Shape Grammars for Intersection Type Choice in Road Network Generation

Basil J. Vitins

Kay W. Axhausen

Transport and Spatial Planning   **May 2012**

STRC | **12th Swiss Transport Research Conference**
Monte Verità / Ascona, May 2 – 4, 2012

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Basil J. Vitins
IVT
ETH Zurich
CH-8093 Zurich
phone: +41-44-633 27 02
fax: +41-44-633 10 57
basil.vitins@ivt.baug.ethz.ch

Kay W. Axhausen
IVT
ETH Zurich
CH-8093 Zurich
phone: +41-44-633 39 43
fax: +41-44-633 10 57
axhausen@ivt.baug.ethz.ch

May 2012

Abstract

Urban systems continue to grow worldwide due to population growth and migration. Therefore, urban design guidelines are urgently needed for planning purposes. However, current network and urban design guidelines lack of a fundamental research base for design recommendation. 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 hierarchical shape grammar rules for road networks. It could be shown that they have significant impact on generalized costs.

This paper especially sheds light on various intersection types and the corresponding expected delays for the road users. It is quantitatively shown that intersection delays mostly depend on their number of arms and the current through traffic shares. Propositions for shape grammars and future standards are made regarding intersection type alignment. The proposed alignments are evaluated in virtual networks, generated on featureless planes. The generation of virtual network layouts respects the shape grammars under consideration. The travel times are compared regarding the corresponding shape grammars. The results show the high performance of roundabouts for variable demand. The proposed Matrix 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 land use interactions, and growth processes.

Keywords

Urban, simulation, intersection, delay, shape grammars, road, network.

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 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. Firstly, the delay calculation for the four intersection types signal lights (Section 2.1), roundabouts (Section 2.2), two-way-stop-controlled intersections (Section 2.3) and all-way stop-controlled intersections (Section 2.4) are described in detail. 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.

2.1 Signal Lights

2.1.1 Introduction

Numerous factors have to be considered for intersection modeling, and (semi-) automatic control is often implemented in urban and rural intersections. We refer here to a simple mode, and vary below only the green time according to the link type. Additional parameters are e.g.

- "Right-Turn-on-Red" movement (RTOR) is not very common in Switzerland (Europe) and therefore not considered further.
- Upstream filtering adjustment factor accounts for the effect of an upstream signal on vehicle arrivals to the intersection in consideration.
- Pedestrian and bicycles highly influence signal light operation.

2.1.2 Delay Calculations for Signalized Intersections

The total delay is calculated as:

$$d = d_1 + d_2 + d_3$$

d: control delay [sec/veh.]
d_1: uniform delay [sec/veh.]
d_2: incremental delay [sec/veh.]
d_3: initial queue delay [sec/veh.]

Uniform Delay d_1

The following formula describes the uniform delay when vehicles arrive randomly throughout the cycle. It is similar to (Dion *et al.,* 2004) and their time-dependent stochastic delay model. The saturation flow rate *s* depends on many adjustment factors, like pedestrians, heavy vehicles, lanes, etc. Here, *s* is set to 1'800 [veh./h] which in line with other studies (Pitzinger and Spacek, 2009, Dion *et al.,* 2004).

$$d_1 = \frac{0.5 \cdot C \cdot (1 - g/C)^2}{1 - [min(1, X) \cdot g/C]} \qquad and\,for \quad X = \frac{v}{N \cdot s \cdot \frac{g}{C}}$$

d_1: Uniform delay.

C: Cycle length (= 120sec maximum), sum of green times, yellow and red clearance, ped walk and clearance.

g: Green time, standard values for different road types.

X: Volume to capacity ratio.

v: Volume of incoming lane.

N: Number of lanes (= 1 as a default).

s: Saturation flow rate [veh./h/lane].

d_1 mainly depends on the g/C ratio. d_1 ranges from $0.5 \cdot C \cdot (1 - g/C)$ to $\frac{0.5 \cdot C \cdot (1 - g/C)^2}{1 - [g/C]}$.

Incremental Delay d_2

The incremental delay consists of the delay due to the effect of random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity, evidenced by the occasional overflow at the end of the green interval. The second component is due to sustained oversaturation during the analysis period. This delay occurs when aggregate demand during the analysis period exceed aggregate capacity. Incremental delay does not account for initial queue delay. The formula is from (Transportation Research Board (2010) p. 18-56).

$$d_2 = 900 \cdot T \cdot \left[(X_A - 1) + \sqrt{(X_A - 1)^2 + \frac{8kIX_A}{c_A T}} \right]$$

d_2: Incremental delay.

T: Analysis period duration.

X_A: Average volume to capacity ratio.

k: Incremental delay factor.

I: Upstream filtering adjustment factor (= 1 for isolated intersection).

c_A: Average capacity.

Inital Queue Delay d_3

The initial queue delay depends on the queue length before the analysis period. It is neglected here for simplicity. However, d_3 has to be implemented when accounting for consecutive time periods.

Unlike roundabouts or unsignalized nodes, signal control delays mainly depend on the capacities for lane discharge. The green time can vary between different incoming roads. They are set according to Transportation Research Board (2010).

2.2 Roundabouts

2.2.1 Introduction

Unlike signal controlled intersections, roundabouts have three major flow rates: entry flow rate v_e, conflicting flow rate v_c and exit flow rate v_{ex} (Figure 1). The conflicting flow rate v_c refers to the circulating traffic inside the roundabout, which forces entering traffic to yield. The proposed formulae are derived from Transportation Research Board (2010) and refer to single entry and circular lane roundabouts. The delay calculations are based on a lane-based regression and cap-acceptance model.

Figure 1: Roundabout flows v_e, v_c, and v_{ex}.
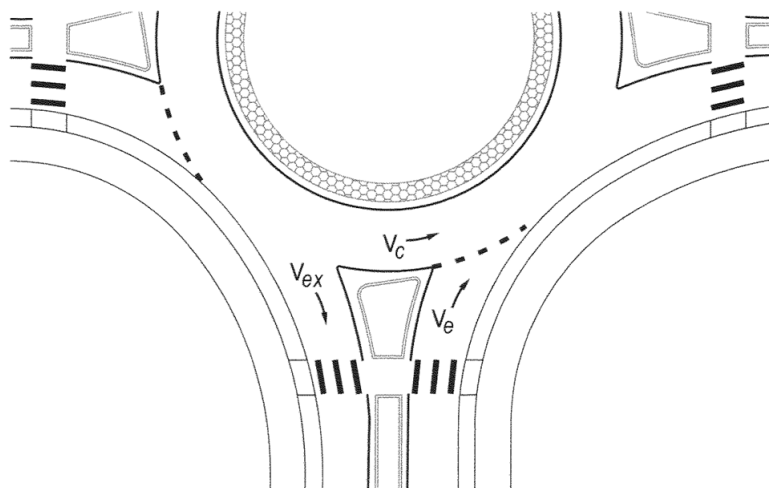
Source: Transportation Research Board (2010) p. 21-5.

2.2.2 Delay Calculations for Roundabouts

The capacity c_e of the entry lane depends on the conflicting flow rate v_c. The formula below refers to observations, and reflects a lower bound of roundabout capacities, which increases with familiarity and aggressive driving.

$$c_e = 1130 \cdot e^{-0.001 \cdot v_c}$$

c_e: Capacity of entry lane.

v_c: Volume of conflicting circulating traffic.

The total delay d is calculated as the following (Transportation Research Board (2010) p. 21-19):

$$d = \frac{3'600}{c_e} + 900 \cdot T \cdot \left[x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3'600}{c_e}x}{450T}} \right] + 5min[x, 1]$$

d: Average control delay.

x: Volume capacity ratio of subject lane.

c_e: capacity of subject lane.

T: Analysis period duration.

The formula above has to be adjusted for additional entry lanes or bypass lanes. Unlike signal control intersections, roundabout delays do not depend on the incoming lane capacity. Delays rather depend on the capacity $c_e = f(v_c)$, a function of the conflicting volumes. Therefore, the delay function is equal for all incoming road types. Exception are multiple incoming lanes and bypasses, which are neglected in this paper.

2.3 Two-Way Stop-Controlled (TWSC) Intersections

2.3.1 Introduction

The majority of the TWSC intersections have a major street, which is uncontrolled, and a minor street, which is controlled by a stop sign. Left-turning drivers from the major street may have to yield to oncoming major-street trough or right turning traffic. However, they are not required to stop in absence of oncoming traffic. The principles of TWSC intersection modeling rely on gaps and the chance for a driver from a minor street to fill the gap. Again, a setting with one lane each leg and without bypasses or pedestrian interaction is modeled in this paper. Additionally, no upstream gap producers and no U-turn movements exist in the model below. The right-of-way rules are applied if two movements are conflicting, and if the movements enter from a road of the same hierarchy.

Because priority is most important in TWSC intersections, the movements are sorted in ranks, according to their priorities:

- Rank 1 movements are through and right turn traffic, both entering on major streets.
- Rank 2 movements are major street left turn traffic, and minor street right turn traffic.
- Rank 3 movements are minor street through traffic.
- Rank 4 movements are minor street left turn movements at four leg crossings.

2.3.2 Delay Calculations for TWSC Intersections

The total conflict flow rate $v_{c,x}$ of a movement x is determined for all turns:

$$v_{c,x} = \sum_i v_{c,i}$$

$v_{c,x}$: Conflicting flow rate of a movement x.

$v_{c,i}$: Flow rate of single movement i, which is in conflict with movement x.

$$c_{p,x} = v_{c,x} \cdot \frac{e^{-v_{c,x}t_{c,x}/3600}}{1 - e^{-v_{c,x}t_{f,x}/3600}}$$

$c_{p,x}$: Potential capacity of movement x.

$v_{c,x}$: Sum of all conflicting flow rates for movement x.

$t_{c,x}$: Critical headway for minor movement x, based on observations.

$t_{f,x}$: Follow-up headway for minor movement x, based on observations.

The potential capacity $c_{p,x}$ is corrected for each road type and rank according to the flows of the other movements, resulting in $c_{m,j}$ (Table 1).

Table 1: Calculation of $c_{m,j}$ depending on the turn movement.

Turn movement	$c_{m,j} =$
Major street left turn	$c_{p,j}$
Minor street right turn movement	$c_{p,j}$
Major street left turn	$c_{p,j} \cdot p_{0,j}^* = c_{p,j} \cdot \left[1 - \frac{1 - p_{0,j}}{1 - x_{i,1+2}}\right]$ with $p_{0,j} = 1 - \frac{v_j}{c_{m,j}}$
Minor left turn movement	$c_{m,j} = c_{p,j} p' p_{0,j}$. $p' = 0.65 p'' - p''/(p'' + 3) + 0.6 \cdot \sqrt{p''}$ with $p'' = p_{0,j} p_{0,k}$.

The delay d_1 for any movement of rank 1 is shown below (Transportation Research Board (2010) p. 19-28).

$$d_1 = \left(1 - p_{0,1}^*\right) \cdot d_{M,LT}$$

d_1: Control delay for rank 1 movement.

$p_{0,1}^*$: Proportion of rank 1 vehicles not blocked.

$d_{M,LT}$: Delay to major left-turning vehicles.

The delay d_{2-4} for rank 2 to 4 movements is calculated as the following:

$$d_{2-4} = \frac{3'600}{c_{m,x}} + 900 \cdot T \cdot \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\frac{3600}{c_{m,x}} \frac{v_x}{c_{m,x}}}{450T}} \right] + 5$$

d_{2-4}: Control delay for rank 2-4 movement.

v_x: Flow rate for movement x.

$c_{m,x}$: Capacity of movement x.

T: Analysis time period [h].

2.4 All-Way Stop-Controlled (AWSC) Intersections

2.4.1 Introduction

AWSC intersections are seldom implemented in reality, especially in Swiss and German urban environments. Sometimes, they can be seen in residential neighborhoods. However, for completeness and comparison reasons, all way stop controlled intersections are introduced here. In the following, a generalized model for single-lane intersections are used to calculate the delay. Since all turn volumes are known and single incoming lanes are assumed, the procedure in Transportation Research Board (2010) is simplified for this work.

2.4.2 Delay Calculations for AWSC Intersections

The approach is based on headways between departing vehicles. The headway depends on the degree of conflict experienced with interfering vehicles.

The headways $h_{s,i}$ depend on a standard headway $h_{base,i}$ and an adjustment headway h_{adj} for the turn type. Heavy vehicles are neglected in the current version. The headway adjustments are calculated as the following:

$$h_{s,i} = h_{base,i} + h_{adj} = h_{base,i} + h_{LT,adj} \cdot P_{LT} + h_{RT,adj} \cdot P_{RT}$$

$h_{s,i}$: Saturation headway for case i.
$h_{base,i}$: Standard base saturation headway for each case i.
$h_{LT,adj}$: Saturation headway adjustment for left turns.
$h_{RT,adj}$: Saturation headway adjustment for left turns.
P_{LT}: Proportion of left turning vehicles.
P_{RT}: Proportion of right turning vehicles.

The saturation headway serves directly as an input parameter in the delay calculation. The saturation headway is bases on the degree-of-conflict case $P(C_i)$. $P(C_i)$ is based on the opposing and conflicting approaches and their occurrences. 5 conflicting approaches exist for single lane incoming streets (Transportation Research Board (2010) p. 20-7).

$$h_d = \sum_{i=1}^{5} P(C_i) \cdot h_{si}$$

$P(C_i)$: Probability of degree-of-conflict case C_i, $i \in \{1, ..., 5\}$ in single lane approaches.
h_{si}: Saturation headway for each case.

The final average delay is calculated as the following:

$$d = t_s + 900 \cdot T \cdot \left[(x-1) + \sqrt{(x-1)^2 + \frac{h_d x}{450T}} \right] + 5$$

d: Average control delay.

x: Degree of utilization (= $vh_d/3600$, v for traffic volume).

t_s: Service time.

h_d: Departure headway.

T: Length of analysis period [h].

The formula reassembles the formula above for TWSC intersection. It is assumed, that the traffic volume v, to calculate x, is the total volume of the intersection (not clear in (Transportation Research Board, 2010)).

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

3.1.1 Signal Control Delays

Figure 2 refers to the delay of signal controlled intersections. Figure 2 is subdivided in three cases with different incoming road capacities. For the incoming links, the three link types local, collector and minor arterial roads are assumed in the simulation. Figure 2 shows three cases, derived from the three road types. d_1 refers to the uniform delay, d_2 to the incremental delay, and $d_3 = d_1 + d_2$.

Incoming traffic volumes mainly influence delay. This is clear with the delay calculation described in Section 2.1.2. The signal light delays are similar to Dion *et al.* (2004), regarding different traffic volumes and corresponding delays. However, Dion *et al.* (2004) have a lower base delay d_1 of about 10 sec. For longer green times, a higher base delay d_1 seems more reasonable.

For comparison reasons, the total delays for three and four legs intersections are summarized in Figure 3.

The different number of legs leads to a different uniform delay d_1. This is due to the adjusted capacity. The higher the adjusted capacity c_A, the higher the ratio of traffic volume to c_A. This

Figure 2: Uniform and incremental delays for increasing loadings in 4 legs signal controlled intersections.

(a) Local roads crossing with green time = 15sec.

(b) Collector roads crossing with green time = 20sec.

(c) Minor arterial crossing with green time = 30sec.
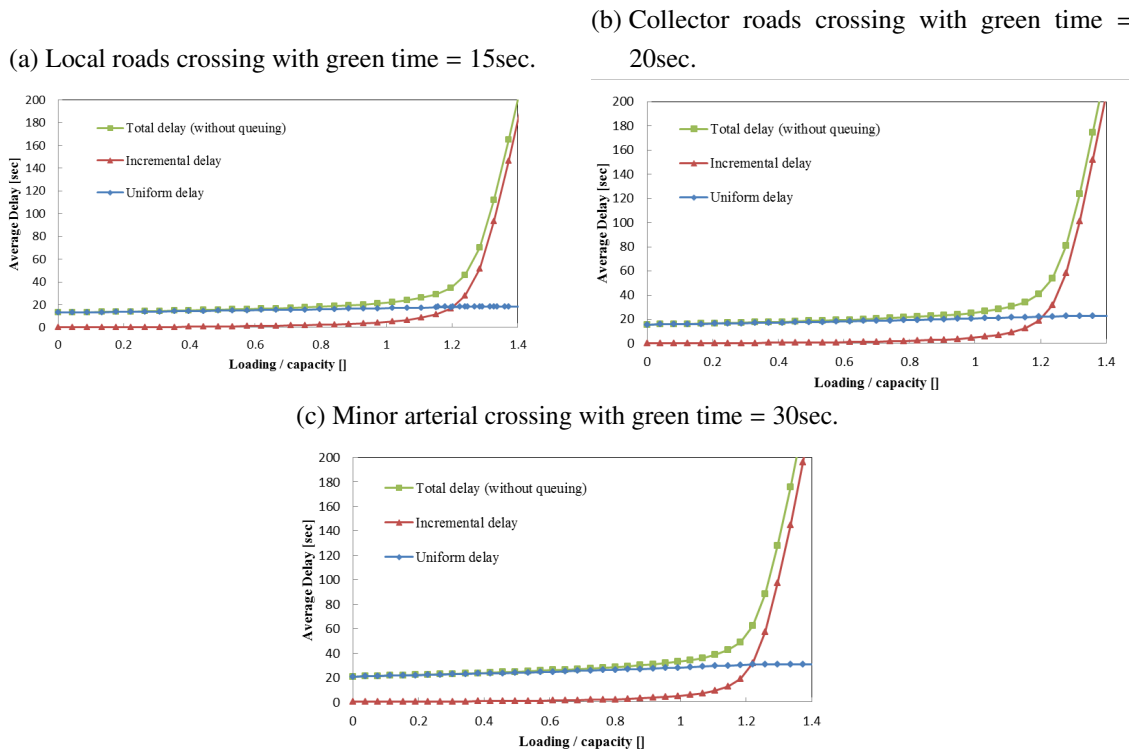
Figure 3: Total signal light intersection delays.

(a) Three legs.

(b) Four legs.
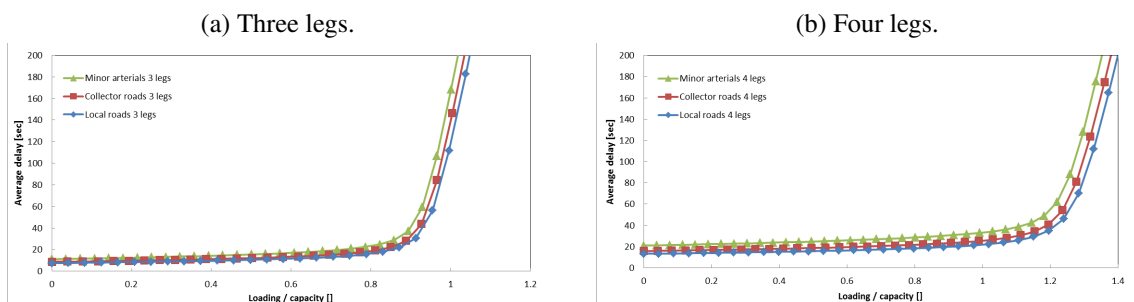
can be seen in small scale between the different cycle lengths. However, the higher capacity of three leg intersections plays a major role in the delay calculations. Therefore, the traffic to capacity ratio is lower.

Figure 4 shows the turn delay of a signal controlled intersection under different traffic volumes and through traffic share. Figure 4 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.

Figure 4: Signal light delays for different traffic volumes and through traffic, in a crossing of an arterial and a collector road.
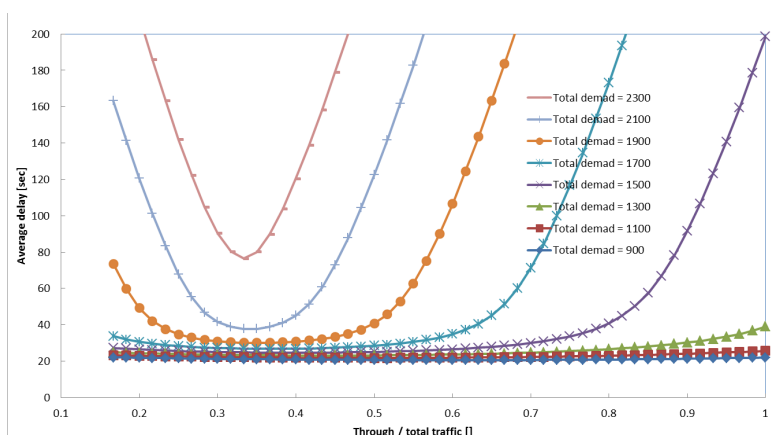
Since green time depends on the incoming road type, the optimum through traffic share is between 0.0 and 1.0 due to the different incoming road types in Figure 4. The optimal through traffic ratio in Figure 4 of about 0.33 is similar to the ratio of the different green times (20sec/30sec). Derivation from the optimum through traffic share increases delays. This can be improved with more flexible green time.

3.1.2 Roundabout Delays

Unlike the delays of signal controlled intersection, the delays of roundabouts mainly depend on conflicting volumes, than on the incoming road capacity. Therefore, the incoming road capacity is neglected in this simulation. Figure 5 shows the roundabout delay for all road types.

The delays of the roundabout are shorter than of the signal controlled intersection, unless the capacity of the signal lights, and the incoming road capacities, are high enough (Figure 2). The average delays of a 3 leg roundabout are similar compared to a 4 leg roundabout. However, high traffic volumes lead to higher delays in 3 leg roundabouts. This is due to the higher volume / capacity ratio, a major factor in the delay calculation (see Section 2.2). The high volume / capacity ratio overcomes the effect of the conflicting flow rate v_c. v_c would rather decrease the delays at 3 leg intersections.

Figure 6 displays the turn delay of a roundabout under different traffic volumes and through traffic share.

Figure 6 shows low delays regardless of the through traffic share. However, delay especially

Figure 5: Roundabout delays for all road types.
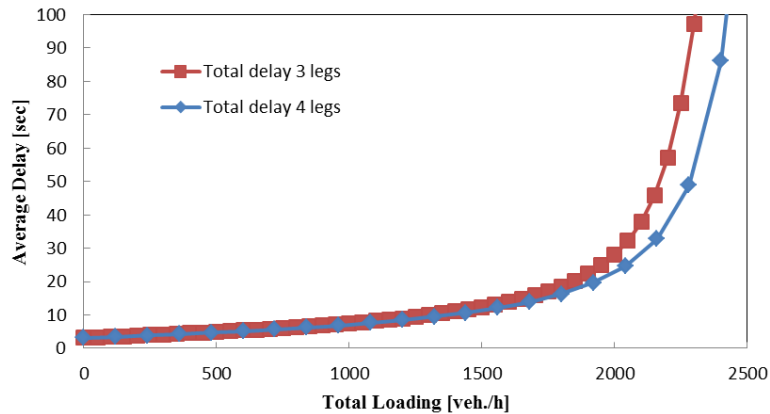
Figure 6: Roundabout delays for different traffic volumes and through traffic at four leg intersections.
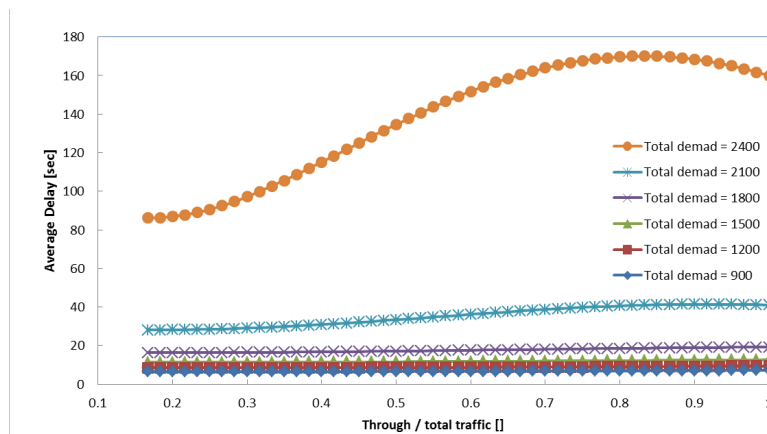
increases when demand and trough traffic share are high. This origins from the exponential influence of the conflicting circular volumes already in the roundabout (Section 2.2). The delay is decreasing again with (nearly) only through traffic, due to the absence of any conflicts.

3.1.3 TWSC Intersection Delays

As roundabout delays, the TWSC intersection delays mainly depend on conflicting movements and volumes, than on the incoming road capacities. Therefore, the incoming road capacity is neglected in this simulation. Figure 7 shows the TWSC intersection delay for all road types with uniform distributed traffic loading.

Figure 7: Average TWSC intersection delays for all road types.
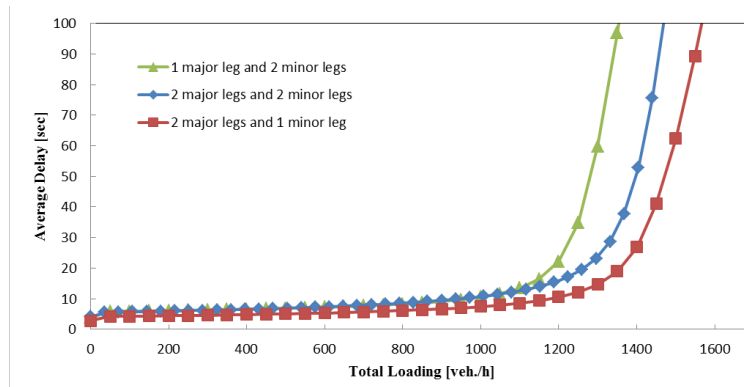
Figure 7 refers to a uniform turn movement distribution. The average delay is between the delays of signal controlled intersections and roundabouts. The delays of 3 leg intersections differ from four leg intersections. The situation is interesting where 2 major legs are joined with 1 minor legs. The delays are minimized due to the minimal conflict flows.

Through traffic plays a major role in TWSC intersections. Figure 8 shows the delay of TWSC intersection under different traffic volumes and through traffic shares.

Figure 8: Average TWSC intersection delays for different traffic volumes and through traffic at four leg intersections.
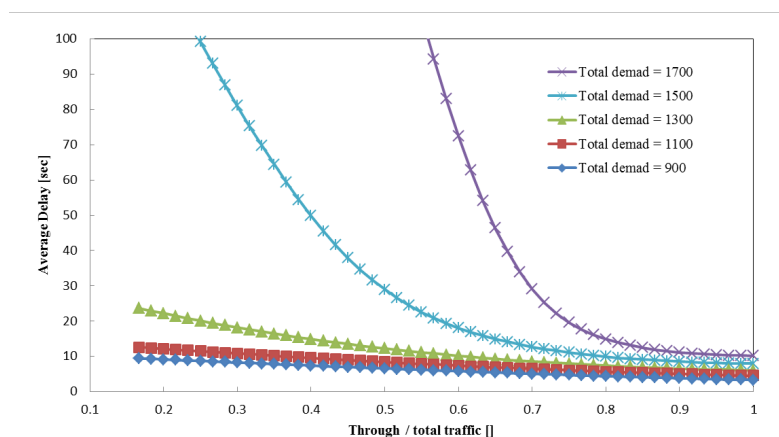
Figure 8 shows the high dependency of the through traffic share and the total delay. The higher the share of through traffic, the lower the total delay. Uniform delay seems to increase average delay. This is especially important with high total volumes, like in urban environments. Only through traffic (share close to 1.0) leads to a lower delay again (see Figure 8) because of the absence of conflicting movements.

3.1.4 AWSC Intersection Delays

Similar to TWSC intersection, the delay of AWSC intersections mainly depend on the conflicting volumes. However, AWSC intersections slightly depend on the incoming road capacity, as needed when estimated the degree of utilization of incoming roads.

Figure 9: Average AWSC intersection delays for all road types.

(a) Three legs intersection.   (b) Four legs intersection.
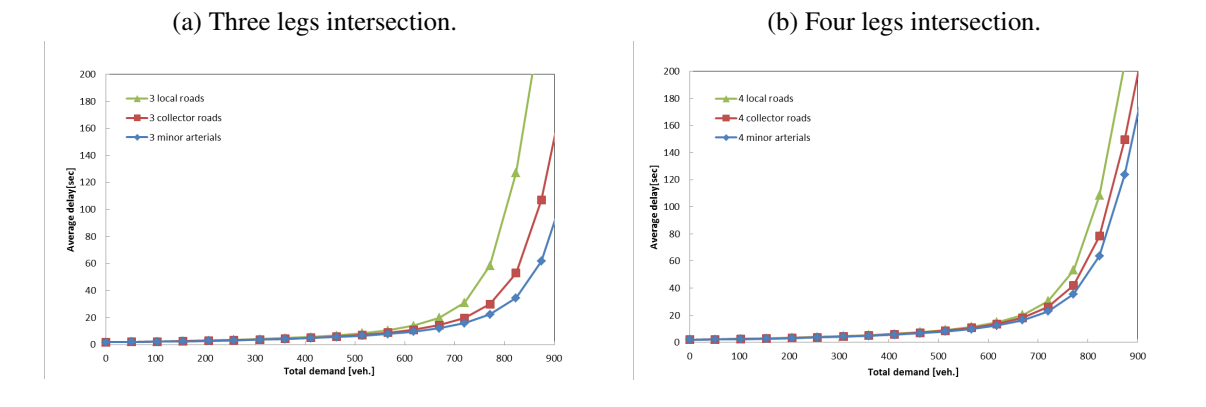
The total delay is rather high and comparable with small signalized crossings. AWSC intersections only perform well with low volumes. Due to the missing signal cycle, AWSC intersections perform better than signals with low and uniformly distributed traffic volumes.

Figure 10: Average AWSC intersection delays for different traffic volumes and through traffic at four leg intersections.
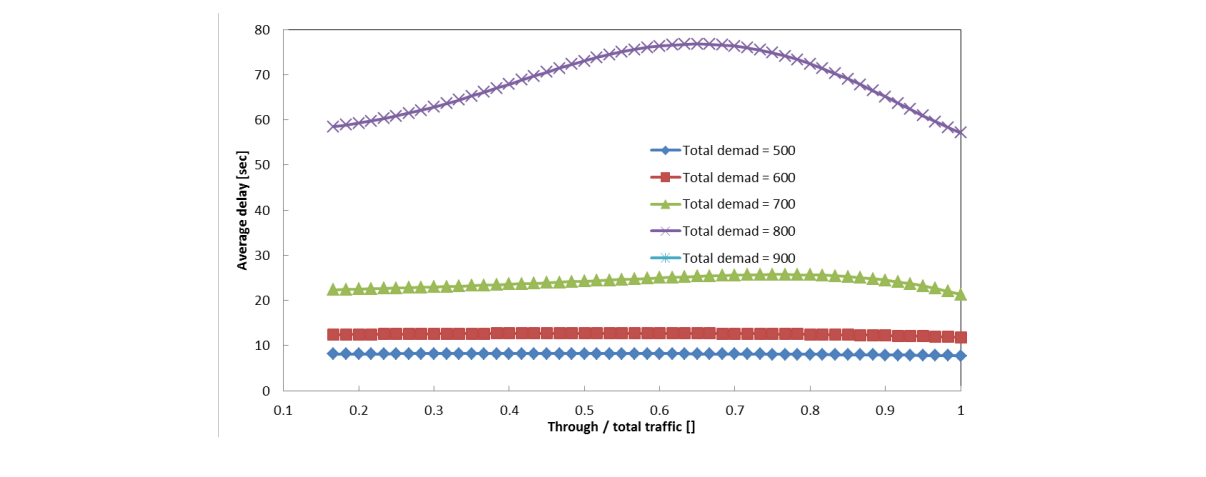
The total delays of AWSC intersections depend mainly on the total loading, the delay is stable when increasing through traffic (Section 2.4). Only for very high total demand, the total delay increases with increasing through share. This is due to the conflicting volumes. Generally,

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.

3.1.5 Comparison Between Different Intersection Types

In the following, the delays are compared between the different intersection types. The formulae and the parameters remain the same as above. Figure 11 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 11(b) - 11(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.
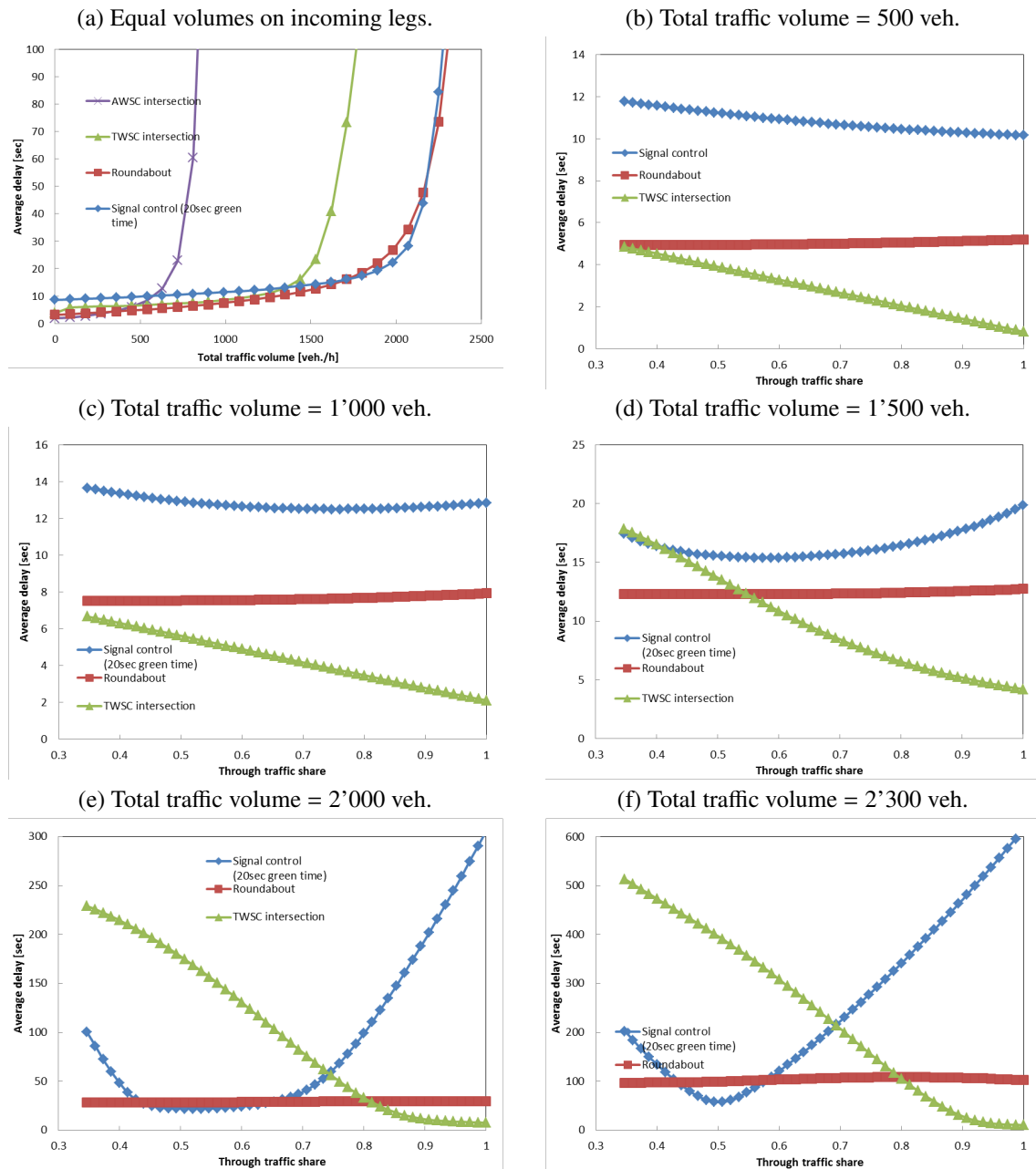
Figure 11(a) shows a uniform traffic distribution with variable total traffic volumes. The delays in Figure 11(a) vary significantly between different volumes when comparing AWSC, TWSC and roundabouts. However, roundabouts and signal controlled intersections almost have the same delays. Small differences 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 12 shows the delays of the intersection types TWSC, AWSC, roundabout and signal control for four legs. Similar to Figure 11, AWSC intersections are not considered further due to the fact that large through traffic often passes on road types of higher hierarchies.

Figure 12(a) shows a uniform traffic distribution with variable total traffic volumes. In Figure 12(a), roundabouts have the lowest delay for low and high traffic volumes, followed by signalized intersections. Figure 12(a) contrasts the delays of a 3 leg intersections (Figure 11(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.

Figure 11: Delay comparison between different intersection types with 3 legs.

(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.

3.2 Implementation in Network Design

3.2.1 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. Table 2 and

Figure 12: Delay comparison between different intersection types with 4 legs.

(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.
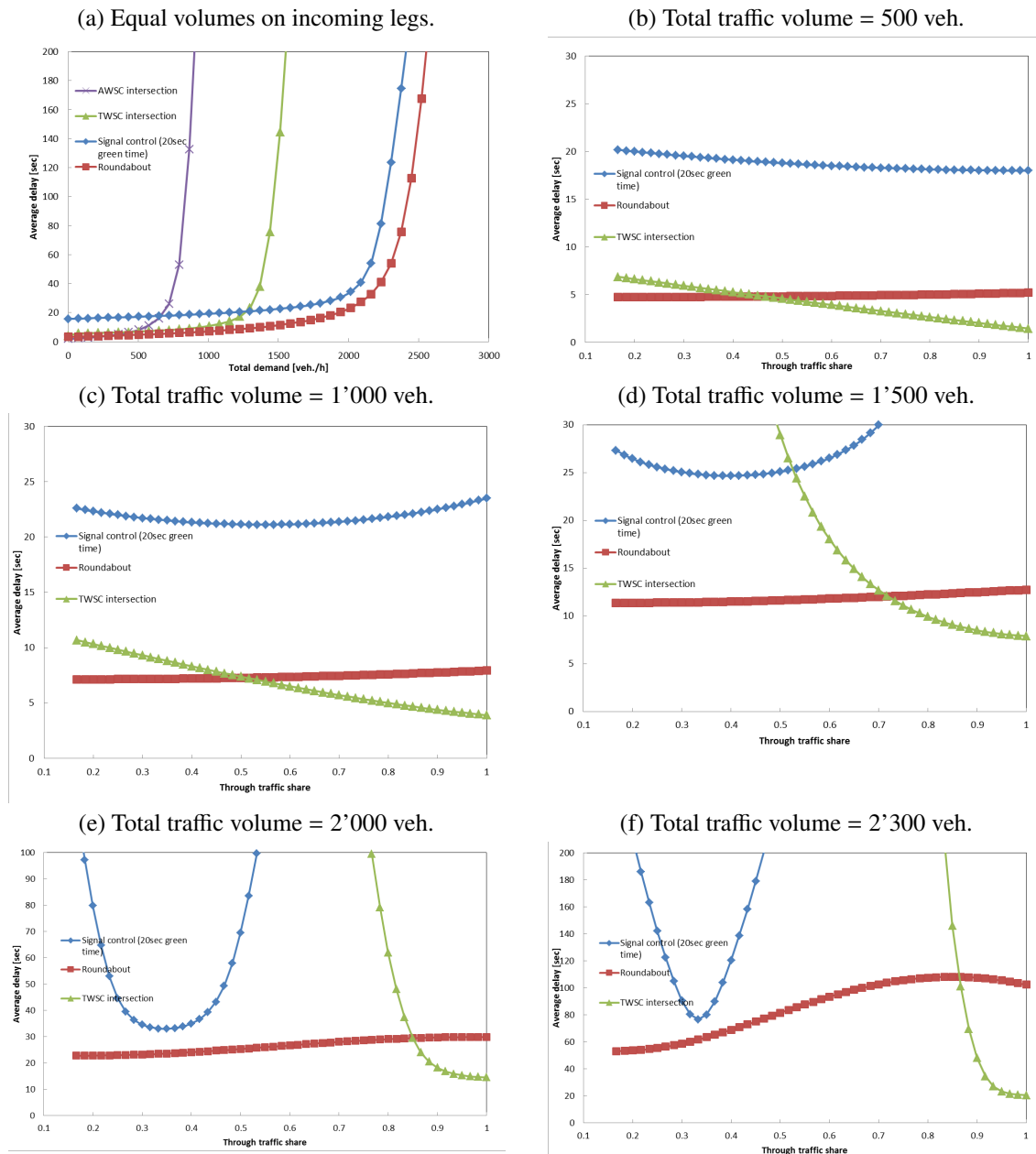
3 list intersection types with the lowest delays, further called Matrix shape grammar rules.

The Matrix shape grammars shown in Table 2 and 3 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.

It is added that, under very low volumes, AWSC intersections generally perform well (Figures

Table 2: Matrix Shape grammar rules for 3 leg intersections.

Total traffic volume	Through traffic share			
	<40%	<60%	<80%	<100%
< 500	⭕ Roundabout	✚ TWSC	✚ TWSC	✚ TWSC
< 1'000	⭕ Roundabout	✚ TWSC	✚ TWSC	✚ TWSC
< 1'500	⭕ Roundabout	⭕ Roundabout	✚ TWSC	✚ TWSC
< 2'000	⭕ Roundabout	⁞ Signal Control	⭕ Roundabout	✚ TWSC
> 2'000	⭕ Roundabout	⁞ Signal Control	⭕ Roundabout	✚ TWSC

⭕ : Roundabout   ⁞ : Signal Control   ✚ : TWSC Intersections

Table 3: Matrix Shape grammar rules for 4 leg intersections.

Total traffic volume	Through traffic share				
	<20%	<40%	<60%	<80%	<100%
< 500	⭕ Roundabout	✚ TWSC	✚ TWSC	✚ TWSC	✚ TWSC
< 1'000	⭕ Roundabout	⭕ Roundabout	✚ TWSC	✚ TWSC	✚ TWSC
< 1'500	⭕ Roundabout	⭕ Roundabout	⭕ Roundabout	✚ TWSC	✚ TWSC
< 2'000	⭕ Roundabout	⭕ Roundabout	⭕ Roundabout	⭕ Roundabout	✚ TWSC
> 2'000	⭕ Roundabout	⁞ Signal Control	⭕ Roundabout	⭕ Roundabout	✚ TWSC

⭕ : Roundabout   ⁞ : Signal Control   ✚ : TWSC Intersections

11 and 12), similar to the proposed roundabouts in Table 2 and 3 above. This is inline with some AWSC intersections observed in residential neighborhoods with very low volumes.

3.2.2 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 4.

Table 4: 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 2 and 3	-7.5%

Table 4 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. 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, considering the geometric layouts of the incoming roads. However, further calculation power reduction is still possible.

3.2.3 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 4. 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 ≤ 3 leg intersections and uniformly distributed turn volumes. This is due to the low conflicting volumes. Additionally, 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 various conflict volumes.

Future research is needed in the adaption of the number of lanes of the incoming roads. The number of lanes can be increased for all intersection types, in order to additionally reduce delays. This suggestions is in line with e.g. Dion *et al.* (2004), focussing on signalized intersections. Pedestrian shares are especially high in very dense areas. 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. Especially adaptive green time lengths may reduce total delays additionally.

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.

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