Intersection Design Tool to Aid Alternative Evaluation

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Abstract

The goal of this project is to develop a structured and objective evaluation process to compare alternative design concepts and evaluate them based on operations, safety, access management, and pedestrian/bicycle accommodations. This approach permits a more objective comparison of all alternatives, since all options target the same operational service level. The Intersection Design Alternative Tool (IDAT) developed through this effort is capable of evaluating 13 different intersection alternatives and it would be invaluable in evaluating alternative designs that could enhance access management and implementing innovative intersection treatments such as alternative left-turn treatments.

1. Introduction

Intersections can act as choke points on the transportation system and improper designs have the potential to block access, increase the potential for crashes, and reduce the effectiveness of access management plans. Intersection design therefore becomes a balancing act of various elements and constraints aiming to produce a solution that addresses mobility, access, safety, environmental, and financial aspects of the project. To achieve this balance, alternative strategies and options must be identified, developed and evaluated in a systematic manner. Traffic control measures have been developed that can improve the operational efficiency and safety of intersections. The implications and effectiveness of such designs are not, however, well understood, nor have significant efforts been undertaken to provide an objective comparison between various types of intersection designs or traffic control measures. Moreover, high level evaluation of how such alternatives operate with regard

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to access control measures is limited. Such an effort will allow for establishing the proper design and traffic control for an intersection and thus enhance the ability for a proper access management and control. It is therefore important to develop an objective methodology for evaluating alternative intersection designs while meeting the project constraints and goals. Current practice, while achieving great strides in improving the efficiency, lacks a systematic, objective and well defined approach to evaluating individual design alternatives.

A review of current literature identified 13 alternative intersection designs. Of interest is the fact that no systematic process can be identified, which compares these alternative designs. Most guidelines identify the need for comparative studies but do not identify the factors or methods that one should apply in determining the most appropriate design for a specific situation. The lack of such specific guidance both at the national and state level is likely to discourage engineers from considering one or more of the alternatives, even though such design may be appropriate. It is reasonable then, to conclude that unwarranted operational or safety problems, or unwarranted costs may be incurred when such suboptimal designs are constructed.

The goal of this project is to develop a structured and objective evaluation process to compare alternative design concepts and evaluate them based on safety performance, access management enhancement, and pedestrian and bicycle accommodations. In order to facilitate this evaluation, the methodologies described in this report were developed into a software based tool identified as the “Intersection Design Alternative Tool (IDAT).” The tool developed provides designers with a list of potential solutions that are based on the minimum number of lanes required to achieve a targeted level of operation.

2. Literature review

The Maryland State Highway Administration had identified a list of unconventional intersections and provided conceptual information and considerations for a wide range of alternative intersection designs [1]. Most of the intersection designs also utilize innovative left turn treatments, provide or accommodate channelization and/or raised medians and accommodate u-turns: all access management components. A number of the alternatives included in the list have been used throughout the country. For example, the median u-turn design has been used in Michigan extensively for years, the jughandle design in New Jersey, and the continuous flow intersection used in New York and Maryland. The use of modern roundabouts is perhaps the most adopted alternative and its use is increasing rapidly throughout the United States.

There is limited guidance on the evaluation, design and implementation of these designs is available despite their long use. Even though the American Association of State Highway Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets contains guidelines on the design of standard intersections along with some guidance on the median u-turn, jughandle, and roundabout alternatives, this guidance is very limited and does not adequately address evaluation issues [2]. A recent report by the FHWA addressed the Restricted Crossing U-turn intersections (Superstreet) and Median U-turn at-grade intersections and has issued Technical Brief on their use [3]. A review of states identified twelve states that have developed roundabout guides which address the planning, design and operations of roundabouts, primarily based on the FHWA Roundabout: An Informational Guide [4], though several have much more comprehensive guides.

A review of the design guides used by each state examined the factors considered in intersection design and how decisions regarding control type and size are reached. Of the 41 state transportation agencies reviewed only Florida, Missouri, New Jersey, New York, Texas, and Washington have developed their own intersection design guidelines contained within a separate Intersection Design Manual or included within their roadway design manuals. All states reviewed have intersection design guidance that adhere to or follow the AASHTO guidance and Manual of Uniform Traffic Control Devices (MUTCD) for determining traffic control (mainly for signalization). Of those states with independent guides, the most frequently considered design factors are operational analysis and construction cost (five of six states with specific guidance). These two factors are considered controlling for designing and evaluating intersection options, since they define the operational and
construction efficiency of the intersection. No manual provides specific guidance for selecting appropriate intersection design or control types; most manuals simply note that comparisons among alternatives should be performed. It is apparent that there is a lack of any tools that provide designers or planners with an estimate of appropriateness for different intersection designs.

The review of state practices revealed that there is limited guidance on evaluating alternative intersection designs and no state has developed a systematic process that compares such alternative designs. Most manuals identify the need for comparative studies but none identify the factors that one should consider in weighing alternatives and determining the optimal design. Maryland is the only state that is in the process of developing such an approach but not much progress has been made since 2005 when the concept was initiated. The development of separate manuals for roundabouts by a few states is a step in the right direction for identifying and considering alternative intersection designs; however, these do not provide a means for comparison and may further segregate alternative designs from traditional or other alternative designs. The lack of any specific guidance on the national and state level regarding the specific use and implementation of alternative designs is likely to discourage engineers from considering one or more of the alternatives, even though they may be appropriate.

3. Intersection design procedures

Based on the literature review a total of 13 different intersection alternatives were identified for consideration in the research. These are: 1. Signalized; 2. Roundabout; 3. All-way stop; 4. Two-way stop; 5. Unsignalized inside left turn; 6. Median U-turn signalized; 7. Median U-turn unsignalized; 8. Superstreet, unsignalized; 9. Superstreet, signalized; 10. Continuous flow; 11. Continuous green T; 12. Jughandle; and 13. Bowtie. These intersections may be broadly grouped into two major categories of signalized or unsignalized control.

4. Operational evaluation

A typical problem in comparative analysis of roadway designs is ensuring that all alternatives examined deliver a similar level of targeted operational performance. For instance, a signalized intersection with two approach lanes may service the same volume as a single lane roundabout for a given set of conditions. However, during the initial concept development both alternatives may be compared with two lane approaches leading to comparing alternatives with vastly different operational performance in addition to costs and right of way and environmental impacts. The approach taken here was to identify the minimum footprint for each intersection design for a given traffic demand, while meeting a volume to capacity ratio (v/c) of 0.90. If an alternative meets this threshold, it is considered to be feasible and no larger footprint alternatives for this design are considered. This approach allows for full comparison of other design factors such as access management enhancement, construction costs, right of way and environmental impacts.

The critical aspect of the analysis tool to be developed is to determine the optimum design scenario meeting the desired operational threshold with a minimum footprint which subsequently will have the smallest construction costs and impacts. To achieve this, various techniques such as capacity analysis software or simulations may be used for design and sizing intersections, however, this approach requires an iterative process for each alternative to achieve the desired level of capacity. This approach can be time consuming and limit the range of alternatives to be considered. Therefore, a methodology that directly links the traffic demand, i.e., design hour turning movement volumes, to the optimum lane configuration for each alternative was sought.

The Critical Lane Analysis (CLA) was considered as the most promising approach to be used here. This method allows for the automation of the design process of signalized intersections by systematically linking traffic demand, geometric design and operational level of service [5]. CLA distributes the approach volumes to the available lanes and utilizes developed phasing plans to allow for the appropriate intersection movements.
Critical volumes for each phase are determined based on certain rules and these volumes are summed to determine the total critical lane volume for the intersection. This sum can then be directly related to the level of service definition for signalized intersections. Similar techniques (i.e. estimates of capacity) have been developed for unsignalized intersection designs as well. The Highway Capacity Manual [6] provided intersection capacity estimates based solely on conflicting movements and reserve capacity while considering intersection geometry. Finally, a recent report offered another consideration for estimating capacity for roundabouts [7].

Even though the methods discussed for estimating intersection operational levels could be considered not as refined as current micro simulation models and/or more complex macro models allow for direct linkage between intersection design and operation. The simplicity of the models allows for manipulation through computational models, which permit the automation of preliminary designs for establishing the basic geometry needed to achieve a desired intersection capacity. CLA and unsignalized intersection Level of Service methods have served as the foundation for the calculating procedures used in the current version of the Highway Capacity Manual. These approaches are viewed as a basic, fundamental process for evaluating intersection design alternatives and providing comparable evaluation results. The focal point behind all these approaches is that they provide the potential for a common basis of comparison, i.e. volume to capacity ratios or unused capacity, which can be used in targeting design options and provide a common basis for comparisons.

5. Safety evaluation

Conflict exposure estimates were developed by application of the Safety Surrogate Analysis Model (SSAM). SSAM is a tool developed by the Federal Highway Administration which analyzes vehicle trajectory output from the VISSIM micro-simulation model. SSAM identifies “conflicts” between vehicles, which are defined as instances of near misses between two vehicles. SSAM is capable of categorizing the conflicts as either rear-end, crossing angle and lane changing (sideswipe) crashes. The primary analysis is then concentrated on developing the crash exposure relationship as a function of volumes and lane configuration. This approach was taken over the collection of field data as it is able to remove extraneous or site specific causal factors from the evaluation. As such, clear underlying relationships between the intersection configuration and safety performance can be more readily made. This is possible as an entire range of traffic conditions can be evaluated over a greater range of potential configurations.

The first analytical task was to develop VISSIM and SSAM models for each crash type. Independent left turn, rear end and sideswipe models were develop to eliminate interference from other intersection movements. A range of feasible traffic volumes was evaluated to ensure that all movements operate under capacity, so that congestion related crash patterns will not affect the evaluation. In addition to multiple volume scenarios, various lane configurations were also evaluated for the rear end crashes.

A slightly different approach was undertaken for simulating and estimating crash prediction models for pedestrians. In this case, specific intersection types were simulated to allow for developing the relationships between specific designs and vehicle-pedestrian interaction. This was required because the exposure was varied by each intersection design type as well as due to the need to consider all potential conflicts to pedestrians from vehicular flow patterns at the same time. For all scenarios examined, the traffic parameters included the volumes along the major and the minor streets and the pedestrian volumes. The turn percentages for the right and left turns were also varied to allow for identifying their effect on the potential presence of conflicts. Finally, the number of lanes per approach was varied to properly estimate their effect on conflict potential. It should be noted that the number of pedestrians simulated per approach is relatively high which was considered essential to allow for identifying an adequate number of conflicts in order to develop reliable prediction models.

The VISSIM software was used to produce vehicle trajectory files for each scenario developed. Trajectory files for each of the crash scenarios were processed by the SSAM program to determine the resulting conflicts. Default SSAM parameters including 1.5 second time to collision and 5.0 second post encroachment time were used in the analysis. For the purposes of this analysis, only those conflict types matching the primary conflict type were used.
in the development of the models. Conflicts for each model run were evaluated and a database developed matching the independent evaluation variables described above with the number of conflicts observed.

Regression models were developed using the SPSS statistical software to determine the influence and significance of the independent variables consider in the analysis for both vehicular and pedestrian conflict models. In addition to the independent variables, several other variable transformations were also examined. The step-wise regression approach was used to narrow the list of significant variables and develop the final models. The basic premise for the development of the combinations examined was to pair an exposure estimate (volume or other combinations of volume with variables such as lanes or green percent of cycle) with the number of conflict points in the traffic stream. Finally, linear, log, exponential and polynomial models were evaluated to determine the best fit to the data. The full range of independent variables evaluated for inclusion in each of the models is summarized below. All models have been evaluated for colinearity of variables and have a variance inflation factor (VIF) less than 2, indicating there is not significant multi-colinarity among the variables [8]. Parameters of all models also have an associated p-statistic less than 0.01, indicating statistical significance of the parameter included in the final model [9]. The models developed for the vehicular conflicts are summarized in Table 1. The final models all have an R² value greater than 0.67 with the rear end having the highest R² value of 0.84. R² is a measure of the goodness of fit of the model and a measure of the data variability explained by the numerical model. This high level of fit, demonstrates that the models developed here can explain over 67 percent of the variability seen in the conflict distributions.

Table 1 Summary of vehicular conflict prediction models

| Crash Type (R²) | Model | Variables |
|----------------|-------|-----------|
| Left Turn (0.73) | 38.612 +0.00007626(x₁) +0.006(x₂) – 0.559(x₃) | (Left turn volume) × (Opposing through volume) × (Number of lanes) |
| Rear End (0.84) | -3.284 – 0.007(x²) +1.463(x₁) | (Approach critical volume) / (Percent of green time allocated to phase) |
| Sideswipe (0.67) | 0.290 + 0.000001279(x₁) +0.001(x₂) – 0.00004(x₃) | (No. of lanes – 1) × (Turn volume) × (App. vol.) / (No. of lanes) |
| Right Angle (0.80) | -0.632 + 0.095(x₁) + 0.0001(x₂) – 0.006(x₃) | Right Turn Volume |

For pedestrian-vehicle models, the approach undertaken was to develop a specific model for each intersection type that would allow for distinguishing such conflicts by the location of the conflict, i.e. whether it occurred along the major or the minor road. The models considered several variables including conflicting volumes, number of lanes, percentage of left turns, and traffic and pedestrian volumes. The conflicting volume is defined in this study the product of the number of vehicles conflicting with the number of pedestrians at each intersection area. In the case of unsignalized intersections and roundabouts, the conflicting volume was equivalent to the approach and turning vehicular volume conflicting with the pedestrian volume crossing a conflicting leg of the intersection. For the signalized intersections, it was equivalent to the turning vehicles conflicting with pedestrians at the adjacent leg of the intersection. Traffic and pedestrian volumes were considered only for models that did not include the conflicting volume to avoid using variables that are related and thus violate the assumption of independence among predictors. In general, the conflicting volumes were better predictors than the traffic and/or pedestrian volumes alone. General linear regression, exponential regression, Poisson and negative binomial models were evaluated. Overall the results indicated that the Poisson and negative binomial models are not appropriate, based on the ratio of the deviance to degrees of freedom that was less than 1 indicating an under-
dispersed response variable (i.e. there is less randomness than anticipated or too many cases with no conflicts in the data). The pedestrian-vehicle conflict prediction models are summarized in Table 2.

Table 2 Summary of pedestrian conflict prediction models

| Intersection Type (R²) | Model | Variables |
|------------------------|-------|-----------|
|                        |       | x₁        | x₂        | x₃          | x₄ |
| Unsignalized (0.60)    | -0.42 +0.10(x₁) +0.08(x₂) - 0.92(x₃) | Conflict volume | Turn percentage | Conflict location |
| Signalized (0.32)      | -0.48 +0.008(x₁) +0.03(x₂) + 0.53(x₃) - 1.16(x₄) | Conflict volume | Left-turn percentage | Number of lanes | Conflict location |
| Roundabout (0.71)      | 2.21 +0.1(x₁) - 4.86(x₂) + 0.93(x₃) | Conflict volume | Conflict location | Number of lanes |

6. Intersection design alternative tool (IDAT)

Each intersection design considered for evaluation could be manipulated through the use of a basic design (signalized, unsignalized or roundabout) and redirected or channelized turn movements. This approach was undertaken for estimating both operational and safety performance. For example, the median U-turn operates as a signalized intersection at its center, paired with two adjacent intersections to accommodate left-turning movements. This approach allows for utilizing the basic methods identifying before to estimate the operational efficiency of each design and determine the minimum lane requirements to achieve the desired v/c ratio 0.90. In addition, safety, right-of-way requirements, and access capabilities are considered to evaluate relative advantages and disadvantages and establish a composite score that could identify candidate designs for the given set of conditions. The following sections identify the components of the IDAT software.

For each intersection design a variety of lane configurations is evaluated. These include eight different left and right turn auxiliary configurations for each of one, two and three through lane combinations for a total of 24 combinations for each approach. All combinations of each approach are evaluated with each approach, except that a restriction is placed that both the major and minor street have the same number of through lanes. Fig. 1 shows the eight different approach combinations for a single through lane alternative.

These eight approach configurations developed for the signalized intersections served as the basis for the other intersection alternatives, which were modified to meet the unique demands of each of the differing designs. Each of the eight approach configurations were scored based on 1) the total number of lanes used in the design and 2) the desirability of the configurations from an operational, safety and driver expectancy (i.e. commonality of design used) standpoint. Lane configurations were rated as follows:

- 1: 8 (Highest Score)
- 2: 6.5
- 3: 6.5
- 4: 5
- 5: 4
- 6: 2
- 7: 3
- 8: 1 (Lowest Score)
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A total intersection score is estimated for the designs with a v/c ratio of less than 0.90 (i.e. feasible combinations) as the sum of the individual approach scores. The combination with the highest score is then chosen as the preferred configuration for that alternative. For each alternative design, a preferred configuration is evaluated for single-lane, two-lane and three-lane approaches on the major street. If multiple approach lane configurations are feasible for a given alternative, those with a greater number of through lanes are identified as “Not Recommended” to identify that a configuration with a smaller footprint is feasible.

Each alternative is also evaluated based on the safety performance regarding with respect to vehicular and pedestrian conflicts. Estimates of the number of potential conflicts are obtained for each alternative and these are normalized based on the range of conflicts using a score between 1.0 (worse) and 5.0 (best). The alternative with the lowest number of conflicts receives a score of 5.0 and the one with the highest receives a score of 1.0. All other alternatives are scored based on this relative scale.

The feasible alternatives are then further evaluated using a weighted scoring scheme to identify the most appropriate designs that merit additional detailed evaluation. The scoring system examines the right-of-way requirements (based on the number of lanes), safety performance considering the safety scores for vehicular and pedestrian safety as well as bicycle safety, and access management capabilities. Each category is assigned a weight to indicate its level of importance in the project. In this version, IDAT uses an equal weight (0.33) for each criterion (right-of-way, safety and access management). Each alternative is scored against these criteria and a composite total score is developed.

An expert panel was employed to develop the alternative scoring to evaluate bicycle accommodation, access management potential and bicycle safety. The panel consisted of traffic operations, highway safety, and design engineers who were asked to evaluate and score each intersection design based on their a priori experience. For example, roundabouts may be ranked higher for access management potential than a traditional signalized
intersection as they can implicitly accommodate turning vehicles redirected by the circulatory roadway. Superstreet or Median u-turn alternatives may score higher still as they require restrictive medians and accommodate u-turns. The scoring method used a five-point scale where 1.0 represents the lowest score and 5.0 the highest. The safety level was scored only for bicycle traffic, since vehicular and pedestrian estimates were obtained through the potential conflict prediction models. A unique score for each category is created in this manner, since there are different safety concerns for each travel mode. Even though these scores are subjective, they are the only means for establishing such comparisons since such data is not available for all the intersection types examined.

For the right of way, the size of intersection was used to develop the scores. The size of the intersection becomes a critical determinant of suitability of each design, since all alternatives are developed to operate at the same level of efficiency. This is a relative comparison between alternatives, since precise estimates at the preliminary design stage are typically not available due to topographic or other constraints on the site. The scoring method provides 5 points for an approach with a single lane. Approaches with 5 or more lanes receive 0 points. Turn lanes, such as a left or right auxiliary lane are counted as ½ of a lane, since they will likely be required for only a short length. The average score of all approaches for the design is used in the final scoring. Jughandle and Bowtie designs were deducted 2 points overall due to the increased space requirements for this design. Even though intersection size may be disaggregated into components, including number of approach lanes, intersection number of lanes (including auxiliary lanes) and physical intersection area, such a detailed approach was not deemed appropriate for the level of anticipated use of the evaluation tool. An example of the IDAT output is shown in Fig. 2. The data entry required for the model is the peak hour turning volumes along with pedestrian traffic by approach. This is typical data required for any design and therefore no specific or additional data is required.

7. Conclusions

Intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. Moreover, intersection crashes account for approximately 30 percent of all crashes in Kentucky (Kentucky State Police, 2007). As a critical component of the state transportation system, intersection design requires an objective methodology to identify the most appropriate solution that meets the purpose and need of the project as well as addresses site constraints. The current state of practice, while achieving great strides in improving the efficiency of Kentucky’s roadway system, lacks a systematic, objective and well defined approach to evaluating individual design alternatives.

A major component of this effort was the development of methods to size different intersection designs. IDAT identifies the most efficient design (minimum number of lanes) that is capable of meeting a targeted level of operation. As such, the design team will be presented with several options, which meet the minimum operational requirements, allowing examination of other trade-offs such as right of way impacts, safety considerations etc. This approach will eliminate the need to compare different alternatives with varying performance levels across different types of traffic control measures.

It should be emphasized here that this tool is to be utilized as a preliminary evaluation tool in order to determine the most appropriately sized options to be further explored. It is not recommended to be used in lieu of detail analysis of intersection options, where more specific data may be needed for an accurate estimation of the operation of each selected design. Under this concept, the comparison of simple and complicated designs is valid and allowable, since it only compares their potential operational level and safety implications at a common ground. This approach allows for identifying simpler solutions that could address a situation without having to resort to expensive, multi-lane designs.

The CLA approach was utilized to estimate the capacity for each intersection design and it was used as predictor of the delay. This approach allows for evaluating each intersection design and developing the minimum
required lane configuration for a given intersection traffic control scheme while achieving a targeted level of capacity for a given traffic volume. In this version of IDTA, the minimum lane requirements for each intersection design are estimated assuming a level of operation at 90 percent of capacity. This approach allows for developing a comparison where all options will operate at similar levels. This also alleviates the problem of different levels for different designs options and thus makes comparison among alternatives more difficult and often highly subjective.

Safety estimates were also developed for vehicle and vehicle-pedestrian conflicts that could allow for establishing the potential safety performance of the intersections considered. Safety performance of the intersection was quantified by estimating the potential conflicts for each intersection design alternative evaluated for a given scenario. The models were developed by applying the FHWA SSAM on a series of simulated scenarios for each design option. The SSAM identifies potential conflicts that could result in a crash which can be then be linked to the geometric and traffic demand characteristics of the intersection. A variety of volume
combinations were used for each scenario simulated and models were developed that allow the user to predict the number of potential conflicts for each design alternative for a given set of design volumes. Models for vehicular and vehicle-pedestrian conflicts were developed separately and incorporated in the IDAT for screening design alternatives and allowing for a complete and systematic approach for identifying appropriate intersection designs.

The software developed as part the study is ready to be distributed for use to the practitioners. The software allows for the preliminary evaluation of all intersection designs considered and provides a basic method for comparing all of them at an equal level of operation. The software also provides a more robust safety evaluation method for at-grade intersections predicting the number of conflicts for vehicles and pedestrians for each design considered. It should be noted that the evaluation of the alternatives is mainly based on their operational performance and the safety scores for the vehicular and pedestrian safety potential. Both of these indicators are objective in nature, since they are based on current capacity practices (operations), prediction models (safety), and size based on number of lanes (right of way). The only subjective elements are the effects of an alternative on access management and bicycle safety. The proposed alternative is clearly based on objective metrics and thus can provide an accurate list of potential alternatives to initiate a final evaluation of designs.

This paper documents the efforts and approach used to develop a systematic effort for developing and selecting proper intersection designs that could improve operations, safety, and access management. The prescribed tool and methods identified allow for an expanded evaluation of intersection functions beyond a basic comparison of operational performance. By designing an intersection to fit the operational parameters desired all intersection design may then begin on equal ground. The final determination of the preferred alternative can then be made, not on which alternative has 10 seconds less of delay, but rather which best accommodates an access management plan, provides desirable pedestrian or bicycle safety, or fits within the available right of way. As a result this tool will be invaluable in pursuing alternative treatment plans such as access management corridors and implementing innovative intersection treatments such as roundabouts and alternative left-turn treatments.

The ultimately applicability of this approach is to identify a wider range of feasible intersection design alternatives with significantly less effort, than is currently afforded through the independent evaluation of intersection designs through capacity software or micro-simulation programs. Notable is the approach taken to sizing intersection alternatives to deliver a targeted performance level so that comparative evaluations do not have to involve comparison of operations, but instead can focus on costs and impacts to the associated project area. The proposed approach provides a greater efficiency in the evaluation and conceptual design of intersection alternatives, with the intent to achieve greater operational efficiency and improved safety performance. This allows for a more appropriate and properly customized design for each intersection avoiding the use of “standard or typical” designs.

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