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The Influence of Geometry on Operational Performance of Signal-Controlled Junctions

by Dimitris Sermpis

The aim of this study is to investigate the influence of geometry on the performance of signal-controlled road junctions under fixed-time and system D traffic responsive signal control by using 16 experimental scenarios with several different traffic and geometric characteristics. In the estimated log-linear models for delay per unit of time, the principal effects of lane width and turning radii were as expected. The effect on delay of the interaction between lane width and turning radii was found to be of substantial importance at light traffic flow, while the interaction between turning radii and signal control was found to play a significant role at medium traffic flow.

INTRODUCTION

In designing a signal-controlled junction, there are a number of elements that must be considered, two of which are the geometric layout and the signal control strategy. These two elements have a reciprocal relationship. A fixed geometry can be used as a starting point in the design process and the appropriate signal control strategy that results in the best operational performance of the junction can then be chosen. Furthermore, after deciding on the desired signal control strategy, small changes in the geometric characteristics of the junction can be made to further improve its operational performance.

There are many computer packages that can help a traffic engineer design a signal-controlled junction, calculate the signal timings and estimate its operational performance. The aim of this study is to investigate the influence of junction geometry on the operational performance of isolated signal-controlled junctions under different signal control strategies and arrival traffic flows. As a measure of operational performance, the rate of delay due to the presence of the signals (given in vehicle-hours per hour, or simply vehicles) was used. For a traffic stream this rate of delay is defined as the product of the mean delay due to the presence of the signals and the arrival rate in the examined traffic stream. The sum of the rates of delay due to the presence of the signals for all the vehicle streams at the junction gives the rate of delay due to the presence of the signals for the whole junction.

The remaining sections of this paper successively describe the methods of estimating delay at junctions using a microscopic model, the experimental scenarios used in this research, the methodology, the main analysis and the discussion of the results, and the conclusions of this study.

METHODS OF ESTIMATING DELAY AT JUNCTIONS USING A MICROSCOPIC MODEL

There are two methods of estimating delays at road junctions, steady-state and time-dependent. During periods of heavy demand, it is rarely economic to provide junctions with sufficient capacity to cope with all conditions of operation likely to occur. During these periods, the results of steady-state methods of estimating delay do not apply. From the steady-state category, the Webster (1958) method and the HCM method (Transportation Research Board 2000) are most commonly used. From the time-dependent methods, the Australian method (Akcelik 1981, 1988, 1990a, b) and the Kimber and Hollis (1979) method (which is an approximation method, allowing the growth and decay of the queues to be predicted within recourse to probabilistic calculations) are commonly used. These methods take geometry into account in the estimation of saturation traffic flow and hence, the degree of the saturation of the junction. For the needs of this research, the Kimber and Hollis (1979) delay expression was used for comparison because it is a well established formula and better accommodates the needs of this study.

For the needs of this study, the microscopic simulation package SIGSIM (Silcock 1993, and Law and Crosta 1999) was used. SIGSIM is a vehicle-by-vehicle traffic simulation program that can be used to model an isolated signal-controlled junction or a signal-controlled road network. For the simulation of vehicle movement, it uses a mathematical model developed by Gipps (1981, 1986). SIGSIM can simulate vehicle movement under a number of signal control strategies including fixed-time and traffic-responsive system D signal control. The system D traffic-responsive signal control strategy seeks for gaps, which will indicate that few vehicles are arriving in the streams having right-of-way. In that case, these traffic streams will no longer be shown a green signal if there are vehicles waiting in conflicting traffic streams. Because the simulation is for steady-state arrivals on each approach, the scope of the system D traffic responsive signal control to outperform the fixed-time signal control is limited to allowing for random variation about the steady mean arrival rate. In practice, however, traffic-responsive signal control also typically adjusts for systematic variation in mean arrivals rate over the period of time for which any particular signal timing is implemented.

After a thorough comparison between the estimates of the simulation program SIGSIM and the results of the Kimber and Hollis delay expression – in terms of rate of delay – it became apparent that there was a substantially and statistically significant difference between them. The reason is that SIGSIM simulates the whole movement of each vehicle, and therefore the total rate of delay, comprises not only the rate of delay arising from the presence of the junction and the operation of the signals, but also the rate of delay due to other vehicles. This delay occurs because vehicles travel some or all of the distance through the simulated network at less than desired speed due to the presence of other vehicles.

A method named 'Realistic – Ideal' (Sermpis 2003) was developed to overcome this phenomenon. The concept of this method of analysis is to simulate vehicles' movements realistically (as they move under the prevailing signal control characteristics) and also ideally, as if each stage was shown 100% of green time. In that way, the rate of delay as a result of the vehicles' ideal movement can be compared to the rate of delay as a result of the vehicles' realistic movement. If the other forms of delay have the same effect on the realistic and the ideal movement of the vehicles, they would be eliminated by the subtraction of the estimates of the rate of delay produced by the two simulations. Therefore, the difference between the two rates of delay should be an estimate of the rate of delay due to the presence of the signals.

In this method of analysis, road link length has an effect on estimated delay. To match the rate of delay given by the well-established and widely used Kimber and Hollis (1979) delay expression, it was decided to adopt a practical approach to test different road link lengths for different traffic flow arrivals and to find out which one broadly matches the rate of delay given by the Kimber and Hollis delay expression across the various scenarios. On the basis of pilot simulations, link lengths of 800 meters for heavy traffic flow, 600 meters for medium traffic flow and 400 meters for light traffic flow produced rate-of-delay values which were not statistically significantly different from those of the Kimber and Hollis delay expression.

EXPERIMENTAL SCENARIOS

For the purpose of this study, two types of junctions were examined, crossroads and T-junction; the types that are more frequently used in practice. The whole analysis was based on left-side driving. For each junction type, two different sets of movements were chosen. For crossroads, in the first set, right-turns were prohibited and only four left-turns were allowed (Scenarios [1], [2], [5], [6] – Figure 1), while in the second set two right and two left-turning movements were allowed, one for each direction and the same for opposing directions (Scenarios [3], [4], [7], [8] – Figure 2). For T-junctions, in the first set, all the movements were allowed except the one possible right turn from the major road (Scenarios [9], [10], [13], [14] – Figure 3), while in the second set all the possible movements were allowed (Scenarios [11], [12], [15], [16] – Figure 4). In addition, two sets of turning percentages commonly found in practice were examined. Wherever there were two movements from the same arm, the one being straight ahead and the other being a turn, the arrival traffic flow was either split into 75% moving straight ahead and 25% turning or 50% moving straight ahead and 50% turning. The exception is a minor road at a T-junction, where the arrival traffic flow was always split into 50% turning to the left and 50% turning to the right. Each arm had the same amount of traffic.

Figure 1: Experimental Scenarios [1], [2], [5], [6]

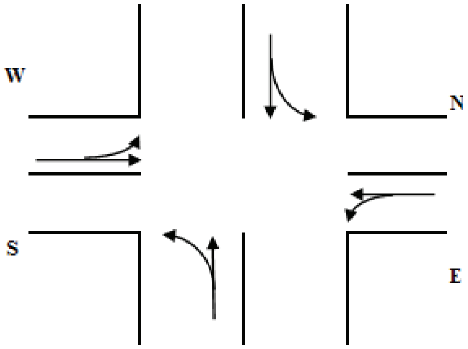


Figure 2: Experimental Scenarios [3], [4], [7], [8]

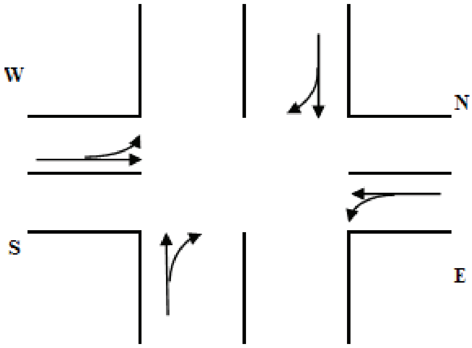


Figure 3: Experimental Scenarios [9], [10], [13], [14]

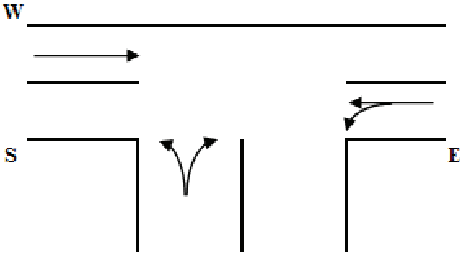
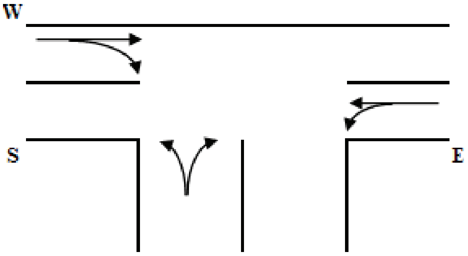


Figure 4: Experimental Scenarios [11], [12], [15], [16]



In relation to vehicle movement and number of lanes, two different cases were examined. In the first case there was just one-lane per approach road, and the analysis was based on the existence of one traffic stream per approach road. In the second case, there were two lanes per approach road. In this case, in the scenarios where the arrival traffic flow was split into 75% moving straight ahead and 25% turning, the vehicles which would move straight ahead could use both lanes and the vehicles which would turn could only use the one lane closest to their turn. On the other hand, in the scenarios where the arrival traffic flow was split into 50% moving straight ahead and 50% turning, one lane was used only for the straight ahead movement and the other one only for the turn.

A zero gradient (i.e., a flat area) was used throughout. For the lane width and turning radius, three different values were examined. The three lane widths were 3.00, 3.25 and 3.50 meters. For the left turning radius, values of 5, 8, and 11 meters were used, corresponding to different possible curb turning radii. For the right turning radius, values of 10, 15, and 20 meters were used respectively for the right-turning radius. The difference between the two turning radii was larger than the lane width of a single lane to allow for a possible island, ghost-island or hatch space (i.e., vacant space) in the middle of the road, which could take higher values as the turning radii increased. The value of the right-turning radius depended on the number of lanes on each approach. For the calculation of the right turning radius in the two-lane scenarios, four meters were added to the value of the right turning radius in the corresponding one-lane experimental scenario to account for the bigger junction layout. The value of four meters was equal to the value of the lane width of one extra lane plus slightly more for choice of path for the turn.

The scenarios were simulated for three different levels of traffic flow, described as heavy, medium and light. The heavy traffic flow would result approximately in a degree of saturation in the critical traffic streams with delay-minimizing timings in the range between 0.90 and 1.00 (slight overload where the maximum acceptable degree of saturation is 0.90), the medium traffic flow would result approximately in a degree of saturation in the range between 0.70 and 0.80 and the light traffic flow in a degree of saturation less than 0.65.

The previously described scenarios were simulated to investigate the influence of the different geometric features of the junction on its operational performance using the simulation program SIGSIM. As a measure of the operational performance, the rate of delay due to the presence of signals was used, because this is a measure that is useful not only to the traffic engineer for analyzing traffic conditions at junctions, but also as an economic variable for further analysis.

The simulation scenarios were run for both fixed-time and system D non-optimizing traffic responsive signal control strategies. The delay-minimizing objective was used for the calculation of fixed-time timings, which also provided maximum green time for system D control, since the rate of delay was used as the operational performance measure. By taking into account all the above cases, 16 experimental scenarios were examined as shown in Table 1.

The combination of the values of lane width and pairs of right- and left-turning radii produced nine different geometric cases for each of the 16 experimental scenarios. An analysis was made for these nine cases in all 16 experimental scenarios, for both fixed-time and system D traffic-responsive control.

Table 1: Identification of Experimental Scenarios

Scenario No.	Junction	No. of lanes	Turning movement	% of turning traffic
[1]	Crossroads	1	left	25%
[2]	Crossroads	1	left	50%
[3]	Crossroads	1	Right / left	25%
[4]	Crossroads	1	Right / left	50%
[5]	Crossroads	2	left	25%
[6]	Crossroads	2	left	50%
[7]	Crossroads	2	Right / left	25%
[8]	Crossroads	2	Right / left	50%
[9]	T-junction	1	left	25%
[10]	T-junction	1	left	50%
[11]	T-junction	1	Right / left	25%
[12]	T-junction	1	Right / left	50%
[13]	T-junction	2	left	25%
[14]	T-junction	2	left	50%
[15]	T-junction	2	Right / left	25%
[16]	T-junction	2	Right / left	50%

METHODOLOGY

The methodology used comprises three distinct elements. The first part deals with the calculation of the signal timings for each scenario, the second involves the simulation procedure, and the final one involves the fitting and the analysis of the models.

Calculating Signal Timing

For this part of the methodology, the SIGSIGN (Silcock and Sang 1990) package was used. SIGSIGN is a phase-based optimization procedure that provides signal settings for a single junction and was used to calculate the signal timings and the rate of delay for each case of each scenario, by minimizing delay. The saturation traffic flows were calculated for each experimental scenario using the formula developed by Kimber et al. (1986), which takes into account the geometric characteristics of a junction (lane width, turning radius of turn, and slope). For the calculation of the rate of delay, the sheared delay formula was used (Burrow 1987) with a time period of 60 minutes, matching the 60 minutes duration of the simulation time in the SIGSIM runs. The intergreen times were calculated using the German method (RILSA 1981).[1]

Microscopic Simulation

SIGSIM was the microscopic traffic simulation package used for the needs of this research. It takes into account the junction geometry only indirectly. In vehicle simulation, the vehicle behavior close to an intersection should depend on junction geometry. The Gipps (1981, 1986) equations do not take junction geometry directly into account. Therefore this influence is introduced by changing drivers' desired speed to match the desired saturation traffic flow (which takes into account junction geometry). Thus, SIGSIM simply reduces the desired speed of the vehicles approaching the intersection by an amount specified by the user. The vehicles reduce their speed (by a percentage) when they are inside a zone of influence of the junction, using the Gaussian function. This function produces a reduction in desired speed equal to the input value at the stop-line and a smooth increase to the normal desired speed after and before the stop-line. This zone has been set up to 50 meters before and 5 meters after the stop-line. The reduction in speed can be chosen to achieve any realistic saturation traffic flow in the lane concerned and therefore to simulate any combination of the geometric characteristics (to achieve a proxy match between the realistic and the simulated saturation traffic flow, a calibration procedure was made beforehand).

A very important feature of SIGSIM is that it has 'between runs variability.' This indicates that if the simulation is run twice with the same input data, it will produce the same results, but if a different random number seed is used, it will produce different results for the same values of all the other data.

SISGIM was used to estimate the rate of delay due to the presence of signals for each traffic flow level in each case of each scenario under both fixed-time and system D traffic responsive signal control strategies. It was decided to estimate the rate of delay due to the presence of the signals using the 'Realistic - Ideal' method to calculate the average values of the estimated rates of delay, as described in the previous section. It must be noted that arrival traffic flows consisted entirely of passenger cars. A warm-up period was simulated before the beginning of the estimation of the rates of delay. By these means, each route was filled with traffic by the time the estimation of the rates of delay started. For every case of each scenario 20 different random number seeds were used.

Models and Analysis

For this part of the analysis, the GLIM (Numerical Algorithms Group 1986) program was used. GLIM is specially designed to facilitate the fitting of generalized linear models (GLMs) to sets of multivariate data. GLIM deals with models in which the user seeks to explain the variation in a response variable in terms of variation in certain explanatory variables. Variables are classified into different data types, which include continuous, count, proportion and categorical (factors). A factor can take only a finite set of possible values, called levels, and it can be used to divide the data values into separate subsets indexed by its levels.

The geometric and traffic-flow characteristics for every case of each experimental scenario and the types of signal control were used as factors (W for lane width of the lanes, R for the pair of right and left turning radii, F for the level of traffic flow and S for the signal control) for the statistical analysis of the resulting values of rate of delay. Each factor comprised a number of levels equal to the number of the different sets of values that it could take. The coding of the input values in GLIM is shown in Table 2. The logarithms of the average values of the rates of delay due to the presence of the signals for the whole junction from the 20 runs of SIGSIM were used as input values of the dependent variable in GLIM. The logarithmic scale was used to fit models in which the effects of the factors were multiplicative. This allowed comparability between parameter values in models for one-lane and two-lane scenarios where the arrival traffic flows in the two-lane scenarios were almost double the corresponding levels of traffic flow in the one-lane scenarios, resulting in higher rates of delay.

Thus for the fitting of the generalized linear models, the logarithms of the rates of delay due to the presence of the signals were used as the dependent variable and geometric and traffic flow characteristics and type of signal control were used as the independent variables. After that, the individual parameter values in each scenario were examined for statistical significance at 95% confidence level by using F-test.

Table 2: Coding of the Levels of Factors for Input into GLIM

Characteristics	Value	GLIM Code
Width of lanes (meters)	3.00	W(1)
Width of lanes (meters)	3.25	W(2)
Width of lanes (meters)	3.50	W(3)
Right - left radius (meters)	10 / 5 [14 / 5]	R(1)
Right - left radius (meters)	15 / 8 [19 / 8]	R(2)
Right - left radius (meters)	20 / 11 [24/ 11]	R(3)
Traffic Flow level	Light	F(1)
Traffic Flow level	Medium	F(2)
Traffic Flow level	Heavy	F(3)
Signal control	Fixed time	S(1)
Signal control	Traffic responsive	S(2)

For radius the first set of values such as 10/5 shows possible values that right turning radius could take and the values in brackets show what a left turning radius could take.

ANALYSIS AND DISCUSSION OF THE EXPERIMENTAL SCENARIOS

Fitted Models

To examine the influence of each factor on the rate of delay due to the presence of the signals, a common model form was used. In this model, single factors and two-way interactions were in all 16 scenarios, while three-way interactions were included only in those scenarios in which they were statistically significant in the models of individual scenarios. Hence, lane width was not included because it was not statistically significant in any of the individual scenarios. However, traffic flow, turning radius and signal control were included because traffic flow was included in all individual fitted models, and turning radius and signal control were included in most of them.

For two-way interactions, the parameters for the interactions between traffic flow and turning radius, lane width and traffic flow, and traffic flow and signal control were fitted in the common model, since they were statistically significant in all or in most of the individual fitted models. The parameters for the rest of the interactions were not fitted in the common model because they were not statistically significant in any of the individual fitted models.

For three-way interactions, the interaction between-lane width, turning radius and traffic flow was included in the common model because it was statistically significant - or very close to being statistically significant - in most of the individual fitted models. The interaction between turning radius, traffic flow and signal control was included in scenarios [1], [3], [4], [7], [8], [9], [10], [11], [12] and [14] while the interaction between traffic flow, signal control and lane width was included in scenarios [3] and [10], where they were statistically significant. The numbers in brackets refer to the numbers of the experimental scenarios identified in Table 1.

Analysis of Fitted Common Form Models

After fitting the common model to all the scenarios, the effect of each factor and interaction between factors on delay was investigated. The statistical significance of the effect of each factor and interaction on delay was tested at 95% confidence level using F-test. Except for the T-junction with right and left turning movements (scenarios [11], [12], [15] and [16]), the times between two green cycles for critical streams were the same for all nine combinations of lane width and turning radii. Hence, the effects of lane width and turning radius were not influenced by any corresponding change in intergreen time. More specifically, in the three cases in scenarios [11] and [12], where turning radii took their lowest value, intergreen times were greater by one second than for the larger turning radii. In the three cases in scenarios [15] and [16], where lane width took its highest value, intergreen times were greater by one second between some phases, while they were reduced by one second between other phases. This was the case in these four scenarios, because there is not a one-way relationship between intergreen times (as calculated by RILSA 1981) and the geometric characteristics of the junction (used to calculate the distances travelled by the vehicles having or getting right-of-way).

Effects of Traffic Flow

Table 3 shows the effects of traffic flow on delay. In columns seven and eight are the delays per arriving vehicle at medium (and heavy) traffic flow as percentages of light traffic flow. At medium traffic flow in numbers [15] and [14] the percentage changes were between 151% and 215%, and at heavy traffic flow in scenarios [3] and [14] these percentages varied from 330% to 1218%. To calculate the actual percentage difference between medium or heavy traffic flow and light traffic flow, 100% must be subtracted from these values. Performing this subtraction, at medium traffic flow, the delay per arriving vehicle was 51% to 115% higher than at light traffic flow, and at heavy traffic flow the delay was 230% to 1118% higher than at light traffic flow. These results show that traffic flow was the most significant factor affecting delay in all the 16 scenarios. Note that the values of scenario [6] were anomalous, but efforts to find out why were unsuccessful. The effect that traffic flow has on delay was expected. This was because traffic flow is the most dominant factor in the estimated rates of delay due to the presence of the signals.

Effects of Lane Width

The delays at lane widths (2) and (3) (i.e. second and third levels of the lane width factor), versus lane width (1) (i.e., the first level of the lane width factor) are shown in Table 4 for fixed-time control. The percentages in Table 4 that correspond to the size of the effect of lane width on delay should be considered in conjunction with the base values (for the first level of every factor), as shown in Table 3.[2] In scenarios [15] and [16], the intergreen times at lane width (3) were different from those at lane widths (1) and (2), as described previously. In these scenarios, according to the sensitivity analysis in SIGSIGN, a small increase in delay (by about 0.2% in Scenario [15] and 0.5% in Scenario [16]) was expected at lane width (3).

At heavy traffic flow, wider lane widths result in less delay in comparison to the narrowest lane width because vehicles have more space and drivers become less cautious. This results in higher saturation traffic flow values; hence, more vehicles can pass through the junction during the green period resulting in less delay. At heavy traffic flow, wider lane widths have a more significant effect on delay than at medium and light traffic flows, where delay seems to be less sensitive to the small difference wider lane widths can have on saturation traffic flow. More specifically, at heavy traffic flow, wider lane widths make a larger difference in delay in comparison to the narrowest lane width in the crossroads with left-turning movements (scenarios [1], [2], [5], and [6]) than at crossroads with right and left turning movements (scenarios [3], [4], [7], and [8]). Vehicles turning left have to slow down more than vehicles turning right because the left-turning radius is smaller than the right. It seems plausible that this should result in delay being more sensitive to lane width than in cases where fewer of the vehicles are turning left. Thus, wider lane widths have a large effect on delay in comparison to the narrowest lane width at crossroads with left-turning movements than at crossroads with both right- and left-turning movements. This means that in the crossroads scenarios where not

Table 3: Delay per Arriving Vehicle at Heavy and Medium Flows Versus Light Flow

Scenario No.	Delay/unit time at light flow (vehicles)	Delay/unit time at medium flow (as % of light flow)	Delay/unit time at heavy flow (as % of light flow)	Flow at medium flow (as % of light flow)	Flow at heavy flow (as % of light flow)	Delay/arriving vehicle at medium flow (as % of light flow)	Delay/ arriving vehicle at heavy flow (as % of light flow)
[1]	3.63	269%	1143%	150%	200%	179%	572%
[2]	3.65	311%	2218%	150%	200%	207%	1109%
[3]	3.9	239%	660%	150%	200%	159%	330%
[4]	3.86	252%	822%	150%	200%	168%	411%
[5]	8.75	252%	1466%	150%	200%	168%	733%
[6] *	10.47	707%	4064%	150%	200%	471%	2032%
[7]	6.42	282%	1253%	175%	250%	161%	501%
[8]	8.81	272%	1089%	155%	209%	176%	521%
[9]	2.09	279%	1089%	157%	214%	178%	509%
[10]	2.09	280%	1282%	157%	214%	178%	599%
[11]	2.36	307%	1455%	167%	233%	184%	624%
[12]	2.37	322%	1879%	167%	233%	193%	806%
[13]	4.17	291%	1202%	162%	223%	180%	539%
[14]	4.18	347%	2716%	162%	223%	215%	1218%
[15]	3.92	241%	782%	160%	220%	151%	355%
[16]	3.72	273%	854%	160%	220%	171%	388%

* These values were clearly not consistent with expectations but efforts to find out why were unsuccessful.

all approaches comprise left-turning traffic, the effect of wider lane widths is less than at crossroads in the scenarios with only left turning traffic. This can be compared to the large reduction for wider lane widths in scenarios [9] to [14] at heavy traffic flow discussed in the previous paragraph.

Table 4: Delay Effects of Lane Width: Width (2) and Width (3) Versus Width (1)

Scenario No.	Heavy	Flow	Medium	Flow	Light	Flow
	Width 2	**Width 3**	**Width 2**	**Width 3**	**Width 2**	**Width 3**
[1]	**-11.5%**	**-13.5%**	-1.7%	**-3.3%**	1.0%	1.7%
[2]	**-17.7%**	**-21.1%**	**-3.9%**	**-3.7%**	**-2.6%**	0.4%
[3]	**-6.0%**	**-8.4%**	0.4%	-0.5%	**3.1%**	**3.8%**
[4]	**-5.5%**	**-9.2%**	-0.5%	-1.5%	0.4%	**2.7%**
[5]	0.7%	**-18.8%**	**7.5%**	**4.4%**	0.2%	1.1%
[6]	2.1%	**-8.2%**	**-18.5%**	**-35.1%**	1.6%	-0.5%
[7]	1.0%	**-6.8%**	**9.7%**	-0.7%	-0.5%	1.0%
[8]	**-2.1%**	**-7.0%**	-0.4%	**1.8%**	**2.4%**	**3.0%**
[9]	**-9.2%**	**-11.3%**	-0.7%	-1.3%	0.5%	1.0%
[10]	**-10.1%**	**-13.6%**	-1.2%	**-3.5%**	1.2%	**-2.3%**
[11]	**-8.7%**	**-13.1%**	-2.1%	-0.8%	-0.7%	2.7%
[12]	**-11.4%**	**-16.1%**	-0.5%	-1.8%	0.0%	-1.7%
[13]	**-2.7%**	**-17.4%**	0.6%	-1.0%	0.5%	1.1%
[14]	-0.6%	**-15.2%**	0.7%	-1.9%	1.1%	1.8%
[15]	0.4%	-3.8%	0.7%	**4.6%**	2.8%	1.8%
[16]	-0.6%	**-2.2%**	**2.0%**	**6.2%**	0.5%	**2.8%**

Width 1 – lane width 3 meters, Width 2 – lane width 3.25 meters, Width 3 – lane width 3.50 meters; bold letters were used for those percentages that were statistically significant at a 95% confidence level.

Effects of Turning Radius

The delay at turning radii (2) and (3) in comparison to turning radius (1) is shown in Table 5 for lane width (1) and fixed-time signal control. The percentages in Table 5 that correspond to the size of the effect of turning radius on delay should be considered in conjunction with the base values (for the first level of every factor) in Table 3. In scenarios [11] and [12], the intergreen times at turning radius (1) were larger than at turning radii (2) and (3) as described previously. In these scenarios, according to the sensitivity analysis in SIGSIGN, a considerable reduction in delay (by about 14% in scenario [11] and 15% in scenario [12]) is expected at turning radii (2) and (3).[3]

At medium and heavy traffic flows, larger turning radii result in less delay in comparison to the smallest turning radius. Vehicles have to slow down less at larger turning radii than at the smaller turning radii. Larger turning radii result in a substantial change in the number of vehicles passing through the junction per unit green time, hence less delay is incurred by traffic. The reduction in delay is evident at heavy and medium traffic flows. At light traffic flow, few values are statistically significant and no substantial pattern emerges. Hence, no definite conclusions can be drawn. Moreover, at heavy traffic flow, the results are sufficient to show that turning radius (3) is associated with a larger reduction in delay than turning radius (2).

At heavy traffic flow, the reduction in delay at turning radii (2) and (3) in comparison to turning radius (1) is larger at junctions with left turning movements (scenarios [1], [2], [5], [6], [13], and [14]) than at those junctions with right- and left-turning movements (Scenarios [3], [4], [7], [8], [15], and [16]) as anticipated since the left-turning radius is smaller. The only exceptions are scenarios [9] and [10] compared to scenarios [11] and [12], where much of the reduction in delay is due to the reduction in the intergreen times as stated previously. Moreover, it is apparent that the size of the effect of turning radii on delay is larger at heavy traffic flow than at medium traffic flow. It is also larger at medium traffic flow than at light traffic flow in most cases.

At heavy traffic flow, the reduction in delay at turning radii (2) and (3) in comparison to turning radius (1) is greater than the reduction in delay at lane widths (2) and (3) in comparison to lane width (1). This shows that altering the size of these geometric characteristics does not have the same effect on the resulting delay in either case. Over the realistic ranges of the two characteristics, the resulting delay is more sensitive to an increase in turning radius at a junction than an increase in lane width. This can also be seen by examining the saturation traffic flow calculation formula, where the effect of a change in turning radius on saturation traffic flow is larger than a change in lane width over the relevant ranges. This shows allowing more space for vehicles to pass through a junction is of less importance (in terms of rate of delay) than allowing them more space to make their turns.

Table 5: Delay Effects of Turning Radius: Radii (2) and (3) Versus Radius (1)

Scenario No.	Heavy Flow Radius 2	Heavy Flow Radius 3	Medium Flow Radius 2	Medium Flow Radius 3	Light Flow Radius 2	Light Flow Radius 3
[1]	**-20.6%**	**-29.0%**	**-5.7%**	**-5.9%**	-1.7%	-1.1%
[2]	**-43.7%**	**-55.6%**	**-11.7%**	**-14.4%**	0.5%	-1.1%
[3]	**-6.0%**	**-12.2%**	**-1.9%**	**-2.5%**	0.3%	**1.7%**
[4]	**-14.0%**	**-21.6%**	**-5.7%**	**-8.7%**	**2.1%**	**2.5%**
[5]	**-22.5%**	**-33.0%**	2.2%	0.5%	-0.8%	-0.1%
[6]	**-16.6%**	**-28.2%**	**-41.5%**	**-48.7%**	**-3.8%**	**-3.6%**
[7]	**-3.9%**	**-8.1%**	-0.1%	**-4.5%**	0.9%	**-4.5%**
[8]	**-5.7%**	**-12.4%**	-2.1%	**-4.8%**	**2.1%**	**-4.9%**
[9]	**-22.5%**	**-28.1%**	**-6.0%**	**-8.1%**	0.2%	1.2%
[10]	**-28.5%**	**-38.3%**	**-6.3%**	**-10.7%**	-1.8%	-0.3%
[11]	**-34.5%**	**-39.4%**	**-17.1%**	**-16.7%**	**-9.2%**	**-9.6%**
[12]	**-39.2%**	**-48.5%**	**-21.4%**	**-21.0%**	**-10.3%**	**-11.9%**
[13]	**-22.2%**	**-29.4%**	**-3.4%**	**-4.6%**	0.5%	**2.0%**
[14]	**-28.9%**	**-45.9%**	**-10.1%**	**-13.5%**	1.4%	1.1%
[15]	-3.7%	5.5%	-0.7%	-1.8%	-1.3%	1.0%
[16]	-3.3%	-6.9%	1.1%	1.5%	0.7%	2.7%

Radius 1 – first level of the radius factor; Radius 2 –Second level of radius factor; Radius 3 – third level of radius factor; bold letters were used for those percentages that were statistically significant at a 95% confidence level.

Effects of Interaction Between Lane Width and Turning Radius

The estimates of the effects on delay of the interactions between lane width and turning radius are shown in Table 6 for each level of arrival traffic flow. The percentages in Table 6 that correspond to the size of the effect of the interaction between lane width and turning radius on delay should be considered in conjunction with the base values (for the first level of every factor) in Table 3 and also in conjunction with Tables 4 and 5 where the effects of lane width at turning radius (1) and the effects of turning radius at lane width (1) are shown. These percentages are the amounts by which the sum of the effects of the corresponding lane width and turning radius is adjusted to obtain their joint effect.

From the third-order interaction between traffic flow, lane width, and turning radius, it is apparent that at light traffic flow, the size of the effect of this interaction is larger than that of the individual factors as described previously. Hence, the third-order interaction between traffic flow, lane width and turning radius plays a significant role in the resulting delay at light traffic flow. At medium traffic flow, the size of the effect of these adjustments is substantial and plays a significant role in the resulting delay at some junctions, while at heavy traffic flow the size of their effect is smaller compared to the effect of the individual factors at heavy traffic flow.

Effects of Signal Control Strategy

The effect that signal control strategy has on delay at each arrival traffic flow is shown in Table 7. The percentages in Table 7 should be considered in conjunction with the base values (for the first level of every factor) as shown in Table 3. In a majority of the scenarios, traffic-responsive signal control is associated with less delay than fixed-time control at all levels of traffic flow. This shows that the detectors seem to produce signal timings that result in less delay than the precalculated signal timings. This is the case for all the levels of traffic flow, but it has a larger effect on medium and heavy traffic flows, where the amount of traffic is large. It seems also that traffic responsive signal control distributes cycle time more efficiently (in terms of delay-minimizing) than the precalculated signal timings. At medium and especially at heavy traffic flows, where the detectors tend to produce signal timings close to the precalculated timings, the small change that the detectors can produce in signal timings makes an appreciable difference in the resulting delay.

At medium and heavy traffic flows, in one-lane junctions, traffic-responsive signal control results in a larger decrease in delay compared to fixed-time control than in the two-lane junctions. Traffic responsive signal control results in less delay than fixed-time control, which indicates that the signal timings produced by the detectors result in a better use of the cycle time than the precalculated timings. In the case of one-lane junctions, where traffic streams comprise different movements, a better use of cycle time would also result in a larger gain than in two-lane junctions. In two-lane junctions, traffic streams comprise one movement or different movements, though each lane is being used by vehicles making only one of the two possible movements. Therefore, in two-lane junctions the precalculated signal timings can accommodate traffic better than in the one-lane scenarios, although they still cannot accommodate traffic better than traffic-responsive signal control.

Effects of Interaction Between Signal Control Strategy and Lane Width

A result not shown in any of the tables is that the effect on delay of the interaction between control strategy and lane width is statistically significant in only two of the 16 scenarios. Even here, the statistically significant values are few and do not produce a clear pattern. Hence, the simultaneous existence of traffic-responsive signal control and wider lane widths does not have any substantial effect on delay, so the effect of lane width is the same for both types of signal control strategies.

Table 6: Delay Effects: Interactions Between Lane Width (W), Turning Radius (R) and Traffic Flow

No.	Heavy Flow				Medium Flow				Light Flow			
	R2W2	R2W3	R3W2	R3W3	R2W2	R2W3	R3W2	R3W3	R2W2	R2W3	R3W2	R3W3
[1]	**3.8%**	-1.8%	**4.8%**	2.0%	1.5%	1.8%	2.6%	0.2%	-0.4%	0.1%	-0.6%	1.4%
[2]	**8.0%**	2.0%	**12.6%**	**9.7%**	2.4%	2.4%	2.0%	0.2%	2.0%	**-5.2%**	**5.3%**	1.1%
[3]	**1.3%**	0.4%	**2.2%**	**2.4%**	-0.9%	0.3%	-0.8%	0.0%	-0.9%	**-5.1%**	**-4.8%**	**-1.7%**
[4]	-1.7%	-0.5%	0.7%	**3.9%**	0.2%	2.1%	2.8%	3.3%	-1.9%	-1.4%	-0.5%	-2.6%
[5]	**-6.8%**	2.7%	**-4.7%**	**15.9%**	**-7.3%**	**-4.6%**	**-7.2%**	**6.5%**	1.5%	1.7%	0.6%	0.5%
[6]	**-7.3%**	-1.6%	**-6.0%**	**4.4%**	**17.1%**	**40.4%**	**20.4%**	**35.9%**	-0.5%	3.5%	-0.3%	**3.8%**
[7]	-3.3%	1.5%	1.1%	**5.7%**	**-9.5%**	0.2%	**-4.3%**	**5.4%**	2.0%	3.5%	**7.9%**	**8.3%**
[8]	-0.5%	**-2.5%**	1.3%	**2.5%**	-0.2%	-1.7%	**2.9%**	1.6%	-0.8%	-1.9%	**5.5%**	**7.1%**
[9]	**4.6%**	0.0%	**5.3%**	**3.7%**	-0.2%	0.2%	-0.6%	1.2%	0.9%	1.7%	0.7%	1.9%
[10]	0.6%	1.0%	**8.5%**	**5.8%**	-0.4%	0.4%	1.6%	**2.7%**	-0.2%	**4.7%**	0.0%	**5.0%**
[11]	0.2%	2.2%	1.2%	1.7%	3.4%	1.7%	1.8%	0.8%	0.5%	-2.9%	2.4%	-0.7%
[12]	1.6%	2.2%	**5.0%**	1.6%	1.5%	3.2%	1.8%	3.0%	1.2%	**5.0%**	2.2%	**7.2%**
[13]	-0.8%	**11.6%**	1.2%	**17.0%**	-0.8%	**1.8%**	-0.7%	**2.5%**	0.2%	0.9%	0.2%	0.9%
[14]	**-10.2%**	1.0%	**-5.3%**	**13.4%**	0.0%	0.6%	-0.7%	2.8%	0.5%	-0.3%	1.0%	1.5%
[15]	-1.7%	3.8%	**-7.7%**	**-9.1%**	-0.3%	-1.0%	-0.4%	1.1%	0.4%	2.3%	-3.5%	0.7%
[16]	-2.0%	-0.2%	0.2%	0.8%	-0.6%	-1.4%	-0.2%	-1.4%	-0.5%	1.7%	-0.8%	-1.3%

R2W2 - interaction between the second level of Radius and the second level of width, R2W3 - interaction between the second level of Radius and the third level of width R3W2 - interaction between the third level of Radius and the second level of width, R3W3- interaction between the third level of Radius and the third level of width, Bold letters were used for those percentages that were statistically significant at a 95% confidence level.

Table 7: Delay Effects of Signal Control Strategies for Width (1) and Radius (1)

Scenario Number	Delay Under Heavy Traffic Flow	Delay Under Medium Traffic Flow	Delay Under Light Traffic Flow
[1]	**-4.4%**	-2.4%	**-3.0%**
[2]	**-4.4%**	**-2.1%**	**-3.6%**
[3]	**-22.7%**	**-19.5%**	**-4.3%**
[4]	**-23.0%**	**-21.5%**	**-5.2%**
[5]	-0.8%	0.0%	-0.3%
[6]	0.0%	-0.7%	-0.2%
[7]	**-3.0%**	**-7.4%**	**-9.1%**
[8]	**-1.7%**	**-4.2%**	**-6.2%**
[9]	**-17.1%**	**-18.5%**	**-2.1%**
[10]	**-13.8%**	**-19.8%**	**-4.1%**
[11]	**-33.7%**	**-24.3%**	**-7.5%**
[12]	**-30.2%**	**-27.1%**	**-4.7%**
[13]	**-4.3%**	**-4.5%**	**1.8%**
[14]	**-8.6%**	**-11.2%**	0.9%
[15]	**-5.9%**	**21.0%**	1.7%
[16]	**-4.7%**	**-4.6%**	**3.8%**

Width 1 – lane width 3 meters; Radius 1 – first level of the Radius factor; bold letters were used for those percentages that were statistically significant at a 95% confidence level.

Effects of the Interaction Between Signal Control Strategy and Turning Radius

Estimates of the percentage effects on delay of the interaction between turning radius, signal control strategy and traffic flow are shown in Table 8. These percentages should be considered in conjunction with the base values (for the first level of every factor) as shown in Table 3 and also in conjunction with Tables 5 and 7 where the effects of turning radius under fixed-time control and the effects of signal control at turning radius (1) are shown. Note that these percentages are the amounts by which the sum of the effects of the corresponding turning radius and signal control is adjusted to obtain their joint effect. In scenarios [11] and [12], the intergreen times at turning radius (1) are larger than at turning radii (2) and (3), but this should not affect this interaction because it is part of the effect of turning radius.

In the third-order interaction between turning radius, signal control and traffic flow, at medium traffic flow the reduction in delay at larger turning radii is smaller under traffic responsive signal control than under fixed-time control. At the same time it must be noted that the size of this effect is in most cases smaller than the effects of the individual factors by themselves, although not always by a large amount. At medium traffic flow, this effect is evident in all the one-lane T-junctions (scenarios [9], [10], [11] and [12]) and in all the one-lane junctions with right- and left-turning movements (scenarios [3], [4], [11] and [12]). Hence, it can be concluded that at these junctions the advantage of large turning radii is less under traffic-responsive signal control than under fixed-time control. At heavy traffic flow, there is no clear pattern emerging other than that the size of the joint effect of turning radius and signal control is small compared to that of the individual factors by themselves. However, there is an indication of the reverse effect compared with medium traffic flow, which indicates that the advantage of the larger turning radii is higher under traffic-responsive signal control than under fixed-time control.

Table 8: Delay Effects: Interactions Between Turning Radius (R), Signal Control (S) and Traffic Flow

Scenario Number	Heavy Traffic Flow	Heavy Traffic Flow	Medium Traffic Flow	Medium Traffic Flow	Light Traffic Flow	Light Traffic Flow
	R2S2	R3S2	R2S2	R3S2	R2S2	R3S2
[1]	1.7%	**2.9%**	0.6%	-2.2%	1.3%	1.1%
[3]	-0.9%	**1.7%**	**2.5%**	**3.6%**	**1.1%**	0.5%
[4]	-0.4%	0.3%	**4.1%**	**6.8%**	0.2%	2.4%
[7]	1.6%	0.8%	0.8%	-0.3%	-1.9%	-3.9%
[8]	-0.8%	-1.9%	1.4%	0.6%	0.7%	1.3%
[9]	-2.0%	**-3.1%**	**3.1%**	**4.3%**	0.5%	-0.4%
[10]	**-5.3%**	**-4.1%**	**2.5%**	**4.2%**	1.6%	1.7%
[11]	**3.5%**	**4.2%**	**11.8%**	**12.9%**	3.0%	2.4%
[12]	**-7.3%**	**-4.4%**	**13.2%**	**15.4%**	-1.6%	0.7%
[14]	**-3.6%**	**-4.0%**	**5.1%**	**8.6%**	-0.5%	0.4%

R2S2- interaction between the second level of Radius and the second level of Signal Control, R2S3- interaction between the second level of Radius and the third level of Signal Control R3S2- interaction between the third level of Radius and the second level of Signal Control, R3S3- interaction between the third level of Radius and the third level of Signal Control,, Bold letters were used for those percentages that were statistically significant at a 95% confidence level.

CONCLUSION

This study investigated the influence of geometric characteristics on the operational performance of signal-controlled road junctions. The different characteristics that were examined as single factors, and as interacting with each other were lane width, turning radii, and signal control strategy. These were investigated for different junction types, turning vehicles' percentages and traffic flow levels. It was found that wider lane widths result in less delay under heavy traffic flow in comparison to narrow lane widths. Furthermore, the magnitude of this effect differs depending on junction design. More specifically, wider lane widths result in a larger difference in delay in comparison to the narrowest lane width at crossroads with left-turning movements than at crossroads with right and left turning movements.

Turning radius also has a significant effect on delay at a signal controlled junction. Its effect is evident at medium and heavy traffic flows, where a large turning radius results in less delay in comparison to a small turning radius. Under heavy traffic flow, this reduction is greater at junctions with only left-turning movement than at junctions with both right- and left-turning movements.

The choice of traffic signal strategy at a signal-controlled junction is important and depends on the level of traffic flow. In particular, at medium and heavy traffic flows, traffic-responsive signal control results in less delay than fixed-time control. Furthermore, in six of the eight one-lane junctions, traffic-responsive signal control results in a large decrease in delay compared to fixed-time control than at the two-lane junctions.

Specific interactions of the characteristics also have significant impacts on delay. More specifically, at light traffic flow, the effect of the interaction between traffic flow, lane width and turning radius is substantial. At medium traffic flow, the size of this effect is substantial and plays a significant role in the resulting delay of some junctions, while at heavy traffic flow the size of the interaction effect is smaller compared to the effect of the individual factors. Furthermore, the effect of lane width on delay does not differ significantly with respect to type of signal control. Last, the interaction of turning radii and signal control strategy is significant at medium traffic flow. A reduction in delay where turning radius is large was estimated to be smaller under traffic-responsive signal control than under fixed-time control. At the same time, the size of this effect is in most cases smaller than the effects of all individual factors, though not always by a large amount.

This research identified the significance of the choice of specific elements on the design of a signal control junction. Specific factors and interactions influence significantly the delay at a junction approach, and this impact was determined both qualitatively and quantitatively. The results of this study can provide insight to traffic engineers in the design of a junction in relation to its geometry and the choice of the most efficient signal control strategy.

Endnotes

1. Intergreen time is the time between the end of a green indication for one phase of a cycle and the beginning of a green indication of another phase of a cycle.

2. To fully estimate the effects of each factor on delay (in this case, the lane width factor), the delays at all levels of the examined factor compared to the first level of the examined factor must be seen in conjunction with the base values (for the first level of each factor) in Table 3. Therefore, Table 3 is always mentioned.

3. As stated in the "Analysis of Fitted Common Form Modes" in scenarios [11], [12], [15] and [16] the intergreen times are not the same in all the examined cases. Hence, a decrease or an increase in delay was expected in these cases in these scenarios due to their different intergreen times. This decrease or increase should be taken into account to estimate correctly the effect of the factors on delay. These percentages are the result of the sensitivity analysis in SIGSIGN which is used to estimate the expected increase (or decrease), due to different intergreen times

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