Intersection, Diamond, and Three-Level Diamond Grade Separation Benefit-Cost Analysis Based on Delay Savings

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A method for determining when traffic flow should be grade separated would be an invaluable tool for the traffic engineer/planner. The results of this study facilitate choosing proposed grade separation improvements on the basis of an evaluation of the reduced delay benefits to the cost of a grade separation. This methodology can assist decision-makers in determining when grade separations are appropriate. The analysis is centered on the Federal Highway Administration's TRANSYT 7F model. An economic analysis that presents the benefit/cost methodology for ranking a grade separation project is included.

Transportation engineers and planners are often required to rank intersection-to-interchange improvement projects on the basis of a minimal amount of input. The objective of grade separation is to enhance total overall traffic movement, to rank traffic movement on one functional class of roadway over another, or to perform both of these functions. Grade separation increases operational efficiency and therefore improves the overall traffic movement at the junction of the roadways by increasing the amount of traffic the roadway junction can accommodate, lowering overall delay, and decreasing certain types of accidents.

No guidelines currently exist for warranting a grade separation at a roadway intersection. The possible operational improvement that the grade separation will have on the intersection has not been adequately evaluated. Typical measures of operational improvement are the delay savings and the increased capacity of the interchange versus the intersection. Delay can be used for a relative comparison of the improvement and also in an economic analysis by assigning a value to this delay time. This study was conducted to establish a procedure for evaluating grade-separation projects based on quantifying vehicle-delay improvement. Vehicle delay can then be used as one of the criteria for considering grade separation at an intersection.

A grade separation, prompted by the desire for a gain in operational efficiency, can be accomplished by many different types of interchanges. One set of through movements can be grade separated by a single-point urban interchange, a conventional diamond, a three-point diamond, or a split diamond. Two sets of through movements can be grade separated by a three-level diamond or a stacked diamond. There are many other interchange configurations, with varying levels of operational efficiency. The fully directional interchange serves as the upper limit in efficiency and cost. This analysis focuses on delay improvements gained by grade separation from a high-type intersection to a conventional diamond interchange to a three-level diamond interchange.

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STUDY PROCEDURE

The study was not an attempt to acquire data for estimating delay for every possible variety of intersection and interchange. Rather, its purpose was to identify major characteristics to permit comparison of one type of improvement with another.

A major portion of potential project benefits can be attributed to delay reductions. At an interchange, traffic consists of two components: the grade-separated vehicles and the vehicles that are operating at grade and passing through the signal system. Separate procedures are necessary for evaluating the at-grade and grade-separated portion of interchanges. This report explores the at-grade signalized portion of interchanges. For purposes of this study, grade-separated through volumes less than or equal to 1,800 vph/lane will contribute a negligible amount to the system delay.

After evaluating a variety of alternatives, the TRANSYT 7F computer model was selected for developing relationships among various at-grade configurations. TRANSYT 7F is capable of optimizing the signal controls at intersections, diamond interchanges, and three-level diamond interchanges.

Setting Input Variables

TRANSYT 7F is a macroscopic deterministic traffic model. The required input data for the TRANSYT 7F model (*1*) include geometrics, phasing, clearance intervals, saturation, and traffic volumes. There are an infinite number of combinations of these variables. The comparison presented here is for planning purposes and is intended to be as equitable as possible for evaluation of the operational upgrades from intersection to diamond interchange to three-level diamond interchange.

To simplify the evaluation, all of the at-grade intersections considered had separate left-turn and right-turn bays. Figures 1–3 show the geometric layout of the various types of at-grade signalized intersections. The saturation flow rate was estimated to be 1,700 vph for left turns and 1,750 vph for through and right-turning traffic. Right-turning traffic was phased with its corresponding through movement. Phasing at

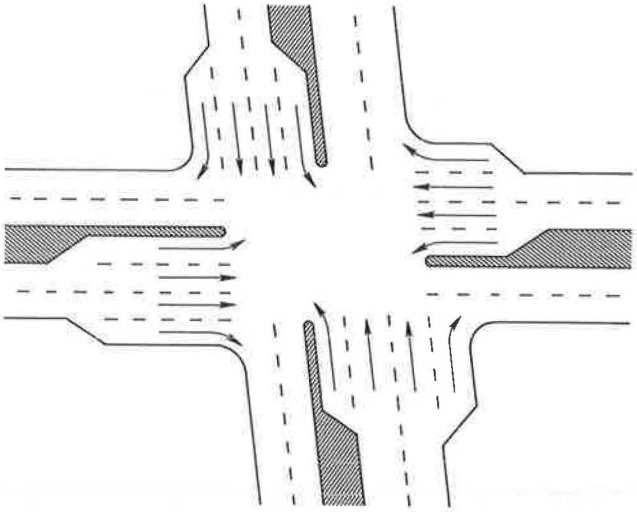

FIGURE 1 Intersection geometrics used in T7F simulation.

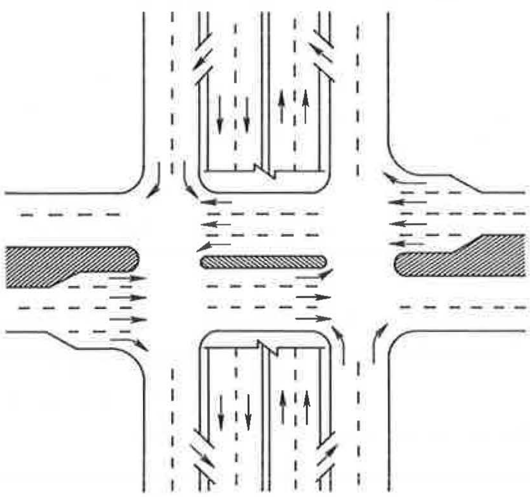

FIGURE 2 Diamond geometrics used in T7F simulation.

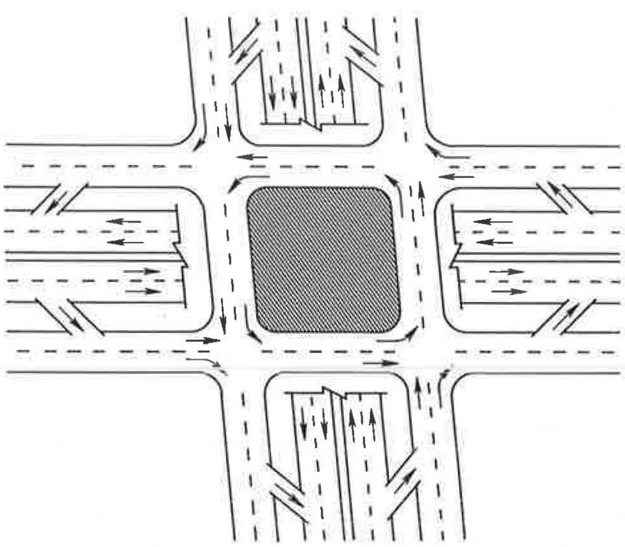

FIGURE 3 Three-level diamond geometrics used in T7F simulation.

the high-type intersection consisted of four phases with leading left turns. The diamond interchange operated on three phases, with an appropriate offset between the two intersections. The three-level diamond ran on a coordinated two-phase pattern.

A minimum cycle length of 30 seconds was used on the three-level diamond interchange, and a minimum cycle length of 40 seconds was used on the intersection and diamond interchange. A clearance interval of 3 seconds was used throughout the simulations. Another simplifying assumption was that the cross-road directional volume split was 1 to 1, or 50/50. Each right- and left-turn movement was light (10 percent) or heavy (20 percent) on each approach. This provided two scenarios on each configuration: light turning movements (right + left = 20 percent of through movement) and heavy turning movements (right + left = 40 percent of through movement).

STUDY RESULTS

Figure 4 presents the total system delay (stopped delay + approach delay) calculated by TRANSYT 7F at the intersection on the basis of hourly volume and turning movement percentages and the other assumptions made with the geometrics, phasing, and clearance intervals. The curves were obtained by starting with a low initial traffic volume and incrementally increasing the volume in each succeeding computer simulation until oversaturation occurred.

The plots in Figure 4 appear to approach a vertical asymptote, much like the underlying TRANSYT 7F delay function. When the total of all four approaches is 6,000 vph, average delay per vehicle is approximately 60 seconds, making the overall system delay 100 vehicle hours.

A diamond, in essence, removes two through movements from the at-grade intersection and replaces one signal with two coordinated signals. When interpreting the delay calculations of TRANSYT 7F, the overall delay of the two-signal diamond interchange system will be compared with the overall delay of the one-signal at-grade intersection system. The same methodology is used when comparing the system delay of the four-signal, three-level diamond with the two-signal diamond and the one-signal at-grade intersection. As a result, the system delay on the ordinate represents a summation of all of the intersection(s) delay within the system. This step was taken to provide an equitable operational comparison of the different grade separation options.

In Figure 5, which is a plot of the diamond interchange simulation results, the same asymptotic relationship is evident. The abscissa is marked with three different scales; the top scale reflects the total number of vehicles in the interchange system. From this total, two of the through movements have been removed by the grade separation, leaving the accompanying turning movements to negotiate the at-grade signals. The bottom two scales reflect the actual number of vehicles entering the at-grade intersections. The two-diamond interchange curves are very similar in shape to the at-grade intersection curves once the abscissa is rescaled or compressed. The three-phase, coordinated signals of the at-grade portion of the diamond interchange approach 100 vehicle hours of delay when total at-grade entering volume is 6,000 vph.

In Figures 1–3, the initial assumptions is that each movement would have at least one lane to travel through the at-

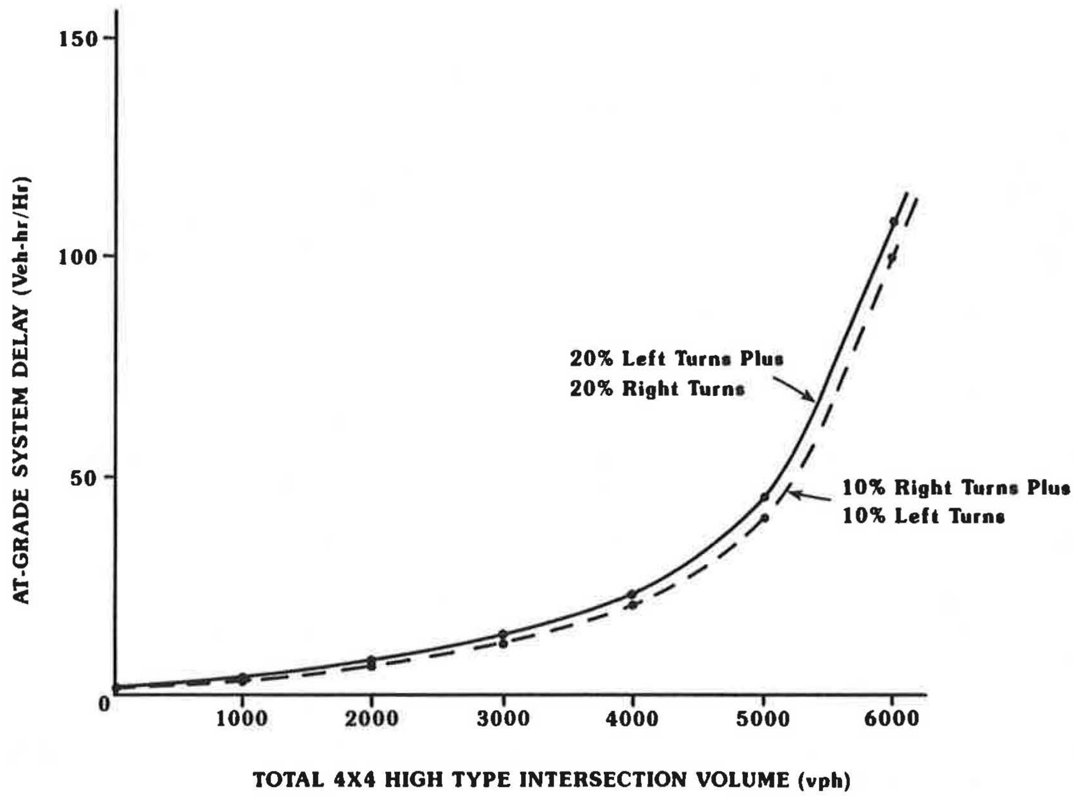

FIGURE 4 System delay for high-type interchanges.

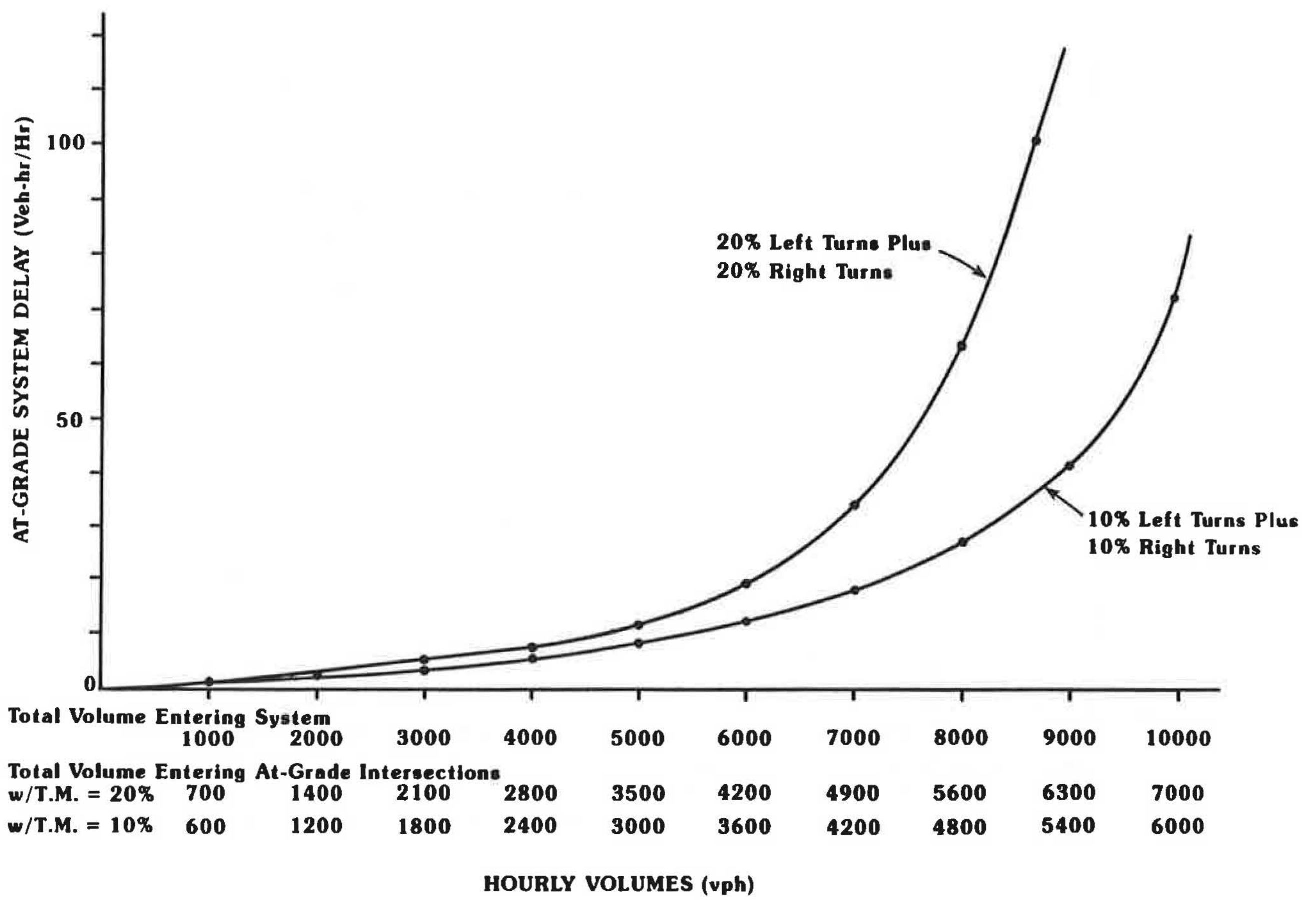

FIGURE 5 System delay for diamond interchange.

grade portion of the system. Both frontage road traffic and u-turning traffic were negated to provide a consistent comparison throughout. This is an appropriate assumption for an arterial-arterial interchange, where no frontage roads would exist. Also, frontage road and u-turning volumes are rarely known at the planning stage.

Figure 6 demonstrates that the same asymptotic relationship exists in the three-level diamond interchange. The top abscissa scale is the total number of automobiles in the three-level diamond system. Four through movements have been grade separated or removed from the at-grade intersection. The remaining turning movements must negotiate the at-grade signals. The two lower abscissa scales reflect the residual of the through movements and are a combination of the right turns plus the left turns. With two through lanes in each direction (Figure 3), the total system capacity for this roadway junction is 4 directions × 2 lanes/direction × 2,000 vph/lane = 16,000 vph. Therefore, the maximum volume that can enter the 4 × 4 system is 16,000 vph.

A three-level diamond interchange would probably have three or more lanes on each at-grade approach. Figure 3 represents the geometrics assumed for this analysis only. Each turning movement had a separate lane while it negotiated a signal controlled intersection. Note that with 40 percent (left + right) of the grade separated through movements exiting, the exit ramp is approaching its capacity [(0.40 × 2 lanes × 2,000 vph/lane) = 1,600 vph]. This factor will act as a constraint on the at-grade capacity of the system. Once the two lower abscissa scales are compressed, a delay relationship very similar to the intersection and diamond relationships is formed. The at-grade, signalized portion of the three-level diamond reaches its capacity at 6,000 vph entering volume when the system is approaching its maximum entering volume of 16,000 vph and there are 20 percent left turns and 20 percent right turns on all approaches.

A family of curves has been developed for the three different geometric scenarios. Figure 7 shows a relative comparison of system delay with total vehicles in the system and a comparison of the amount of hourly traffic that each system can accommodate. Each roadway junction type has an upper and lower limit that is actually set by the severity of the left-turning movement demand and the number of through lanes on each roadway.

Figure 7 also plots the range of intersection delays within each system. This analysis neglects any delay on the free-moving through lanes. By definition, the delay on the grade-separated portion should also be included with the overall system delay if the free-moving through lanes become congested. However, with at least 20 percent or more of the traffic (10 percent right turns and 10 percent left turns) negotiating the at-grade portion of the interchange, this leaves 1,800 vph/lane on the through lanes on the three-level diamond. The grade-separated through lane delay has been omitted and could best be computed by a speed/density analysis. The grade-

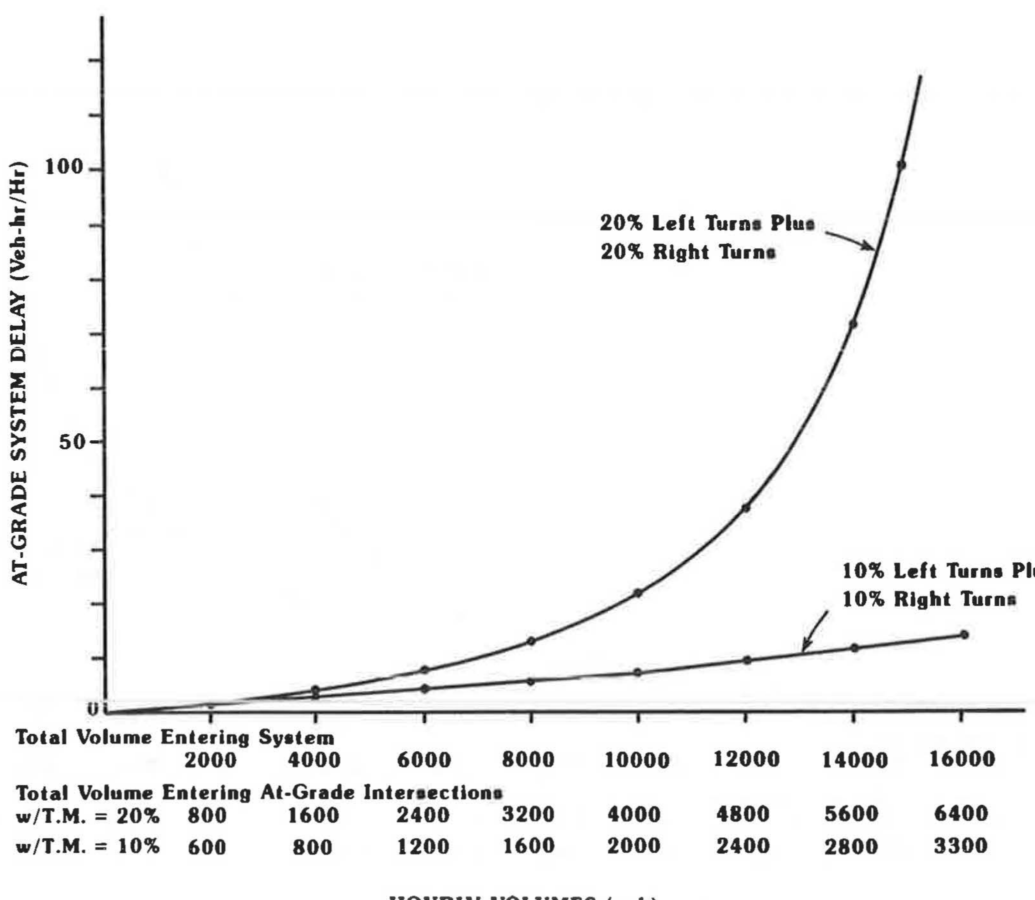

FIGURE 6 System delay for three-level diamond interchange.

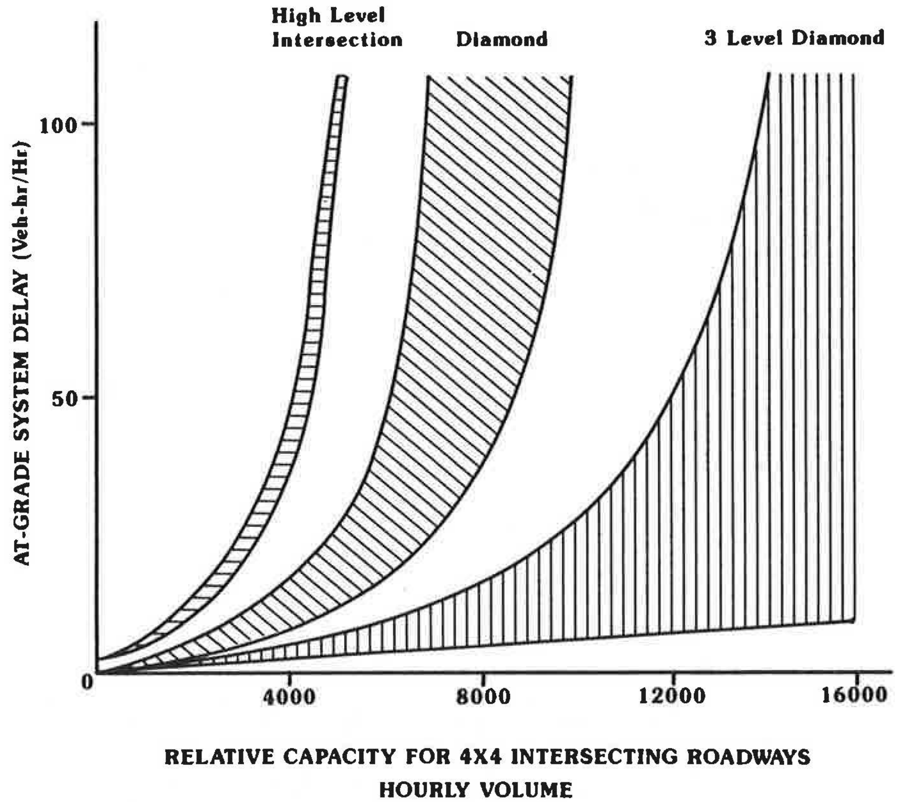

FIGURE 7 At-grade delay versus system capacity.

separated lanes on the diamond interchange are operating at 1,000 vph/lane when the at-grade delay reaches 60 seconds per vehicle, incurring a small amount of delay on the grade-separated through lanes and adding very little delay to the overall diamond system. There are additional volume benefits unaccounted for on the through lanes of the diamond interchange.

The underlying asymptotic delay relationship, as demonstrated in Figures 4–6, follows the same general shape for each at-grade signalized portion of the three types of roadway junctions (with these assumed geometrics). The approximate capacity of all three at-grade intersection systems is 6,000 vph. At the transitions from an at-grade intersection to a diamond interchange to a three-level diamond interchange, it appears that any efficiencies gained by losing a phase and removing two through volumes are counterbalanced by increasing the number of coordinated traffic signals. Therefore, for planning purposes, a single delay equation can be developed for evaluating the delay incurred on the signalized, at-grade portion of these three types of roadway junctions.

DEVELOPMENT OF A DELAY EQUATION

A delay relationship based on assumed geometrics and an hourly volume has now been established. The delay calculation routine can be greatly shortened by fitting an equation to the relationship and using hourly traffic as the only independent variable for calculating delay. This equation can then be used in an hour-by-hour, day-by-day, year-by-year economic planning analysis for evaluating a grade separation under the assumed geometrics.

The similarity among the intersection, diamond, and three-level diamond at-grade delay curves can be used to an advantage. This similarity in shape means that direct comparisons can be made from intersection to diamond, diamond to three-level diamond, and intersection to three-level diamond. Therefore, any amount of traffic removed from the at-grade portion of the intersection becomes a benefit.

By using the SAS curve fitting routine, an equation was derived for the observed delay relationship (*2*). An r^2 of 0.92 was obtained. For a 4 × 4 high-type intersection (four through lanes by four through lanes), the at-grade delay equation is:

$$\text{Delay } 4 \times 4 = 1.1778\ e^{v(.00072452)}$$

where delay is in vehicle hours per hour and v = total volume entering at-grade intersection (veh/hr).

By using the same procedure, a similar equation may be developed for a 6 × 6 high-type intersection. Only an additional through lane has been added to the geometrics; all other variables remain the same.

$$\text{Delay } 6 \times 6 = 1.2662\ e^{v(.00056726)}$$

Delay and v have been defined previously.

In Figure 8, the 6 × 6 delay function yields a higher amount of capacity. The extra capacity comes from the additional through lanes. The delay also goes up in a corresponding manner. An upper limit was placed on the curves. It is rec-

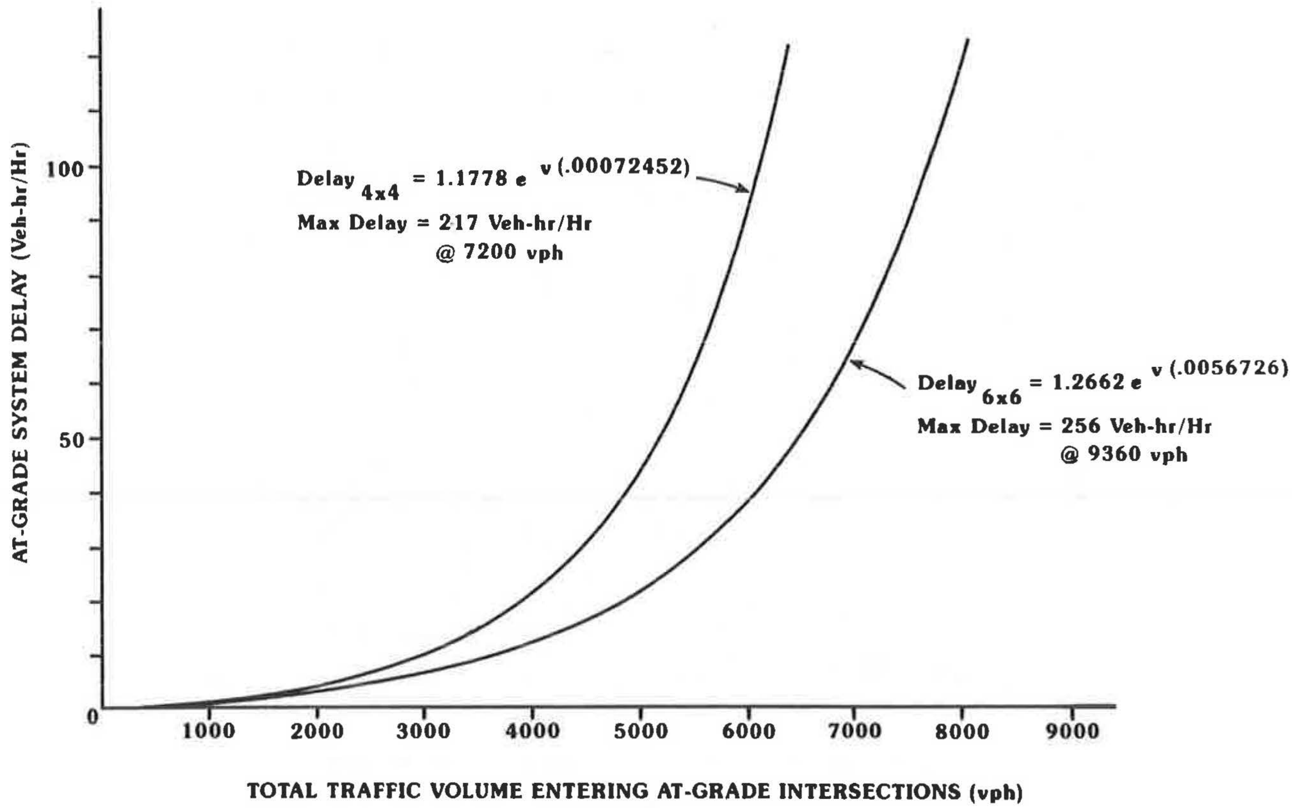

FIGURE 8 Derived delay equations.

ommended that the derived delay relationships be used only for projected demands that are no greater than 20 percent in excess of capacity because it is likely that traffic will divert to other routes. The following economic analysis limits delay when the capacity reaches 120 percent of the at-grade capacity.

ECONOMIC ANALYSIS

The derived equation(s) can be used in an economic analysis to determine if the benefits to the motorists of reduced delay will offset the cost of a grade-separated structure. The procedure is to take an average daily traffic (ADT) volume and an assumed hourly distribution of vehicles and calculate the delay using the derived delay equation. The delay is then summed over the year. A monetary value is assigned to the delay time and a delay cost calculated. The ADT is increased to reflect an average yearly growth rate, and the process is repeated. A net present worth can then be computed and a relative comparison made.

Grade separations cost somewhere between \$3 and \$5+ million, depending on site-specific conditions. If the public's delay reduction over the project's life is equal to or exceeds the construction cost of a grade separation, then the grade separation is warranted.

The economic evaluation assumed a Texas urban and rural traffic distribution developed by Urbanik (*3*). These specific distributions were obtained from a previous study of urban and rural facilities, and the *k* factors are 7.63 percent and 8.78 percent respectively. For purposes of this example, occupancy of each automobile was set at 1.25 persons. A value of \$7.80 per vehicle-hour was allotted for the delay time. The value of commercial truck time was estimated as \$19.00 per vehicle-hour. These values reflect the value of time to the motor vehicle occupants and associated vehicle operation costs (*4*). Yearly delay was based on 250 working days. A net present worth approach with 5 percent interest rate and a 20-year project life was used to assess the current economic value of delay. Truck traffic was assumed to be 10 percent. Traffic growth was assumed to be 2 percent per year during the 20-year project life.

Oversaturated conditions in any signal system will yield extremely high delay numbers. For planning purposes, a maximum saturation ratio of 1.2 was arbitrarily designated. Therefore if the assumed capacity of a junction were 6,000 vph, the maximum capacity that could pass through the junction would be 6,000 vph × 1.2 = 7,200 vph. This limits the amount of benefits that a planner can take by putting a maximum upper limit on the hourly volume. No excess volume is carried over into the next hour. It is believed that this is a more conservative procedure, and no undue delay credit is taken.

The following tables were generated with the derived delay relationships. Tables 1 and 2 apply only to high-level, 4 × 4, and 6 × 6 roadway junctions. Any combination of grade separations may be evaluated, for example, intersection to diamond, intersection to three-level diamond, or diamond to three-level diamond. These comparisons can all be made because the benefits are a function of the volume of traffic removed from the at-grade signalized portion of the interchange only.

Tables 1 and 2 represent the total delay costs to the motoring public. To determine if grade separation is warranted on the basis of a savings of delay, the existing at-grade ADT must be known. The benefits are found by determining the amount of traffic removed from the at-grade volume and taking the difference between the delay costs of the existing ADT and the remaining at-grade ADT. The following three examples illustrate this procedure.

- Urban upgrade from 4 × 4 high-type intersection to diamond interchange.

  - Known: Existing at-grade volume = 50,000 ADT
    Will remove 20,000 ADT from intersection
    Remaining at-grade ADT = 30,000
  - Net present worth of delay reduction benefits (millions) = \$7.536 − \$3.497 = \$4.039.

A saving of \$4,039,000.00 in delay to the motoring public is achieved over a 20-year period by building a diamond interchange to replace the intersection. The delay saving benefit for this example is roughly equivalent to the cost of building a diamond interchange.

- Rural upgrade from 4 × 4 high-type intersection to a three-level diamond interchange.

  - Known: Existing at-grade volume = 60,000 ADT
    Will remove 40,000 ADT from at-grade ADT
    Remaining at-grade ADT = 20,000
  - Net present worth of delay reduction benefits (millions) = \$19.874 − \$2.220 = \$17.654.

A saving of \$17,654,000.00 in delay to the motoring public is achieved over a 20-year period by replacing the intersection with a three-level diamond interchange. The delay reduction benefits for this example exceed the cost of building a three-level diamond interchange.

- Urban upgrade from a diamond interchange to a three-level diamond interchange (on a 4 × 4 roadway junction).

  - Known: Existing at-grade volume = 60,000 ADT
    Will remove 20,000 ADT from at-grade ADT
    Remaining at-grade ADT = 40,000
  - Net present worth of delay reduction benefits (millions) = \$17.826 − \$5.831 = \$11.995.

A saving of \$11,995,000 in delay to the motoring public is achieved by building a three-level diamond interchange to replace the diamond interchange. This delay reduction benefit exceeds the cost of building a three-level diamond interchange.

When a diamond is upgraded to a three-level diamond, the number of through lanes on the at-grade portion of the roadway intersection determines which of the two tables to select. The variables that have an impact on the net present worth calculations are value of delay time and operating costs, occupancy of the vehicles, interest rate, ADT, hourly distribution of ADT, yearly growth rate of ADT, project life, and percentage of commercial trucks. All of these variables are used with the delay equation(s) and can easily be incorporated into a computer spreadsheet program.

TABLE 1 NET PRESENT WORTH DELAY EVALUATION

	Total Delay Costs, 4 × 4 High-Type Intersections(s) ($ × 10⁶)	
Average At-Grade Daily Traffic	Rural	Urban
10,000	1.421	1.414
20,000	2.220	2.178
30,000	3.642	3.497
40,000	6.232	5.831
50,000	11.051	7.536
60,000	19.874	17.826
70,000	33.728	30.542
80,000	51.724	45.977

TABLE 2 NET PRESENT WORTH DELAY EVALUATION

	Total Delay Costs 6 × 6 High-Type Intersections(s) ($ × 10⁶)	
Average At-Grade Daily Traffic	Rural	Urban
10,000	1.396	1.392
20,000	1.954	1.930
30,000	2.822	2.749
40,000	4.194	4.014
50,000	6.390	4.554
60,000	9.957	9.135
70,000	15.824	14.181
80,000	24.884	22.386

CONCLUSIONS

For planning purposes, the operational efficiency of a given geometric intersection and its corresponding grade-separated improvements can be quantified by a single delay equation. This equation may be used for estimating the operational effectiveness of a grade separation project for use in a benefit/cost analysis.

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