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Network effects of local intersection design strategies

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Abstract

Various strategies exist to choose the best intersection design considering the operational performance of an intersection. There are model-based strategies which for example choose the design with the minimal average delay or rule-based strategies which choose the design based on the total volume or specific safety preferences. These strategies choose the design for a local situation. The analysis of network effects (e.g. the total travel time in the network) of these strategies is an unexplored area of research. This paper provides some first insights in the network effects of various local intersection design strategies in comparison with a global network optimization. Strategies, advising all-way stop-controlled, two-way stop-controlled and signalized intersections and roundabouts are tested on the well-known Sioux Falls network. Results show substantial differences between the network performances and solutions of the different strategies, providing a base for future improvement of intersection design strategies which benefit a better network performance.

Keywords: Intersection design, design strategies, design rules, Network Design Problem, network optimization, method of successive weighted averages, genetic algorithm.

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1. Introduction

In urban networks a substantial part of travel time is spent on intersections. Hence, delay is a key criterion for choosing the best intersection design. Intersection design encompasses the choice for the main intersection type, such as signalized intersection or roundabout, as well as choices concerning the configuration of the approach and exit lanes, signs, crossing facilities and various geometric measures. For signalized intersections, additional choices concerning the signal settings, such as the cycle length, green times and phase diagrams, are made.

Various strategies can be used to choose the best design considering the operational performance of an intersection. A common strategy is to choose the design which produces the minimum average, volume weighted, turn delay. Or alternatively, the design with the minimum maximum turn delay can be chosen. Both strategies require a model, either a macroscopic analytical model or a microscopic simulation model, to determine the delay for a set of intersection designs and traffic demand (turn flows). These are model-based intersection design strategies. Other strategies use design rules, both to avoid the need for model runs, as well as to reckon with specific preferences from road authorities. An example of a rule-based intersection design strategy is to choose the design based on the total twenty-four-hour traffic flow on the intersection. When the flow is below 18,000 a two-way stop-controlled intersection is advised, when the flow is between 18,000 and 25,000 a roundabout is advised, whereas a signalized intersection is advised for higher flows. This rule is based on two underlying objectives. Two-way stop-controlled intersections and roundabouts are preferred from a safety objective point of view, but their operational performance becomes unacceptable when traffic flows exceed a certain threshold value. There exists a wide variety of both model-based and rule-based intersection design strategies in road design manuals, guidelines and technical reports for numerous countries: e.g. Australia (Austroads, 2013), Belgium (AWV, 2009), Germany (FGSV, 2007; 2013; 2015), France (SETRA, 2002), The Netherlands (CROW, 2008; 2012; 2013), UK (Department for Transport, 2017) and USA (AASHTO, 2010; FHWA, 2012; TRB, 2010a; 2010b; 2010b).

These strategies are used to optimize (i.e. minimize delay for) a local situation and evidently do not reckon with the effects on network level. Decreasing the delay on one route can however cause changes in route choice and possibly an increase of volumes and delays on other parts of the network. This is especially true for urban networks, with high congestion levels and intersection densities. What is best for local situations is not always best for the whole network, i.e. the total delay. It is desirable to compare and analyze the network effects for different local intersection (optimization) strategies applied for one or more intersection locations. Moreover, it would be even better to compare them with the results from a global network optimization, which provides the solution (intersection designs) with the minimum total delay.

Determining and analyzing the network effects of intersection design strategies is an unexplored area of research, both regarding results and modelling. This paper provides the first insights in the network effects of intersection design strategies. This is done by selecting six (both model- and rule-based) intersection design strategies, which are used to choose one out of four intersection design alternatives (all-way stop-controlled, two-way stop-controlled, signalized or roundabout) for each potential intersection location. A modelling framework is developed which determines the intersection design solutions and total delay in the network for both the local strategies as well as a global optimization. The modelling framework is applied on the well-known theoretical network of Sioux Falls. Traffic demand is fixed for a peak hour period and the traffic state is modelled by way of a deterministic static traffic assignment model. Intersection delays are determined by way of the Highway Capacity Manual 2010 methodologies (TRB, 2010a). To maximize the impact of the intersection design strategies, all intersections in the network are determined by these strategies. The resulting total delays, intersection designs and intersection delays are compared and analyzed, and are expected to provide a base for future improvement of intersection design strategies which benefit a better network performance.

The paper continues with a description of the modeling framework and the test case before presenting the results and suggestions for further research.

2. Modelling framework

2.1. Modelling challenge

The problem of optimizing intersection design alternatives which considers the network perspective is a particular case of the Network Design Problem, in which the intersection design alternatives are decision variables, while the network topological characteristics (widths, number of lanes, open or closed links, etc.) are fixed and invariable. In this problem, the link flows are descriptive variables: the analyst cannot directly modify them, but they can be indirectly influenced by changing the decision variable values (Cascetta et al., 2006). The Network Design Problem is generally formulated as a bi-level optimization problem. The upper level represents the behavior of the network authority, which aims to optimize one or more system objectives and controls the decision variables. The lower level describes the behavior of road users, which aim to minimize their own generalized cost (e.g. travel time, cost), by making individually optimal choices in the road network. The network design in the upper level interacts with the behavior of the travelers in the network: the lower level. The lower level is a constraint for the upper level, since the upper level cannot dictate the behavior of the users in the lower level. Any network design the network authority chooses, results in a network state (e.g. travel times and flows), from which system objectives can be derived (Brands, 2015). In this paper, minimizing travel time (or delay) is the sole objective. Two kind of approaches for the optimization of intersection designs can be identified: the local optimization of intersection designs and the global optimization of intersection designs (Cascetta et al.,2006). The local approach can be used to determine the network performance for local intersection design strategies, i.e. the strategies try to optimize a certain objective (i.e. minimize delay) based on intersection model results or rules. The global approach can be used to determine the global minimum, i.e. the set of intersection design alternatives which produces the minimum total travel time in the network.

Literature study showed that for both the local and global optimization of intersection design problems, there seems to be no ready-made framework or modelling approaches. The problem is however similar to the local and global optimization of signal settings problem which was studied extensively. Some examples of recent work, which include reviews of earlier research are (D'Acierno et al., 2012; Gallo et al., 2015) for local optimization and (Liangzhi et al., 2012; Wismans, 2012; Marciano et al., 2013; Ren et al., 2013) for global optimization.

2.2. Local optimization of intersection designs

The local optimization of signal settings problem can be formulated as a fixed-point problem where one has to search for equilibrium traffic flows congruent with link travel times and signal settings, and the signal settings are obtained according to a local control policy (Gallo and D'Acierno, 2015). Cascetta et al. (2006) state that the algorithms proposed to solve this problem can follow two different approaches. Simultaneous algorithms solve a unique problem, in which the signal settings and equilibrium traffic flows are considered as unknown variables. Sequential algorithms solve alternately a problem of signal regulation (with known flows) and an equilibrium network assignment problem (with known signal settings). They concluded that sequential approaches converged more quickly. The approaches they tested were all based on a method of successive averages (MSA) framework, which is widely used for solving traffic assignment problems. Further and more recent research (Gallo et al., 2015; Liu et al., 2009; Bezembinder et al., 2016) showed that the method of successive weighted averages (MSWA) showed the best convergence results. The sequential approach as suggested by Cascetta et al. (2006), including the MSWA as suggested by Liu et al. (2009) will be used for the solution approach for the local optimization of intersection design problem. During each iteration of the sequential approach, the intersection designs for all (potential) intersections in the network are (re-)determined based on the given turn flows and optionally, the turn cost. The intersection design consists of attributes like the main intersection type (stop-controlled, signalized or roundabout), the signal settings, the number of circulating lanes on a roundabout, the sign type, the number and configuration of the entry and exit lanes and the central reservation width. The choice for the intersection design is determined by either a model-based or rule-based (or a combination of both) intersection design strategy. The link cost function is expressed in time ($tt_{l,a}$) and is determined by using the Bureau of Public Roads function:

$$tt_{l,a}(f_{l,a}) = tt_{l,a,0}\left[1 + \alpha\left(f_{l,a}/C_{l,a}\right)^{\beta}\right] \tag{1}$$

where $f_{l,a}$ is the flow on link a, $C_{l,a}$ is the capacity of the link and α and β are model parameters. The turn cost function is also expressed in time (delay) and is determined by an intersection model based on the Highway Capacity Manual 2010 methodologies for all-way stop-controlled, two-way stop-controlled and signalized intersections and roundabouts. These methodologies require an intersection design and turn flows as input. In case of signalized intersections, the signal settings (cycle time, green time) are determined by the Quick Estimation Method as described in (TRB, 2010a) which incorporates an equisaturation control policy method according to Webster (1985).

2.3. Global optimization of intersection designs

The global optimization of signal settings problem, being a bi-level problem, is NP-hard (Gao et al., 2015) and can only be solved by heuristics. The huge number of feasible solutions and the non-convexity of the objective function necessarily requires the adoption of metaheuristic algorithms (Wismans et al., 2012). In various studies, different heuristics such as hill climbing, simulating annealing, tabu search, genetic algorithms, branch and bound, particle swarm and ant (colony) systems, were compared based on their speed of convergence. In the vast majority of studies the genetic algorithm (GA) performed best (Ren et al., 2013). Therefore, a GA will be used as the solution approach for the global optimization of the intersection design problem. The objective of the GA is to maximize the payoff of candidate solutions in the population against a cost function from the problem domain. The strategy for the GA is to repeatedly employ surrogates for the recombination and mutation genetic mechanisms on the population of candidate solutions, where the cost function (also known as the objective function or fitness function) applied to a decoded representation of a candidate governs the probabilistic contributions a given candidate solution can make to the subsequent generation of candidate solutions. The steps of a GA can be implemented in many ways. In this paper, the implementation as suggested by Brownlee (2012) is used. To test the fitness of each candidate solution, a traffic assignment model with intersection modelling using a MSA solution as described in the previous section is used. After the assignment, the total amount of travel time in the network is determined, being the fitness of the individual. Each GA run is performed with multiple random seeds (12345, 23451, 34512, 45123, 54321). The solution from the GA run with the lowest value for the total travel time in the network is chosen for further analysis.

2.4. Evaluation

Both the local and global optimization of intersection designs result in a solution (set of intersection designs in the network) and a total travel time. Since equilibrium conditions are not guaranteed in both approaches, for a fair comparison, the resulting solutions are once again assigned using a MSA based method in order to determine the final total, volume weighted, travel time in the network. For analyzing purposes also data concerning link and turn delays are determined.

3. Test case

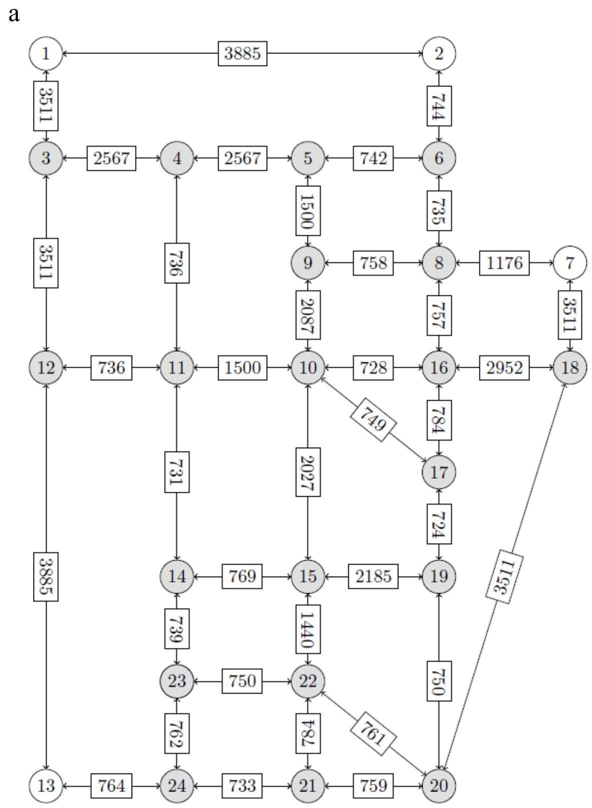
Six intersection design strategies have been chosen for which the network effects will be determined using the well-known Sioux Falls network extended with the choice from four intersection design alternatives for most of the nodes. For each of these variants, the global optimal intersection design solution is also determined. Successively, the Sioux Falls network, intersection design alternatives, intersection design strategies and some necessary model specifications will be explained.

3.1. Sioux Falls network

The Sioux Falls network, which was first published by Morlok et al. (1973), is widely used in transportation studies. In this paper, the variant as reported by Wang et al. (2013) is used as a starting point, because they give a comprehensive description of input and output data. To enable using their Sioux Falls network variant with intersection designs, the following adjustments have been made:

- On twenty of the twenty-four nodes, an intersection definition is added, resulting in fourteen three-leg and six four-leg intersections. The intersection design alternatives will be discussed in the next section;
- Although they don't mention a specific time unit, the link capacities and travel times correspond to a twenty-four hours' period. Because the intersection model requires passenger car units per hour, capacities and demand are divided by a factor of 10;
- To make the size of the link capacities in accordance with intersection capacities, the link capacities are multiplied by a factor of 1.5;
- Although not an adjustment, it should be mentioned that link free flow travel times are interpreted as a hundredth part of an hour. A free flow travel time of 6 would then be 0.06 hours, being 3.6 minutes.

The resulting Sioux Falls network and traffic demand is displayed in Figure 1 and shows the node numbers, intersection locations (gray nodes) and one-way link capacities (pcu/h) for both directions (a) and the traffic demand summarized by the number of departing and arriving trips per node (pcu/h) (b). For additional link attributes and the traffic demand matrix see (Wang et al., 2013).



b

Node	Departures	Arrivals
1	880	880
2	400	400
3	280	280
4	1160	1170
5	610	610
6	760	760
7	1210	1210
8	1670	1670
9	1620	1630
10	4520	4510
11	2230	2240
12	1390	1400
13	1460	1450
14	1410	1410
15	2140	2130
16	2610	2610
17	2340	2340
18	480	470
19	1280	1280
20	1850	1840
21	1100	1100
22	2440	2440
23	1450	1450
24	770	780
Total	36060	36060

Fig. 1 (a) Sioux Falls network with node numbers, intersection locations (gray nodes) and link capacities (pcu/h); (b) traffic demand with node departure and arrivals (pcu/h)

3.2. Intersection designs

In the Sioux Falls network, twenty intersection locations are possible, being fourteen three-leg and six four-leg intersections. The five-leg intersection at node 10 is interpreted as a four-leg intersection, where the leg from node 17 is ignored in the intersection model. For each location, four intersection design alternatives, in accordance with the HCM intersection types, are defined:

- All-way stop-controlled (AWSC) intersection;
- Two-way stop-controlled (TWSC) intersection;
- Signalized intersection;
- Roundabout.

Besides the main intersection type, the number of approaching and exiting lanes as well as the lane allocation is defined for each design alternative. The design alternatives for both three- and four-leg intersections are shown in Figure 2. For the TWSC intersections a choice was made which links must give way. For signalized intersections, no specific signal settings have been defined. The intersection model used will determine the signal settings (cycle times, green times) based on the intersection layout and traffic flows during each call.

3.3. Intersection design strategies

Six (local) intersection design strategies are defined, which are shaped to fit the four intersection design alternatives described in the previous subsection:

- TYPE: The design is always equal to one specific alternative, regardless of the traffic volumes and resulting performances, resulting in four separate strategies corresponding to the intersection design alternatives: AWSC, TWSC, signalized (SIG) and roundabout (RA);
- MINAVGDELAY: The design is chosen by selecting the alternative with the minimum volume weighted turn delay;

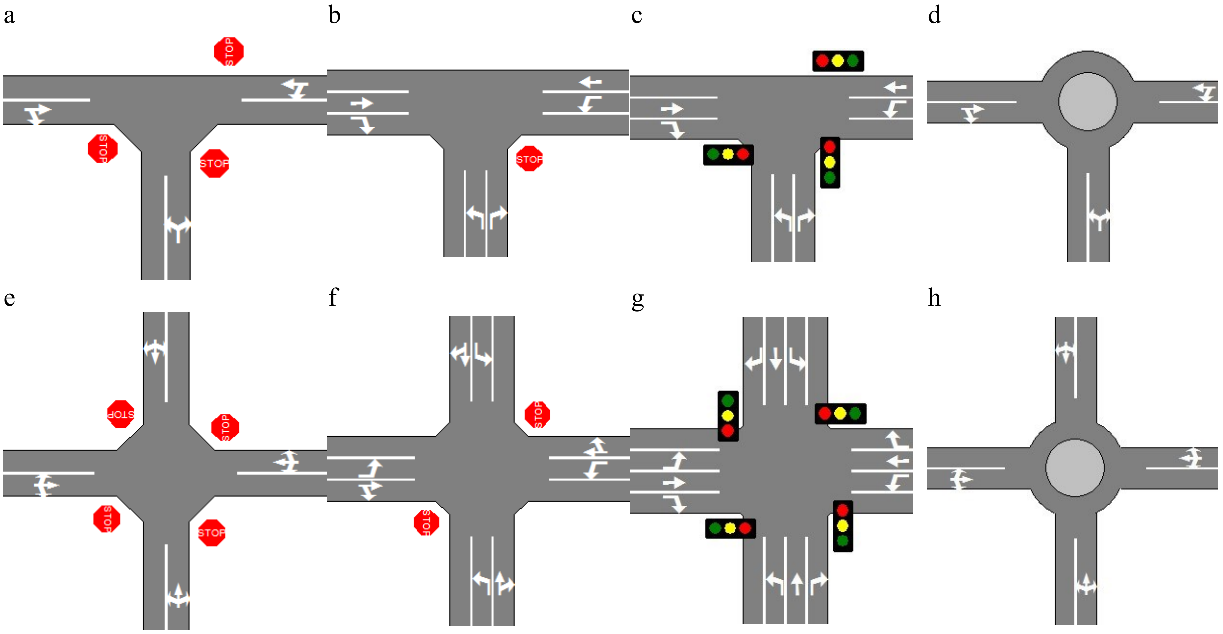


Fig 2. (a) three-leg AWSC intersection; (b) three-leg TWSC intersection; (c) three-leg signalized intersection; (d) three-leg roundabout; (e) four-leg AWSC intersection; (f) four-leg TWSC intersection; (g) four-leg signalized intersection; (h) four-leg roundabout.

- MINMAXDELAY: The design is chosen by selecting the alternative with the minimum maximum turn delay;
- COMDELAY: The design is chosen by selecting the alternative with the minimum volume weighted turn delay for alternatives for which the maximum turn delay is less than a threshold value, set to 20 seconds;
- TOTVOL: The design is chosen by evaluating the total flow on the intersection. A value below 1500 pcu/h produces a TWSC intersection, a value between 1500 and 2000 pcu/h a roundabout and a value above 2000 pcu/h a signalized intersection. For three-leg intersections the threshold values are 1250 and 1500 pcu/h;
- SUSA: The design is chosen based on a sustainable safety preferred order: roundabout, TWSC and signalized intersection. The first two are only used when the average volume weighted turn delay is below 20 seconds.

4. Results

Each model run, i.e. an intersection design strategy applied on the Sioux Falls network given a fixed traffic demand, produces data concerning the network performance, the network solution and the intersection (and link) performances. These will be discussed in the subsequent subsections. The section concludes with a brief analysis of future possibilities for improving local intersection design strategies.

4.1. Network performances

Table 1 shows the network performances of the different local intersection design strategies and the global network optimization (GNO) strategy. The table shows the total loss time (pcuh), being the total travel time minus the free-flow travel time in the network. The loss time is differentiated between the loss time on the intersections and the loss time on the links. The lower the loss time, the better the strategy.

Obviously, the global network optimization strategy gives the best results, with a total loss time of 1788 pcuh, which gets an index value of 100. Approximately 24% of the loss time for this strategy is experienced on intersections. The four TYPE strategies, with one single intersection design alternative in the network, give the highest loss time values, which are 20-40% higher than the optimal value. The strategy advising signalized intersections (TYPE:SIG) gives the best results of these four, mainly because this strategy has a certain flexibility because the signal settings are determined based upon the traffic flows. This causes a distribution of traffic (routes) over the network and a link loss time equal to the value for the global optimization. For the strategy advising TWSC intersections (TYPE:TWSC), the loss time on intersections is relatively low (22%).

Table 1. Total loss time (pcuh) for each strategy.

Strategy	Intersection		Link		Total (pcuh)	Index
	Loss time (pcuh)	%	Loss time (pcuh)	%		
TYPE: AWSC	875	35	1622	65	2497	140
TYPE: TWSC	482	22	1740	78	2222	124
TYPE: SIG	778	36	1363	64	2141	120
TYPE: RA	793	34	1535	66	2327	130
MINAVGDELAY	296	16	1573	84	1869	105
MINMAXDELAY	490	26	1377	74	1867	104
COMDELAY	312	17	1566	83	1877	105
TOTVOL	773	36	1367	64	2140	120
SUSA	560	29	1366	71	1926	108
GNO	424	24	1364	76	1788	100

This is caused by the fact that drivers try to avoid the minor roads and left turns due to their high delays. However, this causes longer routes on links, which can be seen at the 1740 pcuh loss time on links. The three DELAY strategies, choosing the intersection design based on a minimum delay value, give better results, and produce 4-5% higher total loss time values in comparison with the optimal value. The MINAVGDELAY strategy has, by far, the lowest value for intersection loss time. This is obvious since it chooses the intersection design alternative with the lowest average delay. Intersection loss time is only 16% of the total loss time. The loss time on links is however, relatively high. The MAXAVGDELAY strategy produces slightly less total loss time and has a corresponding percentage of loss time on intersections (26%) as the global optimization (24%). This implies that there is a certain optimal ratio of intersection and link loss time. The TOTVOL and SUSA strategies have both relative high loss times on intersections. The cause of this will become clear when the solutions are analyzed in the next subsection.

4.2. Network solutions

Each strategy, either local or global, produces a certain set of intersection design alternatives, for which the equilibrium between traffic flows, route choice and intersection design is stable. Table 2 shows the solutions for all strategies except the TYPE strategies. There are twenty intersections in the Sioux Falls network. The first row shows the numbers of the intersections as shown in Figure 1. The colors in the table represent a specific intersection design alternative. The rows show the solutions for each strategy. The bottom row shows the number of legs for each intersection.

Table 2. Intersection design solutions for each strategy.

Strategy	Node number																				Match (%)
	3	4	5	6	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	
MINAVGDELAY	🟥	🟥✚	🟨	🟨✚	🟦	🟥✚	🟩	🟥✚	🟥✚	🟨	🟨	🟥	🟨	🟩	🟦✚	🟦	🟨✚	🟦	🟨✚	🟨✚	45
MINMAXDELAY	🟦	🟥✚	🟩✚	🟦	🟦	🟥✚	🟩	🟥✚	🟥✚	🟥✚	🟩✚	🟥	🟥	🟩	🟦✚	🟦	🟥	🟦	🟦	🟥	40
COMDELAY	🟥	🟥✚	🟨	🟨✚	🟦	🟥✚	🟩	🟥✚	🟥✚	🟨	🟨	🟥	🟨	🟩	🟦✚	🟦	🟥	🟦	🟨✚	🟦	35
TOTVOL	🟩	🟩	🟩✚	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩✚	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	10
SUSA	🟩	🟦	🟩✚	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩✚	🟦	🟩	🟩	🟦✚	🟦	🟦	🟦	🟦	🟦	15
GNO	🟨	🟥	🟩	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟨	🟦	🟨	🟦	🟨	🟨	🟥	🟨	🟨	100
Number of legs	3	3	3	3	4	3	4	4	3	3	4	4	3	3	3	3	3	4	3	3	

🟥 All-way stop-controlled 🟨 Two-way stop-controlled 🟩 Signalized 🟦 Roundabout

✚ Intersection design is the same as the design for the global network optimization

The solution from the global optimization contains seven all-way stop-controlled intersections, nine two-way stop-controlled intersections, two signalized intersections and two roundabouts. As can be seen in the table, the solutions based on the local intersection design strategies are considerably different. The TOTVOL strategy, which did not incorporate a choice for an AWSC intersection, leads to nineteen signalized intersections and one roundabout.

Apparently, the volume threshold values are too low for this network and traffic demand. The SUSA strategy, which also did not incorporate a choice for an AWSC intersection, leads to six signalized intersections and fourteen roundabouts. In this strategy, roundabouts are preferred unless they produce an average delay that exceeds twenty seconds, which is the case for a substantial part of the intersections in the network. This strategy produces an 8% loss in operational performance in comparison with the global optimum (Table 1), but evidently gains in safety performance, which is not considered in this paper. The MINAVGDELAY, MINMAXDELAY and COMDELAY strategies, which share a considerable part of their solutions, generally produce more roundabouts and (to a lesser degree) signalized intersections than the solution from the global optimum. The MINMAXDELAY strategy lacks TWSC intersections, because they generally produce high delays for minor road and left turn traffic. Because the amount of traffic for these movements is limited, the average delay for TWSC intersections is acceptable, as can be seen in the solution for the MINAVGDELAY. The MINMAXDELAY strategy however excludes the TWSC intersections because the delay exceeds the employed threshold value, regardless of the traffic volume. The COMDELAY strategy, which is a combination of the MINAVGDELAY and MINMAXDELAY strategies, does not produce better results than the latter two strategies.

Table 2 also shows the intersection designs which match with the intersection designs from the global optimization (marked by the '✚' sign). The table also shows the total percentage of intersection designs that match with the global optimization. The MINAVGDELAY has a 45% match, which means that nine of the twenty intersections are the same for this strategy and the global optimization. The MINMAXDELAY strategy, which has a slightly better operational performance has a 40% match. No specific type related pattern can be recognized in the intersection designs that match and those that do not match. Generally, the local strategies overestimate the number of roundabouts at the expense of TWSC intersections.

4.3. Intersection performances

The analysis in the previous section showed that there are substantial differences between the intersection design solutions of different strategies and the global optimization. It could be that the designs are different but the underlying average volumes and delays are relatively the same for the different strategies.

Table 3. Intersection data for different strategies.

Number	#Legs	Vol./Leg (pcu/h)	Difference (%)			Delay (s)			
		GNO	AVG	MAX	SUSA	GNO	AVG	MAX	SUSA
3	3	760	5	7	7	15.5	16.2	22.6	49.1
4	3	657	8	10	10	5.5	7.7	6.1	15.7
5	3	1005	-8	-2	-2	73.1	17.3	101.0	96.4
6	3	702	13	8	8	4.7	10.1	17.1	17.1
8	4	604	-5	-2	-2	65.6	16.2	17.4	17.2
9	3	818	-23	-13	-13	6.9	4.2	5.2	16.0
10	4	931	0	-6	-6	35.5	56.7	63.1	65.0
11	4	615	9	2	1	5.4	6.6	6.7	17.6
12	3	567	10	5	4	4.7	5.1	4.6	13.7
14	3	545	-5	4	3	6.2	2.3	6.3	14.2
15	4	1029	-6	-4	-4	124.4	50.6	126.1	133.7
16	4	459	3	8	6	5.9	4.8	5.0	14.3
17	3	352	12	1	-3	12.8	1.4	3.6	22.6
18	3	1191	-9	-3	-2	70.2	105.2	97.9	102.3
19	3	816	-13	-1	-1	34.0	17.1	44.2	47.5
20	3	781	-6	-11	-10	21.4	15.2	14.8	14.9
21	3	600	-1	-4	-4	2.9	2.9	7.2	13.6
22	4	559	17	1	1	6.9	26.7	17.7	17.9
23	3	451	0	-4	-1	3.2	3.8	13.0	13.0
24	3	773	3	-3	-2	3.0	5.2	21.5	16.9

Table 3 shows the volumes per leg (pcu/h) and the average (volume weighted) delay (s) for the intersections for the global network optimization (GNO). The table also shows the percentage differences of the volumes and the delay values for the MINAVGDELAY (AVG), MINMAXDELAY (MAX) and SUSA strategies. These are the three strategies with the best network performance, where COMDELAY is excluded since it is almost the same as MINAVGDELAY (and the latter is better). The table shows that the volume differences are relatively modest. The delay differences however, are very high, especially for the SUSA strategy with no intersection with a delay below ten seconds. On the other hand, the number of intersections with more than twenty seconds of (average) delay is equal for the GNO, MINMAXDELAY and SUSA.

4.4. Future intersection design strategies

Overall, the network performance for MINAVGDELAY, MINMAXDELAY and SUSA is 4-8% worse than the performance for the global minimum. This is primarily caused by the fact that the intersection designs match for only 10-45%. The strategies used in this research are not capable of choosing the 'correct' intersection design alternatives. There is potential for more rule-based strategies, which benefit the global optimization. Table 4 shows some manually clustered results from the global network optimization which provide a starting point for determining rules that might benefit global optimization.

Table 4. Average traffic volumes (pcu/h) for different intersection designs from the global network optimization.

#Legs	Design	Total	Major	Minor	Ratio
3	All-way sign-controlled	1947	1599	347	4.6
	Two-way sign controlled	2254	1622	632	2.6
	Signalized	3015	2153	862	2.5
	Roundabout	1752	1204	548	2.2
4	All-way sign-controlled	2370	1207	1162	1.0
	Two-way sign controlled	2779	1662	1116	1.5
	Signalized	4115	2732	1382	2.0

The table shows average traffic volumes for major and minor road legs for three- and four-leg intersections. Based on this table an improved volume-based intersection design rule could be defined, not only using the total volumes (as in the TOTVOL strategy) but also using the major and minor volumes and/or their ratio (as expressed in the rightmost column).

5. Conclusions and further research

The research presented in this paper provides a modelling framework by which the network effects of different local intersection design strategies can be evaluated and be compared with a global optimization of intersection designs. The framework provides the possibility to compare the network performances, solutions as well as the intersection performances. Six different local intersection design strategies were conducted on the Sioux Falls network. The strategies produced very different network performances. The MINMAXDELAY strategy, which chooses the local design with the minimal maximum intersection delay, produces the best network performance in comparison with the global optimization of total travel time in the network. The intersection design solutions show substantial differences with the solution for the global optimization, providing a base for future improvement of intersection design rules which benefit a better network performance.

To test the robustness of the analysis performed in this paper a next step would be to repeat it for multiple demand patterns. Furthermore, based on the results in this paper, additional (local) intersection design strategies can be defined and evaluated. Additionally, it would be very interesting to expand the framework with a safety objective and performance measure.

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