


# Comparison of hierarchical network design shape grammars for roads and intersections

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1 **Comparison of Hierarchical Network Design Shape Grammars for Roads and Intersec-**  
2 **tions**

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## ABSTRACT

1 Urban systems are growing fast in many countries today and depend essentially on efficient  
2 transport networks. Significant productivity gains in urban systems can be achieved by improving  
3 transport infrastructure and thus reducing overall costs of travel. Shape grammars provide a  
4 solid foundation for coherent transport network design, and concurrently reduce complexity  
5 of planning processes. Shape grammars describe how network elements are joined with each  
6 other. However, only a few are listed in standards for network design without any fundamental  
7 research basis. Therefore, shape grammars remain vague and the standards lack of clear  
8 recommendations.

9 In this paper, shape grammars for hierarchical network design are examined for different  
10 transport networks. The investigated shape grammars include different link and intersection  
11 types. The network models are artificially created to avoid a bias in the results due to history.  
12 The networks are optimized regarding an infrastructure and user cost function. Shape grammars  
13 significantly affect transport network performance. As expected, the distribution of link types  
14 affects the network efficiency. However, intersection types and the corresponding delays in  
15 travel time have a remarkable and even larger effect on network performance. In the future,  
16 more shape grammars will be examined to shed light on the impacts of relevant grammars for  
17 transport network design and to derive clear recommendations for urban planners.

## INTRODUCTION

1 Today, the construction of transport networks is still a major concern for governments and  
2 planners. Because of rural depopulation and migration, the population in existing urban systems  
3 will double between 2005 and 2050 (1), which will increase travel demand and transport  
4 infrastructure requirements. The economies of urban systems depend and benefit substantially  
5 from efficient transport systems, agglomeration processes and low trading costs. Considerable  
6 gains in overall productivity of urban systems are achieved with coherent infrastructure and low  
7 construction, user and maintenance costs (2, 3).

8 The literature on network design covers a large variety of topics with an overall classification  
9 in network optimization and network design. Network optimization deals with existing networks  
10 which are improved with respect to the benefit-cost ratio of the alternatives (4, 5, 6). An extensive  
11 number of contributions addresses the bi-level network optimization approach. Optimization  
12 methods applying a bi-level approach separate the two optimization problems, namely network  
13 design and demand assignment (6, 7, 8). A major proportion of contributions is related to  
14 operational research methods, e.g. (9). Additionally, a large proportion concerns the historical  
15 development of network design, including case studies (10).

16 The construction of new networks is normally following different methods, compared to  
17 the optimization of existing methods. Especially urban planning and design aspects as well as  
18 interactions between transportation and land use issues are crucial when designing new networks,  
19 e.g. (10, 11, 12). The degrees of freedom and the search space are growing substantially when  
20 building or expanding new districts and urban systems, compared to network optimization  
21 mentioned above.

22 For network design, shape grammars are increasingly applied in transport and urban planning  
23 and corresponding software solutions (13, 14, 15, 16, 17, 18). Besides scientific contributions,  
24 shape grammars for transport network design are often found in handbooks and standards  
25 (19, 20, 21, 22). Shape grammars describe in the form of rules how different types of network  
26 elements are added to each other, e.g. if a highway can be crossed by an arterial road or if  
27 local roads can be joined with larger intersections of high capacities. The rules depict how an  
28 existing planning state and geometry is extended to a more desirable state. However, scientific  
29 contributions of shape grammars for transport network design and urban development are scarce  
30 despite their wide application. So far, shape grammars mostly lack a fundamental research  
31 base as well as systematic evaluations, e.g. cost-benefit-analyses, and do not remain explicit in  
32 their recommendations. For a profound application of shape grammars in urban development,  
33 research is needed to support planning guidelines.

34 Shape grammars have a strong architectural background (23) but are also able to include  
35 aspects of spatial planning (24). An early approach is provided by (25). Alexander and his  
36 colleagues (23) were one of the first who stressed the importance of shape grammars in urban  
37 planning. (26) focuses on patterns, link arrangements, link lengths and scaling in larger cities.  
38 In (26), quality of streets depends on the context of space and adjacent buildings and shops. (26)  
39 does not directly define grammar rules, but introduced regularities between different network  
40 elements. (27, 28) developed guidelines and prescriptions for general urban development in a  
41 qualitative way. Their work can be related to the movement of New Urbanism (29, 30).

42 A key advantage of shape grammars is their ease of application in planning processes  
43 (15, 17, 18). Shape grammars can be applied for both network optimization and network  
44 design purposes (31). Practitioners prefer robust and reliable methods. Shape grammars  
45 satisfy these requirements but are at the same time adaptive to different scenarios and are

1 able to incorporate spatial planning rules (24). Shape grammars can serve as decentralized  
2 investment rules. Moreover, the application of shape grammars needs very low computational  
3 requirements (13, 17, 18) and can be implemented in interactive planning tools, e.g. (15). This  
4 is especially relevant since e.g. bi-level network optimization is limited in application due  
5 to high computational requirements and hence the wide application of heuristics in network  
6 optimization (7).

7 The aim is to see to which extent shape grammars influence the result of the efficiency mea-  
8 sure and, thus, the performance of the networks. Only if the influence of the shape grammars for  
9 network design is known, clear recommendations for design standards can be made in the future.  
10 This paper introduces an approach independent of existing network data or case studies because  
11 existing transportation networks and patterns are often biased due to history. Instead, artificial  
12 transport networks are designed that follow different shape grammars under consideration. The  
13 advantage of the application of artificial transport networks are their independence of history  
14 and politically driven decisions. The results are valid detached from existing case studies. The  
15 implementation in artificial networks is similar to e.g. (11, 32, 33).

16 In the following, shape grammars are introduced as well as infrastructure types and corre-  
17 sponding costs. The major findings regarding the network design method and the impact of  
18 the shape grammars are shown in the subsequent section. Afterwards, the resulting networks  
19 with the implemented shape grammars are compared and discussed. This work is a major  
20 extension of (34), and additionally comprises variable intersection types and more detailed shape  
21 grammars. This research focuses on areas with about 100'000 inhabitants and on different link  
22 and intersection types. This work focuses on private car transportation, but is extendable for  
23 other modes.

## TRANSPORT NETWORK SHAPE GRAMMARS

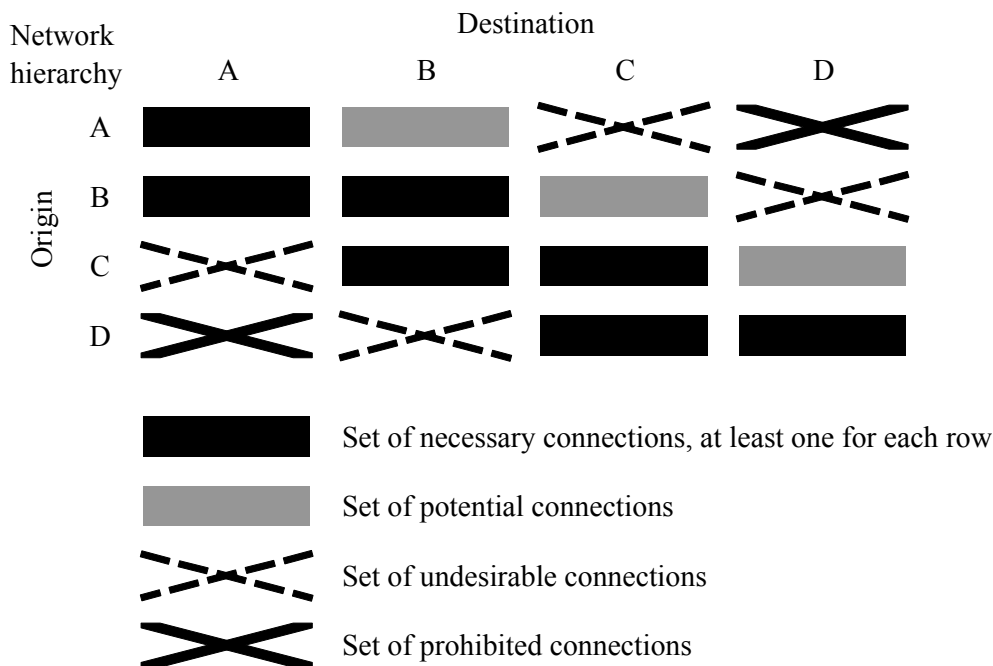
24 Network grammar rules describe how roads and intersections of certain types or hierarchical  
25 levels may be joined with each other. A general example of a set of possible shape grammars  
26 is shown in Figure 1. On the left, the hierarchy of the considered network element is listed.  
27 The potential (at least one), undesirable and prohibited adjacent network elements are listed  
28 row-wise for each hierarchy class.

29 In this example, network elements can only connected with each other if the adjacent link  
30 is of the same type or one type lower or higher. Additionally, it is stated that a link of a given  
31 hierarchy level has to be connected with another link of the same hierarchy level or of one  
32 hierarchy level higher in order to maintain a coherent network. For intersections, the types of  
33 the adjacent links have to be consistent with the considered intersection types.

34 Different handbooks and standards are scanned for comparison of the shape grammars. Three  
35 types are presented below, including USA, England, Germany and Switzerland. Almost all of  
36 them follow a different approach regarding a hierarchical link type network constitution. The  
37 following list shows the grammars regarding adjacent link types. A, B, C, D represent different  
38 link types.

- 39 • Restrictive network design: A-A, A-B, B-B, B-A, B-C, C-B, ...; e.g. Switzerland (21)
- 40 • Moderate flexibility in network design: A-A, A-B, avoid A-C, ...; e.g. USA and England  
41 (19, 20)
- 42 • Adaptive network design: A-A, A-B, A-C, B-A, B-B, B-C, B-D, ...; e.g. Germany (22)

**FIGURE 1 Example set of shape grammars for joining network elements of different hierarchical levels**



1 A strict hierarchical layout is leading to a network with joined links that differ in one  
 2 level of hierarchy at most. If the recommendations are more relaxed, joined links can differ  
 3 in more than one level of hierarchy. It can be seen that the considered guidelines differ in  
 4 their recommendations for a hierarchical structure within network design. The impact of such  
 5 recommendations and their differences are crucial and discussed in this work.

**INFRASTRUCTURE COST**

6 Depending on the budget, link and intersection types can be allocated differently in the network.  
 7 E.g. a lower total budget may lead to a higher share of links and intersections of lower capacities,  
 8 which result in a less expensive network design. Table 1 shows the costs for five link types and  
 9 three intersection hierarchies (35, 36).

10 As expected, considerable differences occur between links in built-up and outlying areas. The  
 11 costs of the major arterial roads are considerably higher compared to collector roads, because  
 12 the major arterial still historically functions as a major carrier, compared to the collector road  
 13 which only carries local traffic. The costs of highway intersections are remarkably high, also  
 14 in comparison to costs for links. This is due to over- and underpasses and larger radiuses for  
 15 curves. A large variety of data can be found for costs of intersections in urban areas. This is  
 16 due to the fact that intersections differ in many aspects, e.g. number of lines, pedestrian and  
 17 bicycle paths and public transportation. Additionally, costs tend to increase over years because  
 18 the cheaper projects were generally built first (37).

**TABLE 1 Costs of network elements in the USA (year 2000)**

Network elements	Links [Mio \$/lane-km]		Intersections [Mio \$/intersection]	
	Built-up area	Outlying area	Built-up area	Outlying area
Freeway	1.6	1.3	9.3	6.2
Highway	1.4	1.2	1.2	2.5
Interstate	1.3	0.8	-	-
Major arterial	1.3	1.1	0.3	0.1
Collector street	0.8	0.6	-	-

## METHODOLOGY OF THE MODULAR NETWORK DESIGN APPROACH

1 The initial setting for the design of the road networks is described in the following section,  
 2 followed by the description of the utility function. Subsequently, the algorithm is introduced for  
 3 generating networks under given shape grammars.

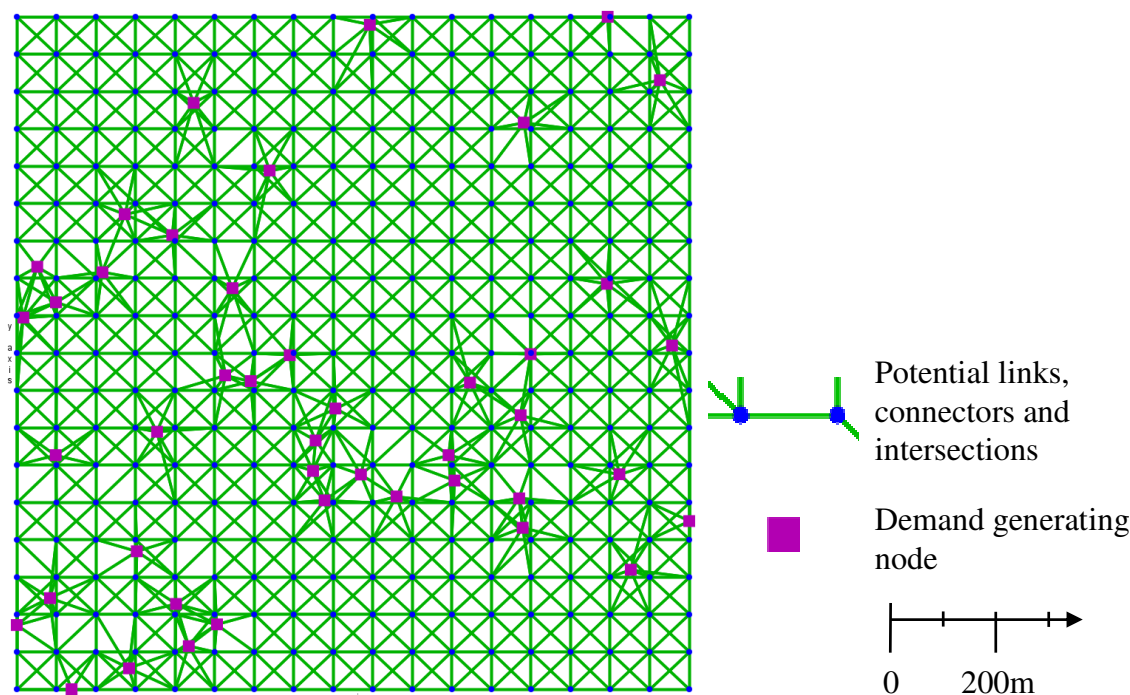
### 4 Initial network settings

5 The goal is to generate a road network with a set of shape grammars in an optimal way regarding  
 6 the utility function. The candidate links are initially distributed on a featureless plane of a  
 7 preliminarily given size, e.g. Figure 2. The advantage of the featureless plane compared to  
 8 real world cases is its lack of historical development and politically motivated decisions. Links  
 9 are joined at nodes which are currently fixed in space. The demand generating nodes, also  
 10 called centroids, are shown as squares, and are connected to the network using connector links.  
 11 They remain fixed in space, but can be relaxed in space in the future (38). In Figure 2, the  
 12 alignment of the demand generating nodes are originally derived from the city of Winterthur  
 13 (39), close to Zurich (Switzerland) with about 100'000 inhabitants. Hence, existing potential  
 14 shape grammars are ignored in the example networks. Travel demand is given in advance for  
 15 each pair of demand generating nodes. Travel times on links depend on the current traffic flow  
 16 and are determined using the BPR function (40). User equilibrium is determined according to the  
 17 method of successive averages. The budget constraint forces the algorithm to keep infrastructure  
 18 low and therefore the number of direct paths between pairs of demand generating nodes.

### 19 Utility function

20 The designed networks are evaluated to capture the effect of the shape grammars which are  
 21 implemented in the design process. The measure to evaluate the network, i.e. the utility  
 22 function, has to be defined in advance and is independent of the grammars and the design  
 23 method. The most commonly used measures are travel time and cost, followed by construction  
 24 and maintenance cost. Currently, the utility function adds travel time and construction costs,  
 25 usually the most relevant cost factors. Calculation of total travel time is the most computationally  
 26 costly measure; the function can be easily extended with further variables without adding much  
 27 computation time.

**FIGURE 2 An example network with all candidate links, nodes and demand generating nodes.**



$$f = \left( \sum_{o=1}^O \sum_{d=1}^D demand_{od} \cdot traveltime_{od} \right) \cdot \gamma + I + p \cdot (I - B)$$

- 1  $o$ : Origin demand generating node.
- 2  $d$ : Destination demand generating node.
- 3  $\gamma$ : Weighting factor (value of time as a recourse), extrapolated for a year.
- 4  $I$ : Infrastructure costs as annuity.
- 5  $p$ : Penalty factor,  $p = 0$  when  $I - B < 0$ .
- 6  $B$ : Budget.

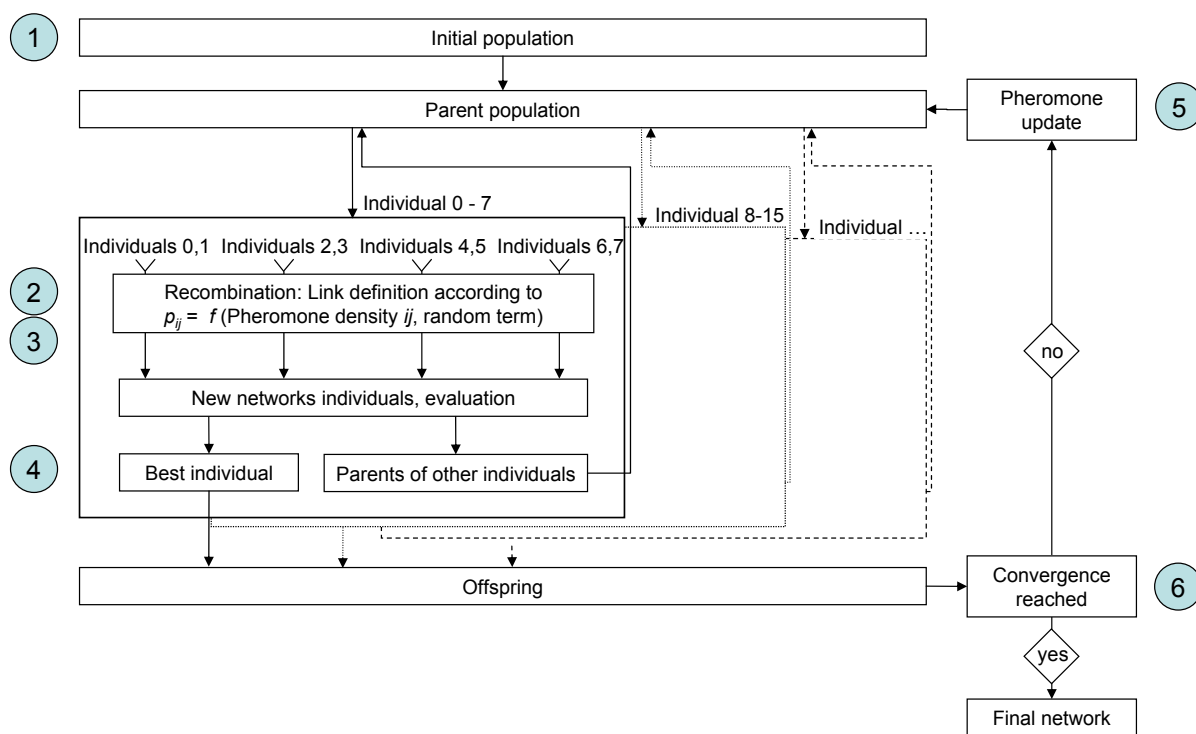
### 7 **Integrated Ant Colony and Genetic Algorithm (IACGA)**

8 In the following, a short overview is provided over the design method for the transport networks.  
 9 (34) refers to additional details. The design method benefits from both the advantages of the  
 10 GA and the ACO methodologies, and therefore is called Integrated Ant Colony and Genetic  
 11 Algorithm (IACGA). E.g. (41, 42, 43) describe the GA and ACO in details. Derived from a  
 12 standard GA, the IACGA is based on population of individuals. Each individual is representing  
 13 a candidate network, which improves over time using a recombination method. Similar to an  
 14 ACO, a learning ability is implemented in the IACGA. The motivation is to improve the weak  
 15 learning ability of a standard GA. As a standard ACO, the IACGA employs the results from all  
 16 previous populations and stores this information, which is later available for further network  
 17 recombination. Additionally, the nature of transport networks is taken into consideration, such

1 as assuring a coherent connected graph between the centroids, or avoiding unnecessary detours.

2 Methods considering both a GA and an ACO already exist, often applying both methods  
 3 alternately. Only White and Yen (44) introduce an integrated GA and ACO which is based on  
 4 very similar structures as the IACGA described here. The proposed algorithm is applied to  
 5 the Traveling Salesman Problem (TSP) successfully. However, the TSP contrasts to transport  
 6 networks in many aspects. In the following, we introduce the IACGA step by step, an overview  
 7 is given in Figure 3.

**FIGURE 3 Overview over the IACGA with numbers referring to the text.**



8 1. The initial population is generated which consists of individuals each representing a  
 9 randomly designed transport networks. The initial population serves as a parent population in  
 10 the first iteration.

11 2. Two randomly chosen individuals of the parent population are merged according to the  
 12 recombination procedure. Unlike a standard GA, the recombination procedure is conducted  
 13 within the network, but without coding a chromosome. Additionally, network elements as  
 14 links and intersections are not exchanged randomly but with the goal to achieve an improved  
 15 offspring individual with a better score. Thus, the potential candidate network elements are  
 16 chosen according to a probability function. The probability function of choosing candidate links  
 17 accounts for the success of the networks, which were generated in previous generations. If a  
 18 candidate link is under consideration, which already was implemented in previous networks  
 19 with high scores, it is more likely that the candidate link is chosen again. Links are chosen with  
 20 probability  $p_{ij}^g$ , where the scores of the previously generated networks are stored as pheromones  
 21 in  $\tau_{ij}^g$  (see step 5 for further details).

$$p_{ij}^g = \begin{cases} \frac{e^{\alpha\tau_{ij}^g} e^{\beta r}}{\sum_{i-j \in L_{Parents}} (e^{\alpha\tau_{ij}^g} e^{\beta r})} & , \text{ when } i-j \in L_{Parents} \\ 0 & , \text{ otherwise.} \end{cases}$$

1  $p_{ij}^g$ : Probability of choosing link  $i-j$  in iteration  $g$ .

2  $\tau_{ij}^g$ : Pheromone density in iteration  $g$  on link  $i-j$ .

3  $e^{\beta r}$ : Accounts for randomness.

4  $\alpha, \beta$ : Parameters, subject to calibration.

5  $L_{Parents}$ : Set of links  $i-j$  which are present in at least one parent network.

6 Links from both parents are chosen with probability  $p_{ij}^g$  until the budget constraint is depleted  
7 (step 3 for more details). Links which are not element of one of the parent networks are not  
8 implemented in the new network. Therefore, the initial population size has to be large enough to  
9 comprise all relevant links.

10 3. The hierarchical shape grammars are applied in the design process according to the  
11 following two consecutive rules. Firstly, the link and intersection types are distributed according  
12 to the shape grammars in consideration. A secondary rule accounts for the current link and  
13 intersection loadings. The higher the loadings, the link and intersection types with the higher  
14 capacities are allocated to the link and intersections in consideration. Both rules simultaneously  
15 maintain the budget restriction. Therefore, both rules follow an optimized type alignment.

16 4. Step 2 and 3 are repeated four times with new parent networks and only the best offspring  
17 is added to the offspring pool. For this purpose, the parent networks are randomly chosen  
18 from the parent population. The parent individuals are returned if their candidate offspring is  
19 outperformed by another candidate offspring generated by other parents. This procedure reduces  
20 the risk of generating infeasible networks. Currently, the number of trials is set to four, which  
21 leads to only very few infeasible networks, but this parameter is subject to further calibration.  
22 Step 2 - 4 are repeated until a new population is generated with the same number of individuals  
23 as the previous population.

24 5. After a new population is generated, the pheromones on all candidate links are updated  
25 with the scores of the individuals of the new population. The pheromones are responsible for  
26 preserving the information of success or failure of the network individuals and are a measure of  
27 success. Therefore, the score of a network individual is used to determine the amount of the  
28 pheromones  $\tau$ . The pheromone amount is saved on each links element of the network. When  
29 two network individuals contain the same link, the higher score is applied for the pheromone  
30 amount. The evaporation rate  $\delta$  is responsible for the adaptive learning process, similar to an  
31 ACO.

$$\tau_{ij}^g = (1 - \delta) \cdot \tau_{ij}^{g-1} + \max(\Delta\tau_{ij}^g)$$

32  $\delta$ : Evaporation rate.

33  $\max(\Delta\tau_{ij}^g)$ : Score of the best individual out of all networks containing link  $ij$ .

34 6. The algorithm returns to step 2 if convergence is not reached yet. Convergence is only  
35 reached when the pheromone densities on single links are not changing any more or when a

1 substantial part of the population consists of individuals with the same networks. The best  
 2 performing cutoff criterion so far applies the pheromone density on links. This criterion bases  
 3 on the fact that only links which are element of high performing networks with high scores  
 4 can maintain their pheromone densities on a high level. Thus, when reaching the optimum  
 5 network, the pheromone densities on all links are decreasing except the densities on the links of  
 6 the optimum network.

### 7 **Convergence behavior**

8 The intermediate results of a sample network design run of the IACGA are shown in Figure 4.  
 9 Both pheromone densities and their changes over time can be seen in the left part of Figure 4.  
 10 Each link bar represents the pheromone density on a network link. The wider the bar, the more  
 11 relevant is the link. On the right, the corresponding intermediate network results are shown.  
 12 Here, the link bars represent the link types. The wider the bar, the higher is the hierarchy of  
 13 the link type. A node with more than two arms represents an intersection, indicated by the  
 14 intersection symbol.

15 The global minimum is reached in 50% or more in test networks (34) with a low standard  
 16 deviation of 0.67%. The standard deviation can explained by the heuristic nature of the IACGA.  
 17 The convergence speed mainly depends on the size of the scenario and the number of demand  
 18 generating points. The IACGA clearly outperforms a standard GA, because of the advanced  
 19 recombination procedure with learning ability (34). A scenario of 1'624 candidate links and  
 20 25 demand generating nodes (setting 1 in Table 2) takes about 5 hours on 16 parallel threads  
 21 with 2.66GHz. The high parallelization capabilities of the IACGA is an advantage, especially  
 22 because of the recent advances in parallelization.

## INITIAL SETTINGS AND SHAPE GRAMMARS UNDER CONSIDERATION

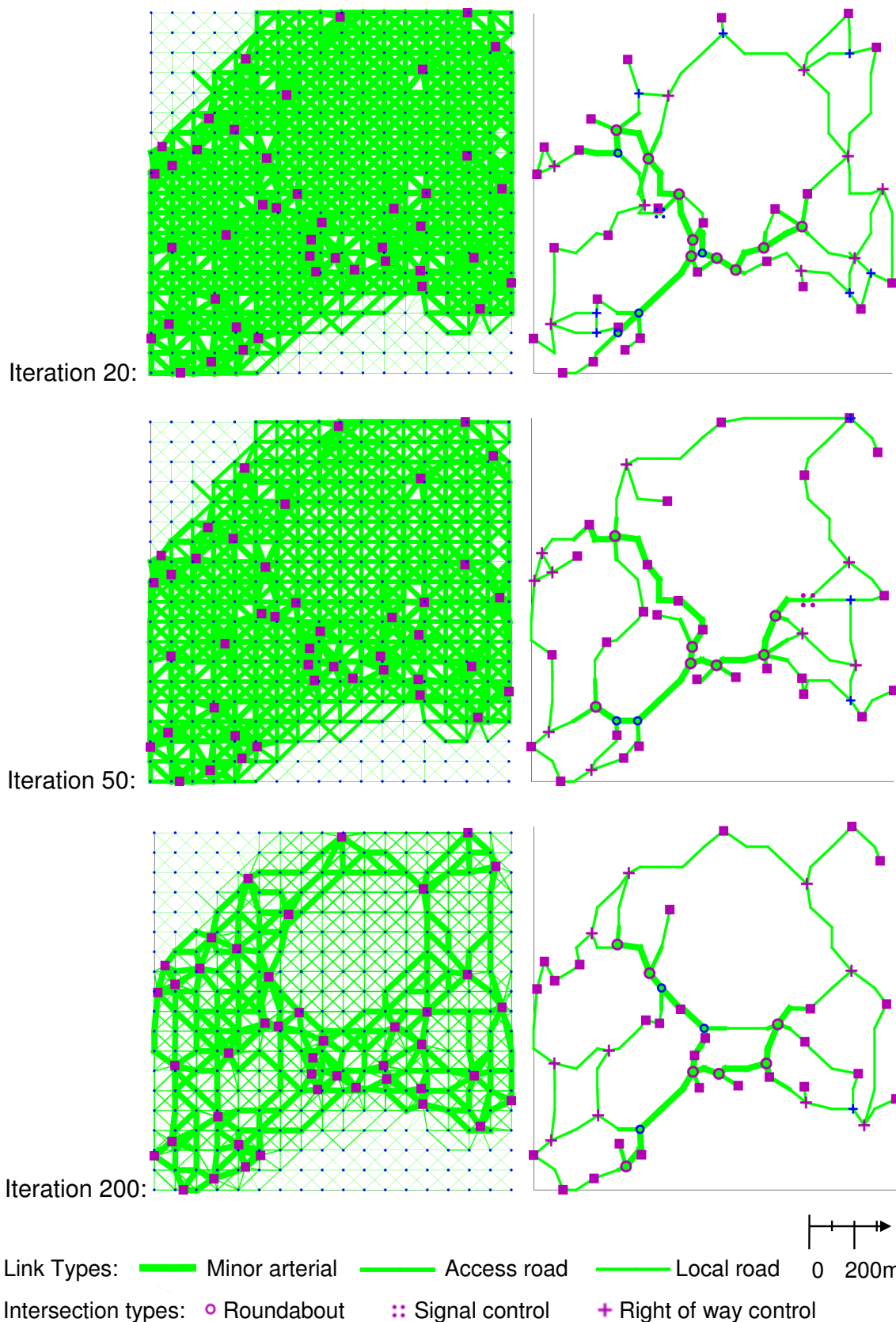
23 Two different initial settings are provided for comparison reasons (Table 2). In initial setting  
 24 1, the demand generating points are distributed evenly on an empty featureless plane. Initial  
 25 setting 2 is identical to Figure 2.

**TABLE 2 Initial settings 1 and 2.**

	# Centroids	# Candidate nodes	# Candidate links	Total travel demand [# vehicles/day]
Setting 1	25	225	1'624	~ 41'000
Setting 2	44	386	2'380	~ 130'000

26 The intersection delays are calculated for roundabouts, signalized intersections and two-way  
 27 stop-controlled intersections (TWSC) according to (45) considering turn movements and their  
 28 delays, but ignoring adapted cycle times for each intersection. TWSC include a right of way  
 29 penalty in the case of unequal link types. Reliable data for intersection costs are scarce, also  
 30 because of many different types. However, the costs of the three intersections types correspond  
 31 to the data of Table 1. The intersection type also should reflect the size of the intersection.  
 32 Therefore, 0.6, 0.3 and 0.2 Mio Dollars are assumed for roundabouts, signal control and TWSC

**FIGURE 4** Convergence of IACGA. On the left, pheromone densities are shown of selected generations, on the right, the link and intersection types of the best network is shown of the corresponding generation.



1 intersections.

2 Four different sets of shape grammars are implemented (Figure 5), derived from (24). Shape  
3 grammar A and B focus only on link alignment, whereas shape grammar C and D also include  
4 intersection alignment.

5 Shape grammar A assumes that every link is allowed to be connected to another link of any  
6 type. When generating new networks, the different link hierarchies are distributed according to  
7 the link loadings on each link to optimize overall travel time. An iterative sampling determines  
8 the optimal share of each link type, accounting for budget restrictions.

9 Shape grammar B is more restricted and states that links of a given hierarchy can only be  
10 jointed to links of the same or a neighboring hierarchy. Additionally, links of type *X* have to  
11 form a coherent network, which means that links of type *X* have to be connected to at least one  
12 other link of type *X* (indicated with arrows in Figure 5). Similar to the implementation of shape  
13 grammars A, link types are distributed according to link loadings to optimize overall travel time.

14 Shape grammar C resembles shape grammar B regarding the link types. Additionally,  
15 different intersection types are distributed according to the intersection loadings. Currently, three  
16 intersection types are implemented in the approach: Roundabouts, signal control and TWSC  
17 intersections. The total infrastructure budget can be invested in both intersections and links,  
18 adding an additional degree of freedom to the network design. Because the optimal share can  
19 not be predicted in advance, it is part of the iterative sampling procedure.

20 Shape grammar D resembles shape grammar C, but differs in the allocation of intersection  
21 types. In shape grammar D, the allocation of intersection types is restricted to the distribution of  
22 link types according to Figure 5.

23 Shape grammar B and D are especially helpful in structuring the transport network due to  
24 a clear overview for the road users due their hierarchical setup. However, the structuring of a  
25 network also can have disadvantages, especially regarding travel times and performance. This  
26 effect of the shape grammars is discussed in the following.

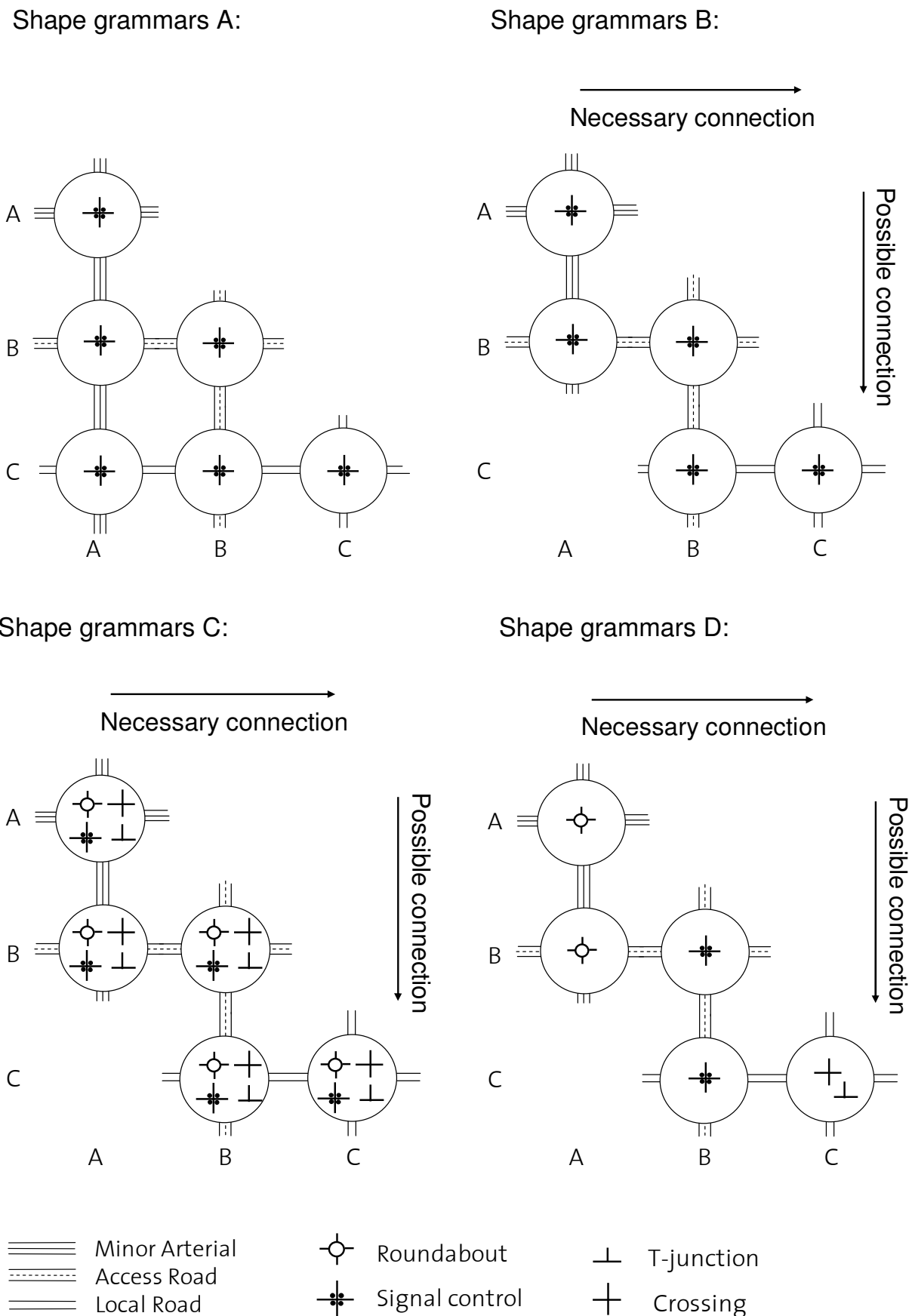
## RESULTS

27 Networks are designed with the IACGA and shape grammars A, B, C or D. Two initial settings  
28 are provided for comparison reasons (Table 2). Table 3 shows the results of the average transport  
29 network scores and a comparison of the different shape grammars. The upper half of Table 3  
30 lists the results of the shape grammars which account for the adjacent links corresponding to  
31 shape grammars A and B in Figure 5. Shape grammars C and D also include intersection types.  
32 It is crucial that the scores of the resulting networks are compared to scores of other network  
33 which were built up in a different manner. In Table 3, the scores of the networks generated with  
34 shape grammar A and B are compared against each other as well as shape grammar C and D.  
35 Shape grammars A, B and C, D are not compared against each other because of the large impact  
36 of the variable intersection types in shape grammars C and D. Due to the long calculation times,  
37 the sample sizes vary, and a Wilcoxon test (46) is not applicable for setting 2.

38 Independent of any shape grammars, coherent network structures are found in the generated  
39 networks, which means that links of the highest hierarchy type A is always joined with another  
40 link of type A. This finding is in line with (32) stating that networks are often built of routes  
41 with continuous attributes.

42 The application of shape grammar B, which is more restrictive regarding the link joining,

**FIGURE 5 Shape grammars under consideration.**



**TABLE 3 Relative difference between the shape grammars under consideration.**

Shape grammar	Initial setting 1 (n = 53)			Initial setting 2 (n = 11)	
	Average score	Relative difference	Wilcoxon rank-sum	Average score	Relative difference
A	-143'200	-		-300'192	-
B	-147'132	2.75%	0.0087%	-317'145	5.65%
C	-144'798	-		-297'301	-
D	-157'690	8.90%	0.048%	-466'909	57.05%

1 decreases the average network score, relative to shape grammar A, a finding that is replicated  
 2 with both initial settings. This finding can be expected, since the fact that the reduction of  
 3 flexibility in shape grammar B is obviously leading to a decrease in network efficiency. However,  
 4 especially in initial setting 1, the impact of shape grammar B is remarkably low. Therefore,  
 5 shape grammar B is not affecting the overall network performance substantially. This is an  
 6 advantage for standards which stress the importance of hierarchical network designs, which are  
 7 normally clearer in their constitution.

8 In contrast to the results above, the lower half of Table 3 summarized the results gained  
 9 with shape grammars C and D, considering three different link and intersection types. The  
 10 distribution of intersection types, accounted in shape grammars C and D, affects network  
 11 performance considerably. The application of shape grammar D decreases the average network  
 12 performance significantly relative to the application of shape grammar C. The lower average  
 13 score with shape grammar D is due to the restrictive shape grammar D. Therefore, the restrictions  
 14 lead to increasing travel times and decreasing the overall network performance. The findings  
 15 show that the intersection type distribution is essential. Therefore, shape grammars on how  
 16 to allocate intersections are of major importance. This findings are especially relevant, since  
 17 investments in new intersections are discussed less often than in new roads. There is strong  
 18 evidence that intersections play a major role especially in urban areas. Total travel times can be  
 19 saved and performance improved when reducing the intersection delays.

## CONCLUSION

20 To our knowledge, a first systematic assessment of the impact of shape grammars in transport  
 21 networks is conducted in this research. While a large body of literature exists about network  
 22 optimization, the impact of shape grammars on network design is not thoroughly investigated  
 23 so far. This paper establishes shape grammars and includes a corresponding evaluation. The  
 24 evaluation does not rely on case studies because of their bias due to history. The evaluation  
 25 takes place on networks built up on featureless planes. Two different initial settings are tested  
 26 which vary in size, the number of candidate links and the travel demand. The design process of  
 27 the transport networks relies on a new Integrated Ant Colony and Genetic Algorithm (IACGA).  
 28 The performances of the emerging network designs are compared using a utility function, which

1 includes travel time and infrastructure costs.

2 It could be shown that the shape grammars have an influence on the overall efficiency of  
3 the network. Two shape grammars affecting link distribution are compared against each other  
4 with significant differences. However, hierarchical link distribution seems to have a significant  
5 but low impact on network performance. This finding supports a hierarchical layout in network  
6 design, as proposed in some standards. Minor losses in performance are acceptable, in return for  
7 a structured network design. However, the implementation of different intersection types, which  
8 are included in additional shape grammars, affects the network efficiency considerably more.  
9 There is strong evidence that the intersection types play a central role in maximizing network  
10 performance. This finding is crucial for further planning purposes, especially in urban areas  
11 with a high density of intersections. The findings have to be confirmed with additional shape  
12 grammars, and eventually a traffic microsimulation to account for more details in intersections.

13 A new method of designing transport networks is applied successfully by this work, which  
14 opens numerous future possibilities. Promising is its modular approach, with allows expansions  
15 of the method, the shape grammars and simultaneously keeps complexity low. More shape  
16 grammars can be evaluated with the applied method, especially focusing on intersections.  
17 Moreover, variable travel demand, and transport and land use interdependencies will be addressed  
18 in the future. Transport and land use interactions, e.g. different land use types, can be modeled  
19 with corresponding shape grammars. This is relevant because of the absence of appropriate  
20 planning guidelines. A comparison with existing case studies of new or reconstructed urban  
21 areas will provide additional insights.

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