Shape Grammars for Road Transport Network Design

The Role of Intersection Types

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Abstract: Urban systems continue to grow worldwide due to population growth and migration. Urban design guidelines are urgently needed for planning purposes. Shape grammars describe in the form of rules how network elements and land used types are added to each other. Shape grammars have the advantage of their ease of application in urban and interactive planning, their comprehensiveness, and their low computational requirements. Previous work showed the impact of road type shape grammar rules for road networks.

A two phase approach is proposed where phase 1 copes with road design and phase 2 with intersection type choice. The two consecutive phases are meaningful considering the results of this paper. Additionally, this paper sheds light on various intersection types and the corresponding expected delays for the road users. It is quantitatively shown that intersection delays considerably depend on the current through traffic shares. Propositions for shape grammars are made regarding intersection type choice. The proposed intersection type choice is evaluated in virtual networks, generated on featureless planes. The results show high performance for roundabouts and variable demand. The proposed shape grammar slightly reduce network performance compared to the most optimal intersection alignment in exchange for a simple shape grammar rule. Future research is proposed, including additional shape grammars for urban areas, and growth processes.

1 INTRODUCTION

1.1 Research Context

Intersection types are often neglected in network models and simulations due to the high number of parameters and their complexity. However, road intersection types have a large impact on urban travel times. Especially for urban design studies, they should not be ignored in scenario development.

Designs for intersection types can be found e.g. in Spacek (2009) for Switzerland, FGSV (2001) for Germany, or AASHTO (2004) for USA. They mainly describe widths, diameters, etc. for the most common intersection types. For Switzerland, Pitzinger and Spacek (2009) provide the performance parameters for intersections, e.g. saturation flow for signal controlled intersections.

Large scale static network models of cities or regions require appropriate turn delays especially for urban areas due to the more accurate modeling of travel times. An increasing number of urban simulations incorporate transportation in their simulation, e.g. (SustainCity, 2011, UrbanVision, 2012, Vanegas *et al.,* 2009). Studies on urban patterns and layouts can additionally incorporate delays (Yerra and Levinson, 2005), as well as network sensitivity (Ortigosa and Menendez, 2012).

Vitins *et al.* (2012) showed a significant impact of different intersection alignments on network design. However, the impact of different intersection types were not elaborated in detail. This paper aims for more detailed intersection delay analyzes and more detailed intersection shape grammars.

Research on intersection delays is broad. Akcelik (1981) describe the basic processes for signalized intersections. Dion *et al.* (2004) have investigated different delay functions for signalized intersections. They compared deterministic and stochastic functions with microscopic simulations and observed data. Corthout *et al.* (2012) proposed macroscopic intersection models for non-unique flows. They refer to general models in dynamic network loading models.

In the following, queueing and spill-over effects are neglected due to their major impact on the simulation. This simplification might be a disadvantage. However, queuing should be reduced in the design process. Total intersection delays should be optimized to minimize queuing from the very first.

1.2 Highway Capacity Manual

Volume delay functions for roads are still better defined, e.g. Huntsinger and Rouphail (2011); however, the delay functions for intersections are more diverse. This paper provides an overview over the formula proposed in the Highway Capacity Manual (Transportation Research Board, 2010), for signal controlled intersections, roundabouts, two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) intersections. Beside the formulae, parameters are inherited from Transportation Research Board (2010) to be consistent with the formulae. Although other manuals provide different delay formulae, the Transportation Research Board (2010) remains a major reference standard for many planners worldwide. The Transportation Research Board (2010) is based on current research, and has been developed and adapted over the years.

This paper aims to provide an overview over the various delays caused by different intersection types. Additionally, it considers various demand volumes and through traffic. This paper does not claim to go to the same depth as e.g. Dion *et al.* (2004) for signalized intersections, or others. It rather compares different types for further planning ideas.

2 METHODOLOGY

The simulations cited above require a robust and feasible network design approach. Various factors have to be considered for road network design. This paper proposes an two phase approach for network design. The approach is explained in the consecutive Section 2.1.

2.1 Two Phase Approach

Road network design is subdivided in three major and interacting domains: *Road Design*, *Intersection Design*, and *Travel Demand*. *Road Design* and *Intersection Design* focus on infrastructure design. *Travel Demand* serves as a basis for design, and strongly interacts with infrastructure. *Travel Demand* bases additionally on land use, like population and job density, or leisure facilities.

The two phase approach states that network design can be conducted in two consecutive phases:

- *Phase 1* focusses on design of the road network in space. Adjacent roads are determined in space, including road parameters like type and length. All facilities or zones have to be connected with each other through the network. Nodes are determined in space. Two or more roads join at nodes for coherency. Topology and other spatial constraints are considered in this phase. Nodes are specified further in *Phase 2*.

- *Phase 2* implements intersection type choice. The design process determines the intersection type for each node, out of a set of different intersection types. It is stated, that intersection type choice strongly depends to the underlying turning volumes of each intersection. Other parameters, like number of arms, grades, pedestrian influence intersection type choice additionally. Turning volumes have to be known in advance, before intersection type choice is taken place. Therefore, intersection type choice takes place after road network design.

The two phase approach is summaries in *Figure 1*.

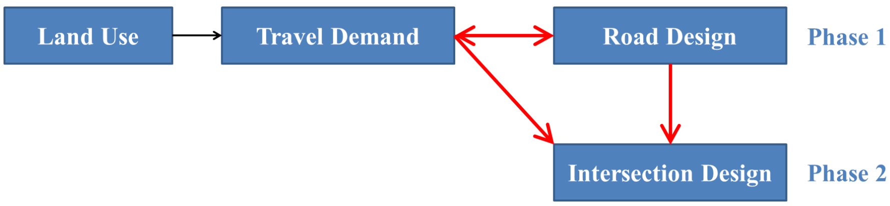


Figure 1. Two phase approach for road network design.

The major focus of this paper lays on the proposed two phase approach. *Phase 1* implements road design. Therefore, routes and traffic volumes can be calculated in a first instance. Turning volumes can be determined for each node. Intersection type choice is conducted after road design due to the strong dependency of the turning volumes on intersection type choice. This procedure allows a separation of two major phases, which are discussed in literature for a long time. However, the two phases are set in an appropriate and profound relation.

The process of network design is evaluated from an economic view point later in this paper. However, the determination of generalized costs can be discussed at this stage. Generalized costs are minimized due to the fact that routes are optimizes in *Phase 1* regarding generalized costs. In *Phase 2*, intersection type choice can build up on the results of *Phase 1* to include and optimize intersection delays, again considering generalized costs.

A major disadvantage of the two phase approach is the interaction between *Intersection Design* and *Travel Demand*. This interaction can be included with additional iterations in the design process. However, the feedback of *Intersection Design* on *Travel Demand* is considered to be low and disregarded in a first instance.

The focus of this paper lays on *Phase 2*. The functions of the intersection delays are evaluated regarding different variables. The conclusion of the two phase approach provided according to the results of the intersection delay evaluation. Regarding the content of *Phase 1*, a short review on road network design is given in e.g. Vitins *et al.* (2012).

2.2 Theory of Intersection Delay Modeling

The overall goal of this paper is to gain insights into intersection delay and the impact of the adjacent street types regarding network efficiency, particularly travel time. The delay calculation for the four intersection types signal lights, roundabouts, two-way-stop-controlled intersections and all-way stop-controlled intersections are implemented in the network design process. The consecutive Section 3 shows the delays of isolated intersections, and compares the intersection types with different adjacent road types regarding delays, in order to provide an evidence base for future street network design.

The following subsections refer to the Highway Capacity Manual (Transportation Research Board, 2010). It is assumed that the intersections are isolated, and not affecting each other. This is an assumption and has to be considered especially critically in urban environments.

The number of incoming lanes for each directions is relevant to calculate the delay for each intersection type. For comparison reasons, the number of lanes are set to 1 for all incoming lanes. The lane number can vary, and adaption is needed, e.g. for left turn movements. Additional adaption is needed for pedestrian, heavy vehicles, lane widths, grade etc.. The same methodology is applied for 3 leg intersections, but with adapted formulas. However, due to lack of space, the delays are not shown in this paper for the 3 leg intersections.

3 RESULTS

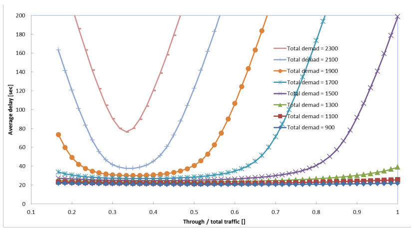
The results of the intersection simulations are subdivided in isolated performance analyzes and comparison between different types. Consecutively, the intersections are implemented in network design studies.

3.1 Performance Isolated Intersections

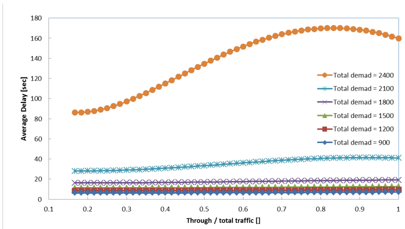
Here, the focus is on through traffic due to lack of space. Please refer to literature for delay functions of single lanes. For variable number of arms, and additional details, please refer to Vitins and Axhausen (2012).

Figure 2(a) shows the turn delay of a signal controlled intersection under different traffic volumes and through traffic share. *Figure 2(a)* refers to a crossing of a minor arterial and a collector road, differing in their capacities. The green times for both road types are 20 sec and 30 sec respectively.

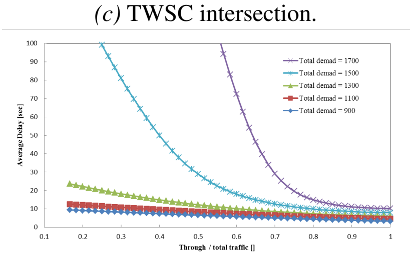
(a) Signal light, crossing of arterial and collector.



(b) Roundabout with 4 legs.



(c) TWSC intersection.



(d) TWSC intersection.

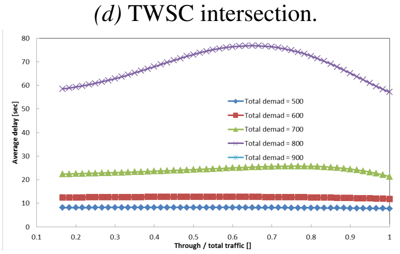


Figure 2. Delay for different traffic volumes and through traffic.

Since green time depends on the incoming road type, the optimum through traffic share is between 0.0 and 1.0 due to the different incoming road types in *Figure 2(a)*. The optimal through traffic ratio in *Figure 2(a)* of about 0.33 is similar to the ratio of the different green times (20sec/30sec). Derivation from the optimum through traffic share increases delays. This can be improved with more flexible green time.

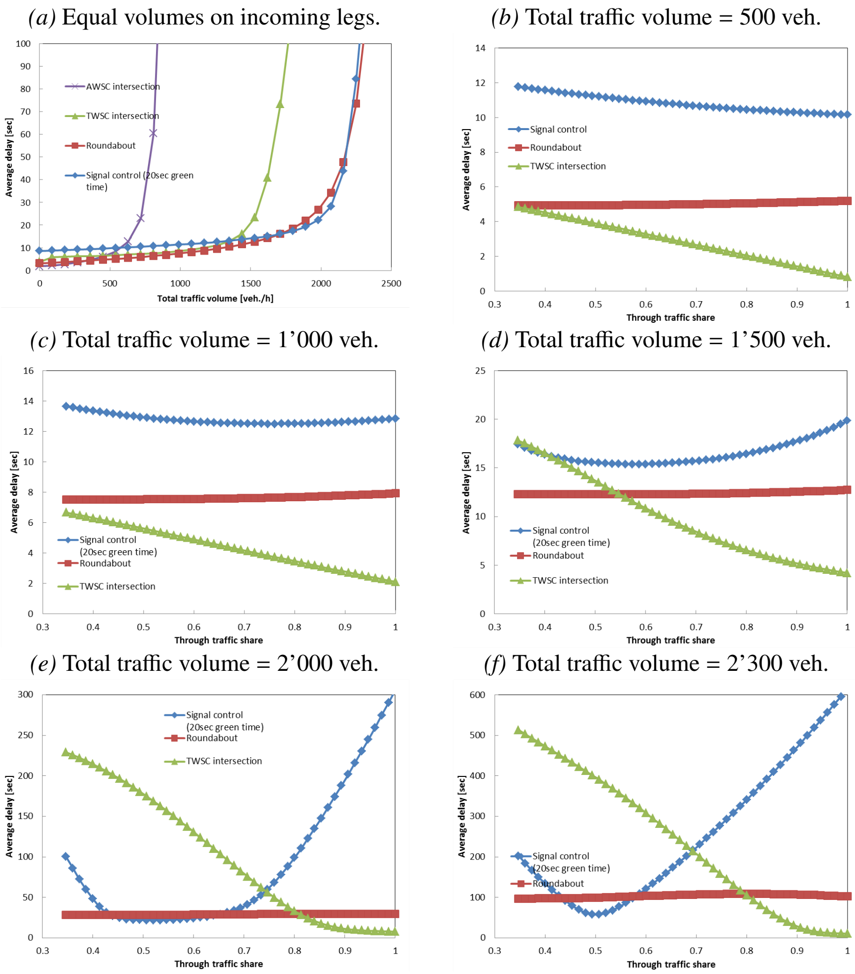
Figure 2(b) displays the turn delay of a roundabout under different traffic volumes and through traffic share. *Figure 2(b)* shows low delays regardless of the through traffic share. However, delay especially increases when demand and trough traffic share are high. This origins from the exponential influence of the conflicting circular volumes already in the roundabout. The delay is decreasing again with (nearly) only through traffic, due to the absence of any conflicts.

Through traffic plays a major role in TWSC intersections. *Figure 2(c)* shows the delay of TWSC intersection under different traffic volumes and through traffic shares. *Figure 2(c)* shows the high dependency of the through traffic share and the total delay. The higher the share of through traffic, the lower the total delay. Uniform delay seems to increase average delay. This is especially important with high total volumes, like in urban environments. Only through traffic (share close to 1.0) leads to a lower delay again (see *Figure 2(c)*) because of the absence of conflicting movements.

The total delay is rather high and comparable with small signalized crossings. AWSC intersections only perform well with low volumes. Due to the missing signal cycle, AWSC intersections perform better than signals with low and uniformly distributed traffic volumes. The total delays of AWSC intersections depend mainly on the total loading, the delay is stable when increasing through traffic. Only for very high total demand, the total delay increases with increasing through share. This is due to the conflicting volumes. Generally, increasing through traffic increases total conflicting volumes. However, a through traffic share close to 1.0 decreases conflicting volumes due to missing alternative turn volumes.

3.2 Comparison Between Different Intersection Types

In the following, the delays are compared between the different intersection types. The parameters remain the same as above. *Figure 3* shows the delays of the intersection types TWSC, AWSC, roundabout and signal control for three legs. However, AWSC intersections are not considered further in *Figures 3(b) - 3(f)* due to the fact that large through traffic often passes on road types of higher hierarchies. Intersections with different adjacent road types mostly are of type of TWSC.



(a) Equal volumes on incoming legs. *(b)* Total traffic volume = 500 veh. *(c)* Total traffic volume = 1’000 veh. *(d)* Total traffic volume = 1’500 veh. *(e)* Total traffic volume = 2’000 veh. *(f)* Total traffic volume = 2’300 veh.

Figure 3. Delay comparison between different intersection types with 3 legs.

Figure 3(a) shows a uniform traffic distribution with variable total traffic volumes. The delays in *Figure 3(a)* vary significantly between different volumes when comparing AWSC, TWSC and roundabouts. However, roundabouts and signal controlled intersections almost have the same delays. Small differences can be found for lower volumes, due to the cyclic nature of signal controlled intersections. Different delays are estimated with low through traffic volumes. Under low through traffic volumes, TWSC intersections perform better than roundabouts. Signalized intersections perform again better under high volumes, but only with a limited through traffic share, corresponding to the green times of the cycle.

In general, roundabouts seem to be resistant to variable through traffic volumes. This is due to the minimized number of conflicting flows and the missing cyclic components. However, in signalized intersections, delays are low when the green times reflect through traffic volumes. It is expected that adaptive green times additionally reduce delays.

Figure 4 shows the delays of the intersection types TWSC, AWSC, roundabout and signal control for four legs. Similar to *Figure 3*, AWSC intersections are not considered further due to the fact that large through traffic often passes on road types of higher hierarchies.

Figure 4(a) shows a uniform traffic distribution with variable total traffic volumes. In *Figure 4(a)*, roundabouts have the lowest delay for low and high traffic volumes, followed by signalized intersections. *Figure 4(a)* contrasts the delays of a 3 leg intersections (*Figure 3(a)*), where signalized intersections perform better under high traffic volumes. Unlike in 3 leg intersections, roundabouts always perform best under low through traffic shares. However, signalized intersections perform almost as good under higher traffic volumes. But, similar to 3 leg intersections, the green times have to reflect the share of through traffic. TWSC intersections perform well under high share of through traffic, especially under high total traffic volumes.

3.3 Implementation in Network Design

3.3.1 Matrix Shape Grammar Rules

Section 3.1 above showed a large dependency of the intersection delays on through traffic shares and total traffic volumes. Due to these dependency, simplified rules are set up for the choice of the three intersection types TWSC, roundabout, and signal controlled intersections. *Tables 1* and *2* list intersection types with the lowest delays, further called Matrix shape grammar rules.

The Matrix shape grammars shown in *Table 1* and *2* sightly favor signal controlled intersections due to the fact that they perform better under more adaptive green time periods. Signalized intersections may perform even better, but more detailed calculations needed to be implemented above to support this assumption.

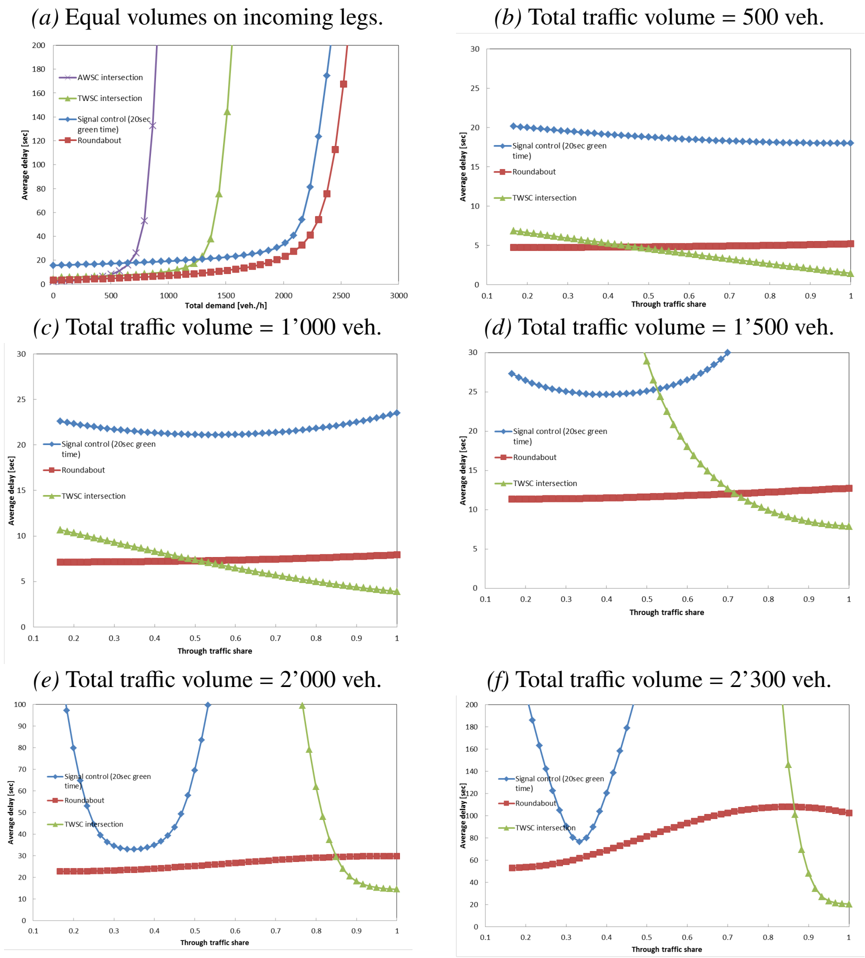


Figure 4. Delay comparison between different intersection types with 4 legs.

It is added that, under very low volumes, AWSC intersections generally perform well (*Figures 3* and *4*), similar to the proposed roundabouts in *Table 1* and *2* above. This is in line with some AWSC intersections observed in residential neighborhoods with very low volumes.

Table 1. Matrix Shape grammar rules for 3 leg intersections.

	Through traffic share			
Total traffic volume	<40%	<60%	<80%	<100%
< 500	○	+	+	+
< 1'000	○	+	+	+
< 1'500	○	○	+	+
< 2'000	○	⁘	○	+
> 2'000	○	⁘	○	+

○ : Roundabout ⁘ : Signal Control + : TWSC Intersections

Table 2. Matrix Shape grammar rules for 4 leg intersections.

	Through traffic share				
Total traffic volume	<20%	<40%	<60%	<80%	<100%
< 500	○	+	+	+	+
< 1'000	○	○	+	+	+
< 1'500	○	○	○	+	+
< 2'000	○	○	○	○	+
> 2'000	○	⁘	○	○	+

○ : Roundabout ⁘ : Signal Control + : TWSC Intersections

3.3.2 Matrix Shape Grammars in Existing Networks

The Matrix shape grammar rules for 3 and 4 leg intersections are applied in a series of road networks to see potential differences regarding the overall performance. The performance function for network evaluation includes travel times, distance and operating costs, as well as road infrastructure costs. The infrastructure costs for intersections are neglected for improved result analyzes.

Intersection types are selected in road networks according to the rules in consideration. 20 existing networks are taken from Vitins *et al.* (2012) to be consistent with past research. Four different rules are applied for intersection type selection. The first reference rule implements only signal lights (S_0) in the networks. The second rule implements only roundabouts (S_R). The third rule scans through all intersection types, implement all types and choose the type with the lowest demand-weighted delay (S_O). The forth rule implements the Matrix shape grammar above (S_M). The outcome of the performance measures is shown in *Table 3*.

Table 3. Relative performance of four different intersection type alignments, considering networks of Vitins *et al.* (2012) (n = 20).

Networks with	Relative difference to Scenario S_0
only signalized intersections (S_0)	-
only roundabouts (S_R)	-8.0%
most optimized intersection choice (S_O)	-8.3%
matrix shape grammars (S_M) of *Table 1* and *2*	-7.5%

Table 3 shows considerable differences between networks only implementing signal lights (S_0), and networks designed with the other three rules (S_R, S_O, S_M). However, the differences between networks of type S_R, S_O, and S_M are small. Out of these three rules, the Matrix shape grammars (S_M) is performing slightly worse than S_R and S_O. However, also the most optimized intersection selection is only somewhat better performing than the networks with only roundabouts.

Additional computational time can be expected when impelemting intersection delay in transport modeling, like above. However, the share for calculating the intersection delays are lower that 10 % of the total computational power needed for a demand assignment. This low computational requirement is especially relevant when modeling large scale networks. The formulae are already implemented in an efficient manner.

3.3.3 Matrix Shape Grammars in Network Design

The rules above are implemented in a network design algorithm to gain additional insights of potential choice of intersection types in road networks. The network design algorithm is proposed by Vitins *et al.* (2012) and Vitins *et al.* (2011) and bases on an integrated genetic algorithm and an ant colony optimization. The algorithm designs road networks under different assumptions and shape grammars. The proposed networks are designed on featureless planes with randomly generated zones. The intersection alignment rules S_R, S_O, and S_M described above are implemented in the design algorithm. The aim is to find additional differences between the effect of the rules. Again, the objective function includes travel times, distance and operating costs, as well as infrastructure costs.

The first series networks only contain roundabouts as standard intersection type (S_R). The second series generates networks with the most optimal intersections, by trying out all intersection types and choosing the type with the lowest demand-weighted delay (S_O). The third network series considers the Matrix shape grammar above.

The results are showing almost no differences between the different rules S_R, S_O, and S_M. The single networks generated differ max. +/- 2.8%, which is most probably due to the random noise of the design algorithm heuristic. The small variance between the network with different choice rules S_R, S_O, and S_M is inline with the results shown in *Table 3*. Eventually, the current sample size of 6 has to be increased for additional insights.

4 DISCUSSION

4.1 Isolated Intersections

This paper examines and compares the delays of different intersection types. Major differences of the delays are detected between different intersection types, between 3 and 4 leg intersections, and between different shares of through traffic.

Roundabouts perform well with $\geq$ 3 leg intersections and uniformly distributed turn volumes. This is due to the low conflicting volumes. Roundabouts cope best with variable through traffic, compared to other intersection types. Also high traffic volumes increase delay only modestly in roundabouts.

Signal controlled intersections seem to perform better with 4 legs during lower traffic volumes due to the shorter cycle time. During high volumes, 4 leg signal controlled intersections seem to perform comparably better. Additionally, signal controlled intersection perform well under medium and high volumes, but only if the green times correspond to the traffic volumes.

Two-way stop-controlled (TWSC) intersections and their delays mainly depend on the right-of-way settings. A through traffic road of higher hierarchy reduce total delay in 3 and 4 leg intersections, compared to all-way stop-controlled (AWSC) intersections. Even high through traffic share increase delay only modestly. However, uniform distributed turn volumes lead to very high delays due to the high conflict volumes.

Future research is needed in the adaption of the number of lanes of the incoming roads. This suggestions is in line with e.g. Dion *et al.* (2004), focussing on signalized intersections. Then, the influence of pedestrians for intersection delays should be further considered to get a further estimate of the delays. Further work is needed in the simulation of signal controlled intersections and adaptive green time lengths.

4.2 Integrated Matrix Shape Grammars in Network Design

The influence of the Matrix shape grammar is not as relevant as expected. The three rules, *only roundabouts* (S_R), *most optimal alignment* (S_O), and *Matrix shape grammar* (S_M) show very similar performance results. Performance is slightly reduced when implementing the Matrix shape grammars. However, the performance loss compared to the most optimal intersection alignment is small. Additionally, as stated above, the high performance of roundabouts can be stressed as well as their adaptability to variable turn volumes. Future research is needed in the improvement of the Matrix shape grammar rule. Additionally, future research is needed for very dense areas of urban development.

4.3 Two Phase Approach

The two phase approach proposes the design of a coherent road network in *Phase 1*, including a first estimation of the turn volumes. The intersection type choice is conducted in *Phase 2*. The two consecutive phases are reasonable since the through traffic share has a substantial influence in intersection type choice. Intersection type choice is therefore only meaningful after insights in turn volumes.

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