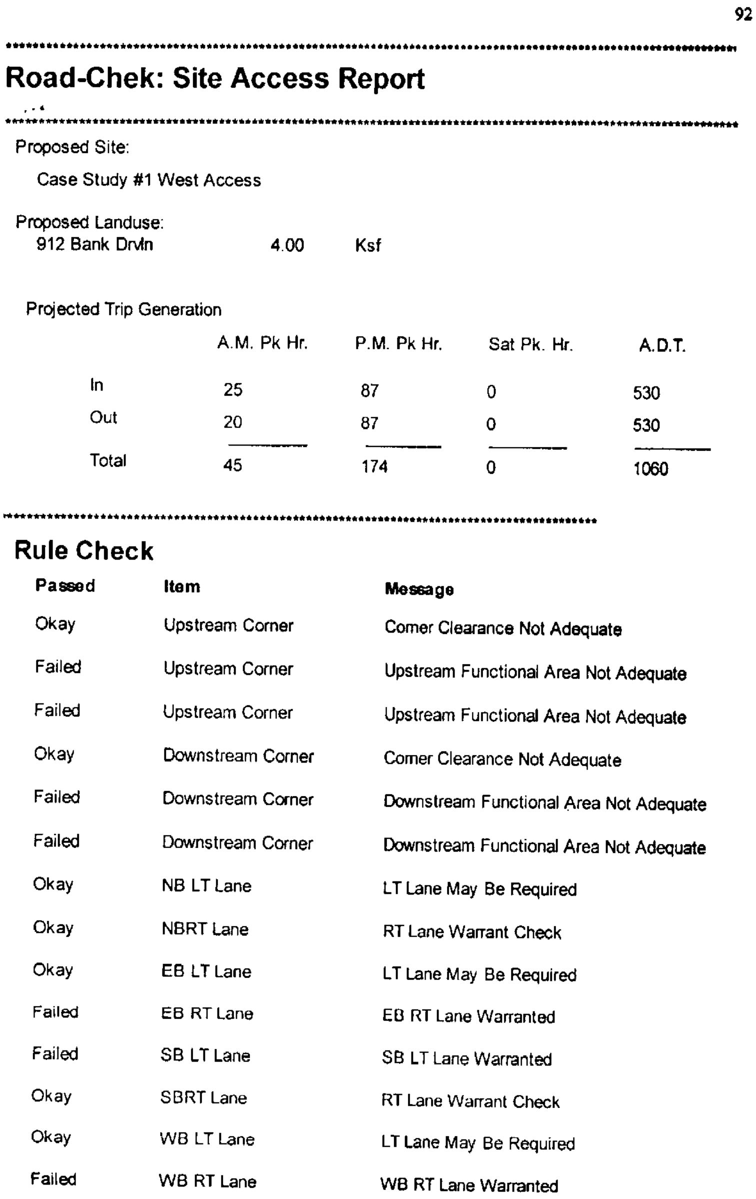
APPENDIX

APPENDIX A

RULE-BASE CHECK LISTINGS FOR CASE STUDY #1



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Road-Chek: Site Access Report

Proposed Site:

Case Study #1 West Access

Proposed Landuse:

912 Bank Drvln 4.00 Ksf

Projected Trip Generation

	A.M. Pk Hr.	P.M. Pk Hr.	Sat Pk. Hr.	A.D.T.
In	25	87	0	530
Out	20	87	0	530
Total	45	174	0	1060

Rule Check

Passed	**Item**	**Message**
Okay	Upstream Corner	Comer Clearance Not Adequate
Failed	Upstream Corner	Upstream Functional Area Not Adequate
Failed	Upstream Corner	Upstream Functional Area Not Adequate
Okay	Downstream Corner	Comer Clearance Not Adequate
Failed	Downstream Corner	Downstream Functional Area Not Adequate
Failed	Downstream Corner	Downstream Functional Area Not Adequate
Okay	NB LT Lane	LT Lane May Be Required
Okay	NBRT Lane	RT Lane Warrant Check
Okay	EB LT Lane	LT Lane May Be Required
Failed	EB RT Lane	EB RT Lane Warranted
Failed	SB LT Lane	SB LT Lane Warranted
Okay	SBRT Lane	RT Lane Warrant Check
Okay	WB LT Lane	LT Lane May Be Required
Failed	WB RT Lane	WB RT Lane Warranted

APPENDIX B

RULE-BASE CHECK LISTINGS FOR CASE STUDY #2

APPENDIX C

Road-Chek: Site Access Report

Proposed Site:

Case Study #2

Proposed Landuse:

720 Prof Office	350.00	Ksf

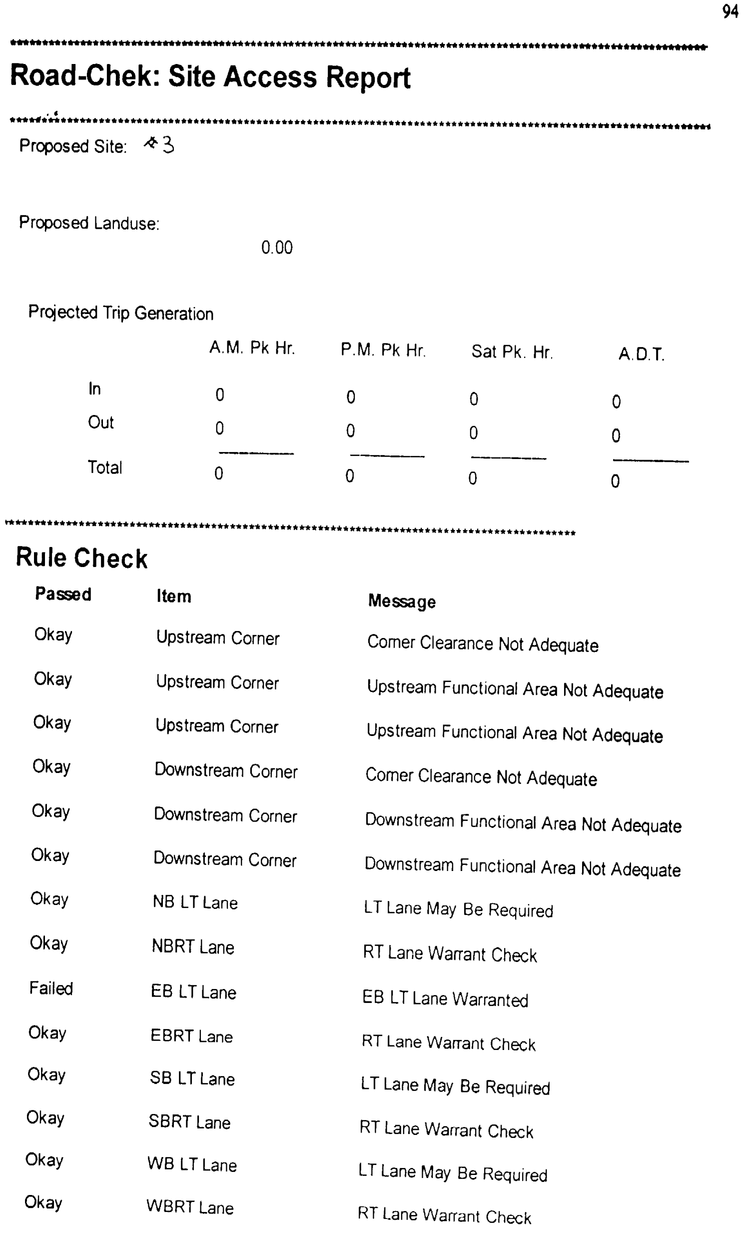
Projected Trip Generation

	A.M. Pk Hr.	P.M. Pk Hr.	Sat Pk. Hr.	A.D.T.
In	725	428	0	5980
Out	217	1000	0	5980
Total	942	1428	0	11960

Rule Check

Passed	**Item**	**Message**
Failed	Upstream Corner	Corner Clearance Not Adequate
Failed	Upstream Corner	Upstream Functional Area Not Adequate
Failed	Upstream Corner	Upstream Functional Area Not Adequate
Okay	Downstream Corner	Corner Clearance Not Adequate
Failed	Downstream Corner	Downstream Functional Area Not Adequate
Failed	Downstream Corner	Downstream Functional Area Not Adequate
Okay	NB LT Lane	LT Lane May Be Required
Okay	NBRT Lane	RT Lane Warrant Check
Okay	EB LT Lane	LT Lane May Be Required
Okay	EBRT Lane	RT Lane Warrant Check
Okay	SB LT Lane	LT Lane May Be Required
Okay	SBRT Lane	RT Lane Warrant Check
Okay	WB LT Lane	LT Lane May Be Required
Failed	WB RT Lane	WB RT Lane Warranted

RULE-BASE CHECK LISTINGS FOR CASE STUDY #3



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Road-Chek: Site Access Report

Proposed Site: #3

Proposed Landuse:

0.00

Projected Trip Generation

	A.M. Pk Hr.	P.M. Pk Hr.	Sat Pk. Hr.	A.D.T.
In	0	0	0	0
Out	0	0	0	0
Total	0	0	0	0

Rule Check

Passed	Item	Message
Okay	Upstream Corner	Corner Clearance Not Adequate
Okay	Upstream Corner	Upstream Functional Area Not Adequate
Okay	Upstream Corner	Upstream Functional Area Not Adequate
Okay	Downstream Corner	Corner Clearance Not Adequate
Okay	Downstream Corner	Downstream Functional Area Not Adequate
Okay	Downstream Corner	Downstream Functional Area Not Adequate
Okay	NB LT Lane	LT Lane May Be Required
Okay	NBRT Lane	RT Lane Warrant Check
Failed	EB LT Lane	EB LT Lane Warranted
Okay	EBRT Lane	RT Lane Warrant Check
Okay	SB LT Lane	LT Lane May Be Required
Okay	SBRT Lane	RT Lane Warrant Check
Okay	WB LT Lane	LT Lane May Be Required
Okay	WBRT Lane	RT Lane Warrant Check

CURRICULUM VITAE

John T. Taber, PE, PP

(April, 1997)

Department of Civil Engineering
Utah State University
Utah Water Research Laboratory
Logan, UT 84322
(801) 797-2410

P.O. Box 682613
Park City, UT 84068
(801) 658-0285
jttaber@aol.com

Professional Interests

Transportation Planning
Artificial Intelligence, Expert Systems
Network and Highway Simulation Modeling

Education

Utah State University, Ph.D. Candidate
Princeton University; M.S.E. Civil Engineering, (Transportation Program)
Lafayette College; B.S.C.E., Cum Laude, Honors

Professional Registration

Professional Engineer, Utah No. 270751
Professional Engineer, Pennsylvania No. PE-041034-R
Professional Engineer, New Jersey No. GE35329
Professional Planner, New Jersey No. LI04983

Professional Experience

Mr. Taber is a research assistant and Ph.D. candidate in the Civil Engineering Department at Utah State University. His research has been in the area of expert systems and artificial intelligence for traffic engineering, computer simulation modeling, highway operations, and transportation management training.

John is currently the principal investigator on an access management expert system research project funded jointly by the Utah Department of Transportation and Mountain Plains Consortium. He is also a research consultant on a NSF research grant at Brigham Young University examining optimization of regional growth versus infrastructure requirements.

He is also actively involved in private consulting in which he works primarily in assisting state and local agencies. He specializes in traffic engineering, planning and the use of computer simulation models including Traf-Netsim, Transyt-7F, Minutp, and Tranplan.

Prior positions include Manager of Transportation Planning for Garmen Associates in Montville, NJ where he had direct responsibility for various traffic impact and planning projects. He represented municipalities as their primary traffic consultant for both master planning studies and development site impact reviews and led the development of a large scale regional model of Southern New Jersey for the New Jersey D.O.T. Mr. Taber also managed preliminary engineering design projects including highway overpasses and arterial corridor improvement plans. Other projects included design and analysis of roadside surveys, application of a geographical information system, and establishment of highway impact fee methodology.

Other prior experience included heading a small transportation consulting firm specializing in computerized systems and software development for the trucking industry. He has also held management positions with several major transportation corporations including Stolt-Nielsen, Consolidated Rail Corporation, United States Railway Association, and the Rock Island Railroad. His responsibilities included: civil engineering, traffic operations, transportation modeling, and strategic planning.

Mr. Taber has instructed in highway traffic modeling at Brigham Young University and taught courses in highway geometric design at Utah State University. He has also previously held adjunct teaching positions at Lehigh University and Lafayette College.

Profession Affiliations

Institute of Transportation Engineers
Transportation Research Board
    Member, TRB Committee on Access Management
    Member, Subcommittee on Planning and Design

PROFESSIONAL PUBLICATIONS AND PRESENTATIONS

Taber, J.T. and Grenney, W.J., "A Multi-Objective Methodology for Evaluation of Driveway Access Control", Proceedings of the 2nd National TRB Conference on Access Management, Vail, Colorado, August 1996.

Taber, J. and Grenney, W.J., “A Knowledge-Base And Simulation Algorithm Hybrid Model For Traffic Congestion at Intersections”, Developments in Artificial Intelligence For Civil And Structural Engineering, Civil-Comp Press, Edinburgh,UK, August 1995.

Taber, J.T. and Grenney, W.J., “A Multi-Media Expert System To Analyze and Optimize Intersection Design”, 1995 Compendium of Technical Papers, International Meeting of the Institute of Transportation Engineers, Denver, Colorado, August 1995.

Flann,N., Taber,J.T., and Grenney,W.J, “Optimizing Traffic Signal Timing Using Applied Machine Intelligence Techniques”, Proceedings of 2nd Annual Computing Congress in Civil Engineering, American Society of Civil Engineers, Atlanta, GA, May 1995.

Taber,J.T., “A Multi-Media Expert System To Analyze and Optimize Intersection Design”, Presented at the Intermountain Section Meeting, Institute of Transportation Engineers, Jackson Hole, WY, May, 1995.

Taber, J.T. and Manser, R., "Using Micro-simulation to Systematically Regulate Driveway Access On Arterial Highways", Presented at the 1993 Institute of Transportation Engineers International Meeting, Hague, Netherlands.

Taber, J.T., "A Linear/Non-Linear Approach to Estimating Peak Hour Work Commute Trips", Presented at the 1993 Fourth National Conference on Transportation Planning Methods Applications, Daytona Beach, Florida, 1993.

Taber, J.T., "A Statistically Based Methodology for Improving The Prediction of Vehicle Trip Generation", Presented at the 1993 Fourth National Conference on Transportation Planning Methods Applications, Daytona Beach, Florida, 1993.

Taber, J.T. "Calculating Highway Design Performance Measures in Site Impact Analyses Using Traffic Simulation Models" Proceedings of 9th Annual Conference of Microcomputers in Transportation, American Society of Civil Engineers, Orlando, FL, 1991.

Taber,J.T., J. Lutin "Feasibility of Light Rail Transit Street Operation", Proceedings of 2nd Annual Light Rail Transit Conference, Transportation Research Board, Boston, MA 1977.

PROFESSIONAL PAPER REVIEWS

“Artificial Neural Networks for Civil Engineers” Proposed monograph sponsored by American Society of Civil

Engineers, Reviewed chapter on transportation applications. August 1994.