Supplementary Material for "Traffic Signal Timing Optimization: From Evolution to Adaptation"

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S.I. Problem Instantiation and Fitness Evaluation

The workflow of the problem instantiation and the fitness evaluation is shown in Fig. S.1. As each TSTO problem is represented by a traffic volume input τ, the problem instantiation process is first carried out to allow fitness evaluation by SUMO software to optimize on $f(x;\tau)$. SUMO software requires a vehicle route file that specifies each vehicle's departure time, the departure lane of the departure edge, and a set of passing edges including the departure edge and the destination edge to trigger a simulation. Hence, we generate the vehicle route file by the built-in tool of the SUMO called *JTRrouter*. By feeding a traffic volume input τ, the JTRrouter randomly samples and constructs the vehicle's trip information until the specified number of vehicles is reached. Since τ only defines the number of vehicles in the entrance edges over a period, each vehicle's departure edge is generated and selected from the set of entrance edges. Note that we use the same random seed for JTRrouter as input for each problem instantiation process of τ for the convenience of reproducing the results. The route file is called "Route.rou.xml".

After the problem instantiation process, we can evaluate the fitness (i.e., average traffic delay) of a solution x (i.e., traffic signal timing) by the SUMO simulator. The traffic signal timing that specifies the phase durations or offsets is written into a file called "TST.add.xml". Then, by feeding the network file called "Instance.net.xml", "Route.rou.xml", and "TST.add.xml" together into a simulation configuration file called "Instance.sumocfg", a SUMO simulation process can be executed. The maximum simulation step is also specified in the simulation configuration files and each simulation step corresponds to one second in the real world. After a simulation process is completed, SUMO outputs a trip file called "tripinfo.xml" that contains the traffic delay of each vehicle. Finally, the average traffic delay can be calculated.

S.II. Detailed Experimental Setting

A. Problem Setting

There is a total of ten different road networks to be tested in the experimental study. Six of them including Net-single1, Net-single2, Net-single3, Net-double, Net-2x2grid, and Net-3x3grid are synthetic road networks, and four of them including Cologne1, Cologne3, Ingolstadt1, and Ingolstadt7 are real-world road networks. The road network geometries of the tested scenes are shown in Fig. S.2. Net-single1, Net-single2, and Net-single3 only contain one signalized intersection. They are different in the number of lanes that an edge contains. The major characteristics of the tested scenes are given in Table S.I. The input dimension is the number of dimensions of a traffic volume input τ, which is also the number of entrance edges of the road network. The solution dimension is the number of variables included in a solution x. Note that in single-intersection scenes, a solution only contains phase durations. As the input dimension or solution dimension of scenes grows, the problem becomes harder to solve since there may be many local optima for a TSTO problem.

For each of the six synthetic scenes, we design three cases defined as different traffic volume input probability distributions. A pair (Scene, Case) represents a TSAP to be solved. For a TSAP with (Scene, Case), all traffic volume inputs in dataset T are drawn independently from a certain distribution that is associated with the case. An example containing the distributions of three cases for the scene Net-single 2 is given in Table S.II. The traffic volume input of Net-single2 contains four entrance edges with different directions, i.e., $\tau_{W\rightarrow \mathrm{E}}$ (west-to-east), $\tau_{E\rightarrow W}$ (east-to-west), $\tau_{N\rightarrow \mathrm{S}}$ (north-to-south), $\tau_{S\rightarrow N}$ (south-to-north). In this scene, we define the west-east as the mainstream that has the major traffic demand. For case 1, the traffic volume inputs are generated from a uniform distribution U(lb,ub) where lb and ub are lower bound and upper bound respectively. For case 2, the traffic volume inputs are also generated from a uniform distribution with a larger range than in case 1. For case 3, we adopt a Gaussian mixture distribution to generate traffic volume inputs with consideration of the real-world traffic situation. There are four sub-distributions that simulate the off-hour, west-to-east busy hour, east-to-west busy hour, and bidirectional busy hour. Specifically, the east-to-west busy hour can model the morning traffic that vehicles tend to come out from home to the office while the west-to-east busy hour can model the evening traffic that the vehicles come home. Each sub-distribution is a Gaussian distribution N(m,s) with m as mean and s as standard deviation. The prior probability of each sub-distribution is 0.25. There is a total of 22 TSAP instances to be tested which contains 3×6=18 cases for all synthetic scenes and 1×4=4 cases for all real-world scenes. For each TSAP, we generate 1100 traffic volume inputs as dataset T.

B. LMM and Simulation Setting

The configuration and parameter settings of the proposed LMM method and the SUMO simulation are as follows. For LMM, the splitting ratio of T_{train} and T_{valid} is 10:1. We set PS=20 as the swarm size of MTPSO in LMM which is a commonly used setting. Note that in MTPSO, we also set NS=PS=20. $MAXNFE$ is set to 500 for the scene Net-single1 and 1000 for the other scenes, and $MAXSTAG$ is set to 200. For the SUMO simulation, the maximum simulation step is 900 corresponding to the 900s=15min of the real world. Each simulation process is fed with the same random seed that is specified in the simulation configuration file for reproducible results. For the problem instantiation, given a traffic volume input, all of the vehicles' departure times are uniformly and randomly generated within the time interval between 0 to 600 seconds. For simplicity, we also feed the JTRrouter with the same random seed for each route generation process. To speed up the evolution process we employ a parallel simulation worker strategy with 20 CPU cores to simulataneosly evaluate multiple traffic signal timings.

C. Compared Algorithms

Comparison against simulation-free TSTO methods: In this paper, the compared simulation-free TSTO methods are Defaut30, Default60, Webster, Max-pressure, and SOTL. The UniformSample method simply uniformly samples a solution from the solution space when an unseen traffic volume input is given. Default30 and Default60, where 30 and 60 are the cycle lengths, are commonly used baselines for TSTO method comparisons. Default30 and Default60 assign each intersection the same cycle length and split the cycle equally to obtain each phase's duration. For the multi-intersection scene, Default30 and Default60 also use a GreenWave method to optimize each offset. Webster timing method is a famous traditional TSTO method that has been widely used. Max-pressure and SOTL are two responsive traffic signal controllers that can respond to the real-time traffic situation. For Max-pressure and SOTL, we use the implementation from [S1], which is an open-source framework for benchmarking different adaptive traffic signal controllers. To make the comparison fair, the hyperparameters of SOTL are optimized and determined by the Bayesian optimization on the validation set of each dataset, using the implementation of the Python library "*scikit-optimize*", on the validation set.

Comparison against simulation-based TSTO methods: To further verify the efficiency of the LMM-PSO, we implement several state-of-the-art TSTO methods for comparison, including a famous variant of PSO algorithm comprehensive learning PSO (CLPSO) [S2] and several advanced PSO algorithms specially designed for TSTO, i.e., MELPSO [S3], REPSO [S4], CTM-PSO [S5], PSO-QL [S6], and BGA-ML [S7]. The tuned hyperparameters of SOTL, PSO-QL, and BGA-ML on different datasets are listed in the Table S.III. Other parameter settings of compared PSO algorithms are kept the same as specified in these papers.

[S1] W. Genders and S. Razavi, "An open-source framework for adaptive traffic signal control," *arXiv preprint arXiv:1909.00395*, 2019

[S2] J. J. Liang, A. K. Qin, P. N. Suganthan, and S. Baskar, "Comprehensive learning particle swarm optimizer for global optimization of multimodal functions," *IEEE Trans. Evol. Comput.*, vol. 10, no. 3, pp. 281-295, June 2006.

[S3] Z. -J. Deng, L. -Y. Luo, Z. -H. Zhan, and J. Zhang, "Knowledge embedding-assisted multi-exemplar learning particle swarm optimization for traffic signal timing optimization," in *Proc. IEEE Congr. Evol. Comput.*, 2021, pp. 248-255.

[S4] C. Zhang, J. Y. Li, C. H. Chen, Y. Li, and Z. H. Zhan, "Region-based evaluation particle swarm optimization with dual solution libraries for real-time traffic signal timing optimization," in *Proc. Conf. Genet. Evol. Comput*, 2023, pp. 111-118.

[S5] L. Tang, Q. He, D. Wang, and C. Qiao, "Multi-modal traffic signal control in shared space street," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 1, pp. 392-403, Jan. 2022.

[S6] Z. Lin, K. Gao, N. Wu, and P. N. Suganthan, "Scheduling eight-phase urban traffic light problems via ensemble meta-heuristics and Q-learning based local search," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 12, pp. 14415-14426, Dec. 2023.

[S7] T. Mao, A. -S. Mihăiţă, F. Chen, and H. L. Vu, "Boosted genetic algorithm using machine learning for traffic control optimization," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 7, pp. 7112-7141, July 2022.

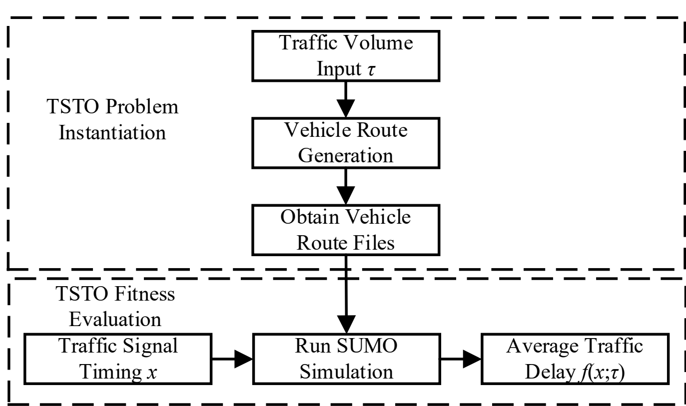
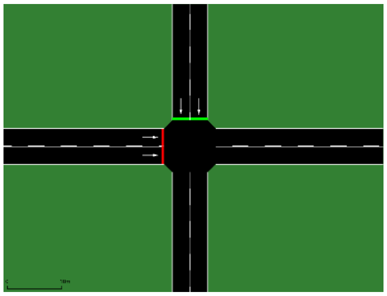
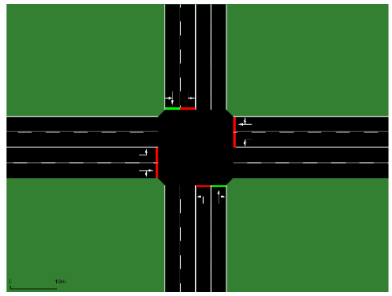


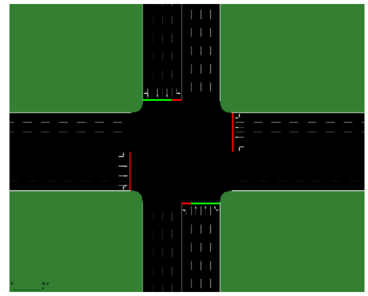
Fig. S.1. Problem instantiation and fitness evaluation.



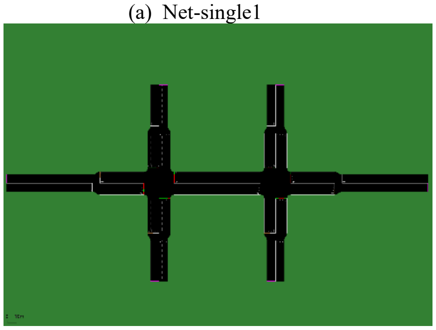
(a) Net-single1



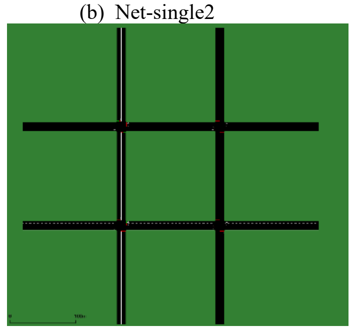
(b) Net-single2



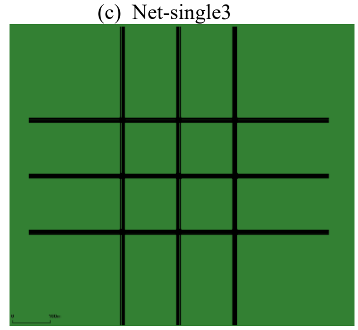
(c) Net-single3



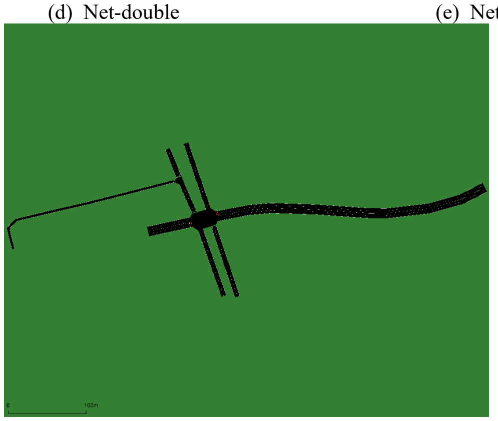
(d) Net-double



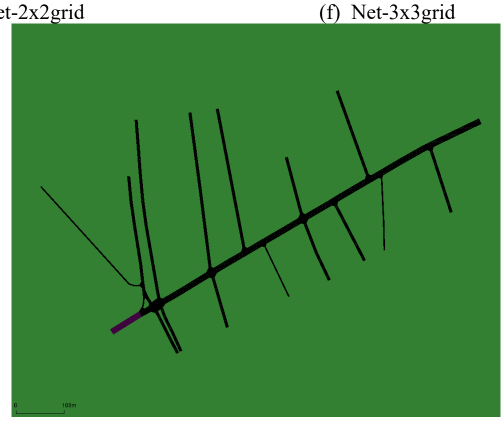
(e) Net-2x2grid



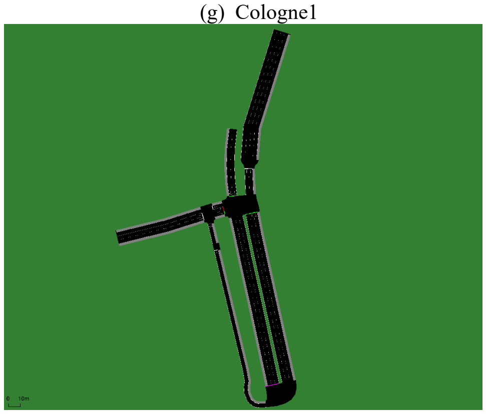
(f) Net-3x3grid



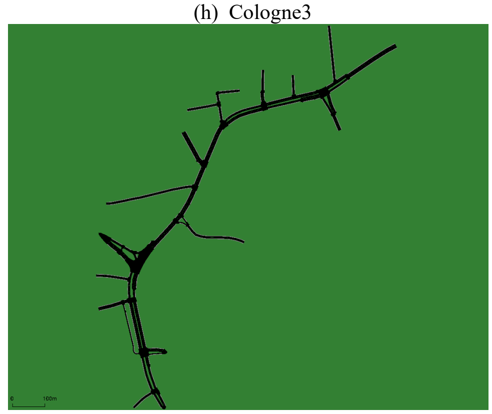
(g) Cologne1



(h) Cologne3

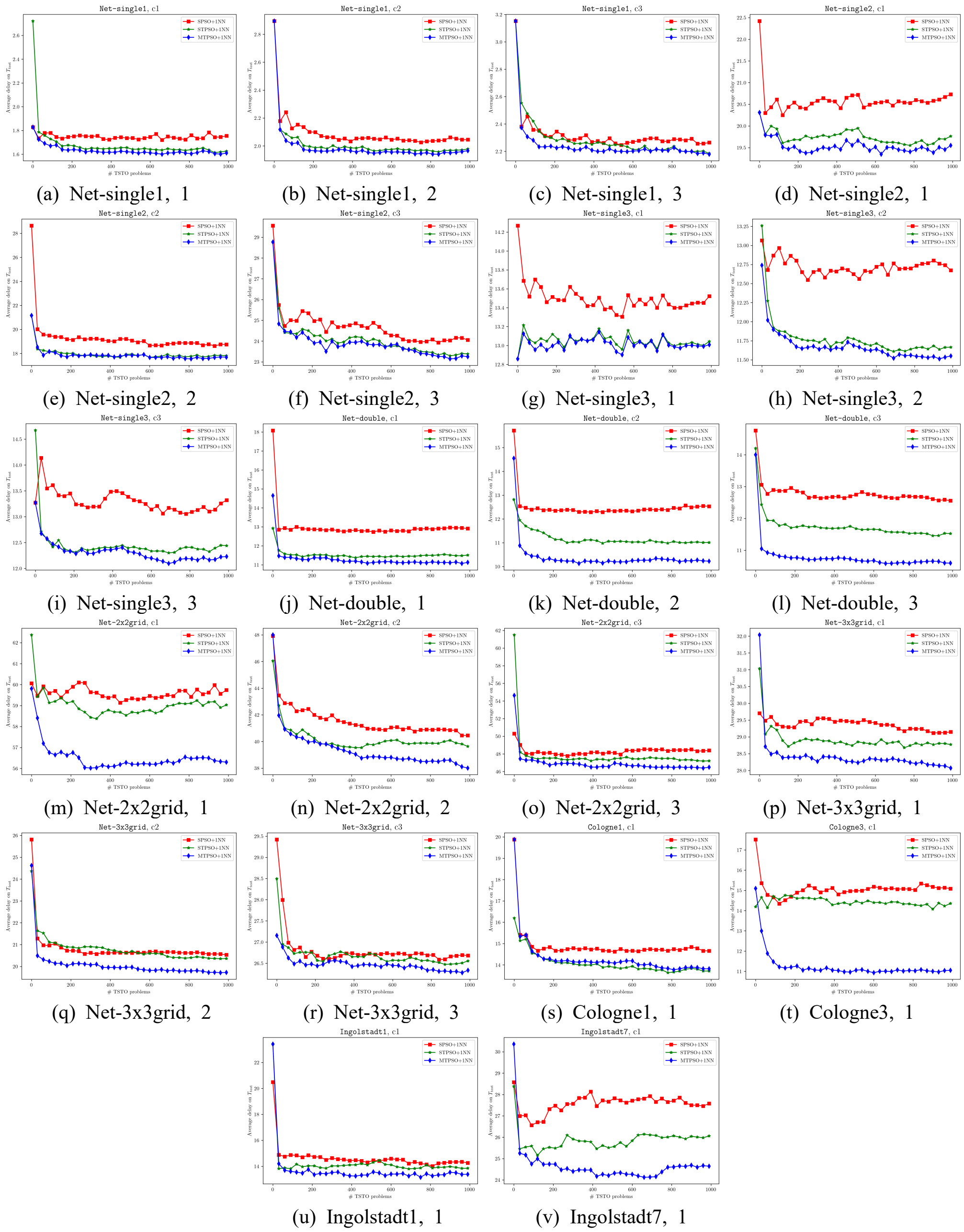


(i) Ingolstadt1



(j) Ingolstadt7

Fig. S.2. The geometry of the road network of 10 tested scenarios (a)-(j).



(a) Net-single1, 1 (b) Net-single1, 2 (c) Net-single1, 3 (d) Net-single2, 1

(e) Net-single2, 2 (f) Net-single2, 3 (g) Net-single3, 1 (h) Net-single3, 2

(i) Net-single3, 3 (j) Net-double, 1 (k) Net-double, 2 (l) Net-double, 3

(m) Net-2x2grid, 1 (n) Net-2x2grid, 2 (o) Net-2x2grid, 3 (p) Net-3x3grid, 1

(q) Net-3x3grid, 2 (r) Net-3x3grid, 3 (s) Cologne1, 1 (t) Cologne3, 1

(u) Ingolstadt1, 1 (v) Ingolstadt7, 1

Fig. S.3. Convergence curve of the test performance versus the number of training TSTO problems on all TSAPs (a)-(v).

TABLE S.I

THE MAIN CHARACTERISTICS OF THE TESTED SCENES

Scene name	Number of intersections	Input dimension	Solution dimension
Net-single1	1	2	2
Net-single2	1	4	4
Net-single3	1	4	4
Net-double	2	6	10
Net-2x2grid	4	8	20
Net-3x3grid	9	12	27
Cologne1	1	5	4
Cologne3	3	13	14
Ingolstadt1	1	4	3
Ingolstadt7	7	14	27

TABLE S.II

AN EXAMPLE OF THE THREE CASES FOR THE SCENE NET-SINGLE2

Case	Characteristics	Distribution
1	Small-range uniform distribution	$\tau_{W\to \mathrm{E}}$, $\tau_{E\to W}$~U(100,150), $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~U(10,50)
2	Large-range uniform distribution	$\tau_{W\to \mathrm{E}}$, $\tau_{E\to W}$~U(10,150), $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~U(10,150)
3	Gaussian mixture distribution (Off-hour, west-to-east busy hour, east-to-west busy hour, and bidirectional busy hour)	$\mathbf{Z}\sim p(\mathbf{Z}=z_1)=p(\mathbf{Z}=z_2)=p(\mathbf{Z}=z_3)= p(\mathbf{Z}=z_4)=0.25$ $\mathbf{Z}=z_1$: $\tau_{W\to \mathrm{E}}$, $\tau_{E\to W}$~N(125,20), $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~N(125,20), $\mathbf{Z}=z_2$: $\tau_{W\to \mathrm{E}}$~N(125,20), $\tau_{E\to W}$, $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~N(50,20) $\mathbf{Z}=z_3$: $\tau_{E\to W}$~N(125,20), $\tau_{W\to \mathrm{E}}$, $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~N(50,20) $\mathbf{Z}=z_4$: $\tau_{W\to \mathrm{E}}$, $\tau_{E\to W}$, $\tau_{N\to \mathrm{S}}$, $\tau_{S\to N}$~N(50,20)

TABLE S.III

TUNED HYPERPARAMETER OF THE STATE-OF-THE-ART SIMULATION-BASED TSTO METHODS

Scene name	Case	SOTL			BGA-ML					PSO-QL		
		θ	ω	μ	max_depth	n_estimators	learning_rate	subsample	colsample_bytree	n_interval	dim	ε
Net-single1	1	40.0	2.7	4.8	6	100	0.1	1	1	50	50	0.1
	2	41.1	5.0	4.2	6	100	0.1	0.6	1	50	50	0.1
	3	41.4	5.0	5.0	6	100	0.1	0.6	1	50	50	0.1
Net-single2	1	48.8	5.0	4.0	6	100	0.1	1	1	50	50	0.1
	2	50.0	5.0	5.0	6	100	0.1	0.6	1	50	50	0.1
	3	42.9	5.0	3.3	6	100	0.1	1	1	50	50	0.1
Net-single3	1	50.0	5.0	5.0	6	100	0.1	1	1	50	50	0.1
	2	50.0	5.0	5.0	6	100	0.1	0.6	1	50	50	0.1
	3	50.0	5.0	5.0	6	100	0.1	1	1	50	50	0.1
Net-double	1	50.0	1.2	1.2	6	100	0.1	1	0.6	50	100	0.1
	2	48.1	5.0	4.9	6	100	0.1	1	0.6	50	100	0.1
	3	50.0	5.0	5.0	6	100	0.1	1	1	50	100	0.1
Net-2x2grid	1	46.9	5.0	5.0	6	100	0.1	0.6	1	50	200	0.1
	2	50.0	5.0	4.2	6	100	0.1	0.6	0.6	50	200	0.1
	3	50.0	5.0	2.7	6	100	0.1	0.6	1	50	200	0.1
Net-3x3grid	1	50.0	5.0	5.0	6	100	0.1	0.6	1	50	450	0.1
	2	40.8	4.6	2.9	6	100	0.1	0.6	1	50	450	0.1
	3	50.0	5.0	5.0	6	100	0.1	1	1	50	450	0.1
Cologne1	1	40.1	4.8	0.2	6	100	0.1	1	1	50	50	0.1
Cologne3	1	43.4	5.0	3.3	6	100	0.1	1	1	50	150	0.1
Ingolstadt1	1	40.4	4.8	0.4	6	100	0.1	0.6	1	50	50	0.1
Ingolstadt7	1	43.3	5.0	2.1	6	100	0.1	1	1	50	350	0.1

TABLE S.IV

DETAILED COMPARATIVE RESULTS BETWEEN LMM AND DIFFERENT SIMULATION-FREE TSTO METHODS

Scene name	Case	LMM	Default30	Default60	Webster	Max-pressure	SOTL
Net-single1	1	**1.64(0.26)**	1.79(0.28)(+)	1.79(0.28)(+)	15.17(7.78)(+)	3.55(0.55)(+)	3.36(0.64)(+)
	2	**1.97(0.46)**	2.18(0.62)(+)	2.18(0.62)(+)	11.06(7.65)(+)	4.40(2.03)(+)	5.57(3.85)(+)
	3	**2.18(0.68)**	2.66(1.15)(+)	2.66(1.15)(+)	15.19(9.85)(+)	5.62(3.42)(+)	8.37(7.43)(+)
Net-single2	1	**18.76(2.31)**	66.18(7.60)(+)	66.18(7.60)(+)	117.97(8.91)(+)	58.91(15.50)(+)	118.80(8.76)(+)
	2	**17.29(3.82)**	39.26(19.34)(+)	39.26(19.34)(+)	75.53(31.78)(+)	40.80(20.92)(+)	72.96(34.22)(+)
	3	**23.96(6.47)**	51.45(18.75)(+)	51.45(18.75)(+)	85.70(25.58)(+)	67.05(26.13)(+)	84.93(26.69)(+)
Net-single3	1	**12.68(1.12)**	26.82(8.77)(+)	26.82(8.77)(+)	87.42(9.19)(+)	17.45(3.18)(+)	83.14(9.86)(+)
	2	**11.44(1.53)**	17.22(6.63)(+)	17.22(6.63)(+)	45.89(25.62)(+)	12.93(3.18)(+)	42.25(24.36)(+)
	3	**12.19(1.62)**	17.95(7.12)(+)	17.95(7.12)(+)	41.30(18.91)(+)	15.85(4.64)(+)	38.43(18.77)(+)
Net-double	1	**10.79(1.05)**	14.33(2.73)(+)	14.33(2.73)(+)	34.82(7.99)(+)	11.95(1.79)(+)	23.27(5.99)(+)
	2	**9.84(1.82)**	11.96(3.33)(+)	11.96(3.33)(+)	24.24(10.45)(+)	10.22(2.16)(+)	20.48(6.14)(+)
	3	**10.32(1.40)**	12.26(3.08)(+)	12.26(3.08)(+)	24.02(9.83)(+)	12.71(2.71)(+)	20.96(6.15)(+)
Net-2x2grid	1	**53.48(5.49)**	95.21(5.11)(+)	95.21(5.11)(+)	131.77(6.30)(+)	83.60(18.47)(+)	130.36(7.42)(+)
	2	**37.54(9.46)**	62.08(15.48)(+)	62.08(15.48)(+)	93.61(19.00)(+)	70.88(15.72)(+)	91.59(19.68)(+)
	3	**45.49(14.15)**	67.65(23.05)(+)	67.65(23.05)(+)	101.11(26.47)(+)	84.99(23.87)(+)	100.59(27.98)(+)
Net-3x3grid	1	27.41(2.78)	32.16(3.47)(+)	32.16(3.47)(+)	41.39(4.05)(+)	**19.07(1.99)(−)**	20.73(2.08)(−)
	2	19.75(2.76)	19.77(3.60)(=)	19.77(3.60)(=)	25.82(6.89)(+)	**12.32(1.92)(−)**	15.09(1.48)(−)
	3	25.86(6.89)	27.03(8.89)(+)	27.03(8.89)(+)	29.82(10.58)(+)	**17.51(5.23)(−)**	20.35(4.77)(−)
Cologne1	1	**13.87(3.05)**	50.49(14.06)(+)	50.49(14.06)(+)	24.86(5.68)(+)	24.86(5.68)(+)	24.86(5.68)(+)
Cologne3	1	**10.24(2.13)**	16.37(4.83)(+)	16.37(4.83)(+)	24.50(6.28)(+)	14.51(3.15)(+)	13.22(3.54)(+)
Ingolstadt1	1	**12.85(5.66)**	25.18(11.74)(+)	25.18(11.74)(+)	20.82(6.77)(+)	20.82(6.77)(+)	20.82(6.77)(+)
Ingolstadt7	1	**22.98(6.47)**	32.57(8.79)(+)	32.57(8.79)(+)	41.49(6.63)(+)	35.82(6.22)(+)	38.11(6.22)(+)
W/T/L		NA	21/1/0	21/1/0	22/0/0	19/0/3	19/0/3
Number of best		19	0	0	0	3	0

TABLE S.V

DETAILED COMPARATIVE RESULTS BETWEEN LMM (TRAINED ON CASE 2) AND SIMULATION-FREE TSTO METHODS ON SYNTHETIC SCENES (TESTED ON CASES 1 AND 3)

Scene name	Case	LMM	Default30	Default60	Webster	Max-pressure	SOTL
Net-single1	1	1.68(0.27)	12.48(23.63)(+)	1.79(0.28)(+)	1.79(0.28)(+)	15.17(7.78)(+)	3.55(0.55)(+)
	3	2.21(0.68)	10.43(14.43)(+)	2.66(1.15)(+)	2.66(1.15)(+)	15.19(9.85)(+)	5.62(3.42)(+)
Net-single2	1	19.01(2.19)	69.12(29.92)(+)	66.18(7.60)(+)	66.18(7.60)(+)	117.97(8.91)(+)	58.91(15.50)(+)
	3	29.09(10.95)	54.99(21.11)(+)	51.45(18.75)(+)	51.45(18.75)(+)	85.70(25.58)(+)	67.05(26.13)(+)
Net-single3	1	12.66(1.25)	46.60(29.08)(+)	26.82(8.77)(+)	26.82(8.77)(+)	87.42(9.19)(+)	17.45(3.18)(+)
	3	12.49(2.08)	33.06(14.63)(+)	17.95(7.12)(+)	17.95(7.12)(+)	41.30(18.91)(+)	15.85(4.64)(+)
Net-double	1	10.91(1.07)	22.33(6.90)(+)	14.33(2.73)(+)	14.33(2.73)(+)	34.82(7.99)(+)	11.95(1.79)(+)
	3	10.56(1.43)	18.27(5.67)(+)	12.26(3.08)(+)	12.26(3.08)(+)	24.02(9.83)(+)	12.71(2.71)(+)
Net-2x2grid	1	55.32(5.95)	85.43(10.78)(+)	95.21(5.11)(+)	95.21(5.11)(+)	131.77(6.30)(+)	83.60(18.47)(+)
	3	47.23(12.55)	66.14(17.89)(+)	67.65(23.05)(+)	67.65(23.05)(+)	101.11(26.47)(+)	84.99(23.87)(+)
Net-3x3grid	1	28.58(3.23)	47.69(8.49)(+)	32.16(3.47)(+)	32.16(3.47)(+)	41.39(4.05)(+)	19.07(1.99)(-)
	3	27.70(7.24)	37.02(12.47)(+)	27.03(8.89)(=)	27.03(8.89)(=)	29.82(10.58)(+)	17.51(5.23)(-)
W/T/L		NA	12/0/0	11/1/0	11/1/0	12/0/0	10/0/2
Number of best (↑)		10	0	0	0	0	2

TABLE S.VI

COMPARATIVE RESULTS BETWEEN THE LMM-PSO AND STATE-OF-THE-ART SIMULATION-BASED TSTO METHODS

Scene name	Case	LMM-PSO	CLPSO	MELPSO	REPSO	CTM-PSO	PSO-QL	BGA-ML
Net-single1	1	**1.55(0.24)**	1.70(0.27)(+)	1.57(0.21)(+)	2.15(0.30)(+)	1.66(0.26)(+)	3.11(0.72)(+)	7.43(1.83)(+)
	2	1.84(0.43)	2.03(0.47)(+)	**1.84(0.43)(=)**	2.42(0.46)(+)	1.93(0.42)(+)	3.88(0.95)(+)	10.86(2.41)(+)
	3	**2.07(0.62)**	2.28(0.62)(+)	2.08(0.61)(+)	2.66(0.56)(+)	2.16(0.57)(+)	4.31(1.17)(+)	11.20(2.22)(+)
Net-single2	1	**17.04(2.00)**	18.84(2.20)(+)	17.13(2.04)(+)	23.77(2.01)(+)	17.83(2.14)(+)	33.87(2.90)(+)	29.05(2.96)(+)
	2	14.88(3.23)	16.79(3.14)(+)	**14.87(3.22)(=)**	20.39(3.86)(+)	15.80(3.13)(+)	27.69(6.66)(+)	28.11(2.98)(+)
	3	**19.13(4.67)**	21.19(4.46)(+)	19.14(4.57)(=)	23.56(4.37)(+)	19.88(4.50)(+)	29.56(4.89)(+)	31.86(3.80)(+)
Net-single3	1	11.83(0.86)	13.02(0.91)(+)	**11.81(0.86)(=)**	17.25(1.00)(+)	12.09(0.82)(+)	16.83(0.63)(+)	20.37(2.16)(+)
	2	10.44(1.35)	11.97(1.15)(+)	**10.42(1.35)(−)**	15.63(1.48)(+)	10.99(1.10)(+)	16.89(1.44)(+)	22.57(3.61)(+)
	3	11.01(1.35)	12.81(1.30)(+)	**10.97(1.33)(−)**	15.90(1.36)(+)	11.60(1.12)(+)	17.57(1.38)(+)	24.80(2.77)(+)
Net-double	1	**9.77(0.75)**	12.08(0.76)(+)	9.86(0.72)(+)	13.93(0.87)(+)	11.06(0.70)(+)	22.48(1.64)(+)	24.90(2.80)(+)
	2	**8.80(1.20)**	11.13(1.04)(+)	8.85(1.07)(+)	12.52(1.34)(+)	10.34(0.89)(+)	20.48(2.14)(+)	24.35(2.61)(+)
	3	**9.24(1.11)**	11.40(0.96)(+)	9.30(1.06)(+)	12.59(1.07)(+)	10.62(0.81)(+)	21.29(2.04)(+)	24.96(2.36)(+)
Net-2x2grid	1	**49.99(5.31)**	59.43(5.19)(+)	51.68(5.20)(+)	65.08(6.05)(+)	50.08(5.27)(=)	83.04(3.99)(+)	73.48(8.88)(+)
	2	**33.33(7.61)**	40.46(8.76)(+)	34.32(7.78)(+)	44.72(10.67)(+)	33.72(7.11)(+)	69.44(8.89)(+)	64.20(9.97)(+)
	3	40.93(12.40)	46.40(12.89)(+)	40.66(11.97)(=)	46.38(14.53)(+)	**39.83(11.47)(−)**	67.97(8.69)(+)	67.47(11.36)(+)
Net-3x3grid	1	25.95(2.37)	28.95(2.50)(+)	26.13(2.18)(+)	31.74(3.06)(+)	**25.91(2.12)(=)**	29.43(1.59)(+)	48.71(4.87)(+)
	2	18.08(2.35)	19.70(2.46)(+)	**17.97(2.22)(−)**	20.83(3.35)(+)	18.25(2.09)(+)	22.49(2.15)(+)	43.84(3.39)(+)
	3	23.83(6.18)	25.50(6.74)(+)	23.62(6.10)(−)	26.09(7.75)(+)	**23.45(5.75)(−)**	26.09(4.69)(+)	49.51(5.95)(+)
Cologne1	1	11.86(2.36)	14.00(2.60)(+)	**11.79(2.29)(−)**	19.71(4.16)(+)	12.76(2.42)(+)	14.91(3.96)(+)	21.00(3.43)(+)
Cologne3	1	**7.67(1.00)**	9.79(1.19)(+)	8.15(1.10)(+)	11.46(1.59)(+)	9.07(1.11)(+)	13.70(1.77)(+)	17.02(2.56)(+)
Ingolstadt1	1	10.62(5.13)	11.28(5.18)(+)	10.61(5.13)(=)	14.22(5.95)(+)	10.97(5.12)(+)	**9.05(3.12)(=)**	21.18(7.26)(+)
Ingolstadt7	1	**18.57(3.74)**	21.81(3.86)(+)	19.81(4.04)(+)	24.04(4.19)(+)	20.20(3.80)(+)	34.42(3.32)(+)	41.50(5.74)(+)
W/T/L		NA	22/0/0	11/6/5	22/0/0	18/2/2	21/1/0	22/0/0
Number of best		11	0	7	0	3	1	0

TABLE S.VII

INVESTIGATION RESULTS ON THE USE OF DIFFERENT MACHINE LEARNING MODELS

Scene name	Case	KNN	RS	GS	LR	NN	DT	RF
Net-single1	1	**1.61(0.26)**	2.08(0.77)(+)	2.62(1.28)(+)	2.11(0.44)(+)	1.88(0.28)(+)	1.61(0.27)(=)	1.82(0.25)(+)
	2	**1.96(0.46)**	5.82(7.46)(+)	5.12(5.34)(+)	2.24(0.53)(+)	2.18(0.56)(+)	1.99(0.50)(=)	2.12(0.52)(+)
	3	**2.18(0.68)**	7.25(10.16)(+)	5.99(7.84)(+)	2.52(0.82)(+)	2.45(0.73)(+)	2.24(0.70)(+)	2.30(0.68)(+)
Net-single2	1	**19.41(2.77)**	21.92(4.87)(+)	22.62(4.70)(+)	19.83(2.59)(+)	19.53(2.61)(=)	19.56(2.90)(=)	19.71(2.85)(=)
	2	**17.62(4.19)**	24.41(9.82)(+)	25.63(13.22)(+)	18.17(5.03)(=)	18.58(4.40)(+)	17.97(4.32)(=)	17.77(4.14)(=)
	3	23.26(6.71)	38.32(18.77)(+)	39.37(15.48)(+)	23.35(6.00)(=)	25.90(7.10)(+)	24.05(6.55)(+)	**22.65(5.69)(=)**
Net-single3	1	**12.96(1.23)**	13.33(1.63)(+)	14.24(2.88)(+)	13.04(1.12)(=)	13.03(1.11)(=)	13.07(1.19)(=)	12.98(1.22)(=)
	2	**11.54(1.61)**	14.83(6.91)(+)	15.31(7.00)(+)	11.63(1.91)(=)	11.57(1.91)(=)	11.55(1.71)(=)	11.56(1.62)(=)
	3	12.27(1.86)	15.12(5.24)(+)	16.71(7.36)(+)	**12.22(1.76)(=)**	13.16(2.32)(+)	12.39(1.97)(=)	12.26(1.74)(=)
Net-double	1	**11.08(1.22)**	11.36(1.28)(+)	13.51(2.40)(+)	12.34(1.19)(+)	12.03(1.41)(+)	11.22(1.32)(=)	12.24(1.33)(+)
	2	**10.23(2.12)**	11.55(3.17)(+)	12.41(3.66)(+)	11.51(2.65)(+)	13.40(4.15)(+)	10.33(2.44)(=)	11.39(2.63)(+)
	3	**10.61(1.59)**	11.98(2.13)(+)	12.63(3.68)(+)	11.14(1.97)(+)	12.02(2.94)(+)	10.73(1.64)(=)	11.03(1.79)(+)
Net-2x2grid	1	**56.31(6.45)**	57.66(6.24)(+)	63.01(6.92)(+)	56.42(5.94)(=)	56.90(6.18)(=)	56.76(6.09)(=)	56.55(6.26)(=)
	2	**38.07(9.23)**	45.50(11.81)(+)	50.93(11.67)(+)	40.75(9.41)(+)	45.08(10.87)(+)	39.01(9.86)(=)	40.43(9.74)(+)
	3	**46.46(14.32)**	52.18(16.26)(+)	56.27(15.61)(+)	47.24(13.60)(+)	48.91(14.31)(+)	47.43(14.54)(+)	47.16(14.05)(+)
Net-3x3grid	1	**28.14(2.71)**	28.41(2.89)(=)	30.13(3.32)(+)	28.63(2.59)(+)	29.12(2.62)(+)	28.33(2.98)(=)	28.85(2.77)(+)
	2	**19.73(2.83)**	22.64(4.40)(+)	23.21(4.85)(+)	20.13(2.65)(+)	22.27(4.21)(+)	20.39(3.26)(+)	20.48(2.80)(+)
	3	26.28(6.84)	28.89(8.26)(+)	30.73(9.41)(+)	**26.20(6.62)(=)**	27.22(7.24)(+)	26.62(7.35)(=)	26.51(6.98)(=)
Cologne1	1	13.83(3.02)	19.69(9.16)(+)	21.49(11.36)(+)	**13.79(3.35)(=)**	13.93(3.44)(=)	14.27(3.94)(=)	13.90(3.57)(=)
Cologne3	1	**11.00(2.41)**	11.58(3.06)(=)	11.94(3.20)(+)	11.08(2.58)(=)	11.69(2.88)(+)	11.20(2.92)(=)	11.18(2.93)(=)
Ingolstadt1	1	13.41(5.95)	16.28(8.37)(+)	16.87(8.28)(+)	13.45(5.73)(=)	14.80(6.40)(+)	13.62(6.08)(=)	**12.98(5.80)(=)**
Ingolstadt7	1	24.66(7.55)	26.62(7.12)(+)	26.77(7.57)(+)	**24.18(6.89)(=)**	25.25(7.37)(+)	24.73(7.23)(=)	24.57(7.12)(=)
W/T/L		NA	20/2/0	22/0/0	11/11/0	17/5/0	4/18/0	10/12/0
Number of best		16	0	0	4	0	0	2

TABLE S.VIII

INVESTIGATION RESULTS ON THE EFFECTS OF COMPONENT MTPSO IN THE DC STAGE

Scene name	Case	MTPSO+1NN	STPSO+1NN	SPSO+1NN	DRR
Net-single1	1	**1.61(0.26)**	1.62(0.26)(+)	1.76(0.38)(+)	8.52%
	2	**1.96(0.46)**	1.97(0.46)(=)	2.06(0.52)(+)	4.85%
	3	**2.18(0.68)**	2.19(0.68)(=)	2.27(0.66)(+)	3.96%
Net-single2	1	**19.41(2.77)**	19.64(2.99)(=)	20.64(3.35)(+)	5.96%
	2	**17.62(4.19)**	17.78(4.17)(=)	18.62(4.35)(+)	5.37%
	3	**23.26(6.71)**	23.40(6.25)(=)	24.08(6.38)(+)	3.41%
Net-single3	1	12.96(1.23)	**12.95(1.23)(=)**	13.41(1.27)(+)	3.36%
	2	**11.54(1.61)**	11.68(1.54)(+)	12.73(1.86)(+)	9.35%
	3	**12.27(1.86)**	12.44(1.85)(+)	13.38(2.62)(+)	8.30%
Net-double	1	**11.08(1.22)**	11.48(1.34)(+)	12.87(1.25)(+)	13.91%
	2	**10.23(2.12)**	11.01(1.69)(+)	12.53(1.59)(+)	18.36%
	3	**10.61(1.59)**	11.56(1.49)(+)	12.55(1.27)(+)	15.46%
Net-2x2grid	1	**56.31(6.45)**	58.97(6.16)(+)	59.78(7.05)(+)	5.80%
	2	**38.07(9.23)**	39.75(9.62)(+)	40.45(8.85)(+)	5.88%
	3	**46.46(14.32)**	47.19(13.33)(=)	48.36(13.98)(+)	3.93%
Net-3x3grid	1	**28.14(2.71)**	28.76(2.77)(+)	29.15(2.59)(+)	3.46%
	2	**19.73(2.83)**	20.40(2.48)(+)	20.56(2.83)(+)	4.04%
	3	**26.28(6.84)**	26.48(6.38)(=)	26.61(6.83)(+)	1.24%
Cologne1	1	13.83(3.02)	**13.75(2.82)(=)**	14.69(3.04)(+)	5.85%
Cologne3	1	**11.00(2.41)**	14.16(4.44)(+)	15.15(4.78)(+)	27.39%
Ingolstadt1	1	**13.41(5.95)**	13.87(6.92)(=)	14.35(6.28)(+)	6.55%
Ingolstadt7	1	**24.66(7.55)**	26.04(8.00)(+)	27.54(7.29)(+)	10.46%
W/T/L		NA	12/10/0	22/0/0	/
Number of best		20	2	0	/

"DRR" refers to the delay reduction rate of MTPSO+1NN against the SPSO+1NN, which is calculated as ($Delay_{SPSO+1NN}$ – $Delay_{MTPSO+1NN}$) / $Delay_{SPSO+1NN}$.

TABLE S.IX

ABLATION RESULTS FOR THE COMPONENT MSRO USING DIFFERENT ML ALGORITHMS IN THE ML STAGE

Scene name	Case	LR		DT		RF		*k*NN	
		MSR	w/o-MSR	MSR	w/o-MSR	MSR	w/o-MSR	MSR	w/o-MSR
Net-single1	1	1.96(0.35)	2.11(0.44)(+)	1.63(0.27)	1.61(0.26)(−)	1.66(0.30)	1.78(0.27)(+)	1.68(0.30)	1.79(0.26)(+)
	2	2.28(0.51)	2.24(0.53)(−)	1.99(0.46)	2.00(0.50)(=)	2.13(0.52)	2.10(0.53)(=)	2.10(0.52)	2.08(0.51)(=)
	3	2.52(0.82)	2.52(0.82)(=)	2.24(0.70)	2.25(0.71)(=)	2.32(0.71)	2.29(0.71)(=)	2.33(0.68)	2.33(0.68)(=)
Net-single2	1	19.83(2.59)	19.83(2.59)(=)	18.75(2.37)	19.53(2.97)(+)	19.33(2.67)	19.88(2.84)(+)	19.17(2.52)	19.64(2.78)(+)
	2	18.54(4.68)	18.17(5.03)(−)	17.22(3.83)	17.95(4.20)(+)	17.46(3.90)	17.83(4.31)(=)	17.33(3.77)	17.77(4.29)(=)
	3	23.92(6.17)	23.35(6.00)(−)	23.94(6.26)	24.29(6.73)(=)	23.77(6.26)	22.58(5.65)(−)	23.45(5.84)	22.92(6.05)(=)
Net-single3	1	12.93(1.18)	13.04(1.12)(=)	12.62(1.11)	13.01(1.21)(+)	12.69(1.17)	12.88(1.19)(+)	12.72(1.14)	12.91(1.15)(+)
	2	11.67(1.75)	11.63(1.91)(=)	11.40(1.57)	11.55(1.69)(=)	11.43(1.52)	11.48(1.58)(=)	11.40(1.47)	11.61(1.56)(+)
	3	12.21(1.72)	12.22(1.76)(=)	12.08(1.51)	12.33(1.71)(+)	12.11(1.57)	12.26(1.65)(=)	12.13(1.61)	12.19(1.67)(=)
Net-double	1	11.92(1.16)	12.34(1.19)(+)	10.82(1.07)	11.21(1.20)(+)	11.40(1.24)	12.26(1.28)(+)	11.27(1.22)	12.22(1.29)(+)
	2	11.38(2.45)	11.51(2.65)(=)	9.89(1.89)	10.32(2.58)(+)	10.15(1.93)	11.42(2.69)(+)	10.38(1.91)	11.13(2.24)(+)
	3	10.88(2.11)	11.14(1.97)(+)	10.30(1.30)	10.71(1.70)(+)	10.53(1.51)	11.14(1.87)(+)	10.49(1.50)	10.87(1.88)(+)
Net-2x2grid	1	54.86(6.38)	56.42(5.94)(+)	53.10(5.89)	56.47(6.57)(+)	54.23(5.91)	56.69(5.81)(+)	54.28(5.67)	56.61(6.46)(+)
	2	41.14(9.25)	40.75(9.41)(=)	37.99(9.89)	39.51(9.65)(+)	38.89(10.07)	40.25(9.47)(+)	39.39(10.04)	40.07(9.46)(=)
	3	47.50(13.43)	47.24(13.60)(=)	45.48(13.73)	47.82(14.32)(+)	46.48(13.59)	47.47(13.90)(+)	46.49(13.57)	47.31(13.90)(+)
Net-3x3grid	1	28.60(2.75)	28.63(2.59)(=)	27.47(2.79)	28.31(2.71)(+)	28.53(2.79)	28.67(2.80)(=)	28.20(2.79)	28.82(2.70)(+)
	2	20.42(2.71)	20.13(2.65)(−)	19.80(2.72)	20.55(3.21)(+)	20.32(2.78)	20.31(2.84)(=)	20.29(2.81)	20.22(2.74)(=)
	3	26.54(6.76)	26.20(6.62)(−)	25.81(6.88)	26.74(7.17)(+)	26.25(6.68)	26.55(7.21)(=)	26.15(6.51)	26.43(7.06)(=)
Cologne1	1	13.66(3.31)	13.79(3.35)(=)	14.38(3.57)	14.16(3.68)(=)	13.96(3.22)	13.90(3.64)(=)	13.77(3.27)	13.77(3.14)(=)
Cologne3	1	10.58(1.87)	11.08(2.58)(=)	10.39(2.23)	10.68(2.40)(=)	10.45(2.10)	10.81(2.36)(=)	10.65(2.14)	11.15(2.83)(+)
Ingolstadt1	1	13.41(5.80)	13.45(5.73)(=)	12.86(5.71)	13.80(6.17)(+)	13.10(5.77)	13.17(5.85)(=)	12.91(5.79)	13.62(5.79)(+)
Ingolstadt7	1	23.20(5.96)	24.18(6.89)(+)	22.82(6.38)	24.95(6.94)(+)	23.08(6.52)	24.47(7.14)(+)	23.17(6.18)	24.75(7.20)(+)
W/T/L		/	5/12/5	/	15/6/1	/	10/11/1	/	13/9/0

TABLE S.X

INVESTIGATION RESULTS ON THE EFFECTS OF COMPONENT MSRO IN THE ML STAGE

Scene name	Case	LMM	LMM-φ_0	LMM-φ_1	LMM-φ_2	LMM-φ_3
Net-single1	1	1.64(0.26)	**1.61(0.26)(=)**	1.61(0.27)(=)	1.64(0.26)(=)	1.78(0.34)(+)
	2	1.97(0.46)	**1.96(0.46)(=)**	1.97(0.46)(=)	2.02(0.54)(=)	2.81(1.10)(+)
	3	**2.18(0.68)**	2.18(0.68)(=)	2.19(0.68)(=)	2.28(0.72)(+)	3.11(0.57)(+)
Net-single2	1	**18.76(2.31)**	19.41(2.77)(+)	19.54(2.81)(+)	18.76(2.31)(=)	19.08(2.24)(+)
	2	**17.29(3.82)**	17.62(4.19)(=)	17.51(3.96)(=)	17.29(3.82)(=)	19.06(3.30)(+)
	3	23.96(6.47)	23.26(6.71)(−)	**23.26(6.60)(−)**	23.96(6.47)(=)	26.19(6.80)(+)
Net-single3	1	12.68(1.12)	12.96(1.23)(+)	12.92(1.22)(+)	12.68(1.12)(=)	**12.66(1.25)(=)**
	2	**11.44(1.53)**	11.54(1.61)(=)	11.48(1.50)(=)	11.44(1.53)(=)	12.10(1.18)(+)
	3	**12.19(1.62)**	12.27(1.86)(=)	12.35(1.82)(=)	12.19(1.62)(=)	13.16(2.32)(+)
Net-double	1	**10.79(1.05)**	11.08(1.22)(+)	11.08(1.18)(+)	10.79(1.05)(=)	10.80(1.08)(=)
	2	**9.84(1.82)**	10.23(2.12)(+)	10.21(2.06)(+)	9.84(1.82)(=)	10.33(2.08)(+)
	3	**10.32(1.40)**	10.61(1.59)(+)	10.58(1.51)(+)	10.32(1.40)(=)	10.79(1.79)(+)
Net-2x2grid	1	**53.48(5.49)**	56.31(6.45)(+)	55.58(6.29)(+)	53.48(5.49)(=)	54.17(5.94)(+)
	2	**37.54(9.46)**	38.07(9.23)(=)	37.71(9.32)(=)	37.54(9.46)(=)	41.20(9.75)(+)
	3	**45.49(14.15)**	46.46(14.32)(+)	46.59(14.48)(+)	45.49(14.15)(=)	46.86(12.38)(+)
Net-3x3grid	1	**27.41(2.78)**	28.14(2.71)(+)	28.04(2.80)(+)	27.41(2.78)(=)	27.55(2.93)(=)
	2	19.75(2.76)	**19.73(2.83)(=)**	19.74(2.76)(=)	19.75(2.76)(=)	20.32(3.08)(+)
	3	**25.86(6.89)**	26.28(6.84)(+)	26.05(6.74)(=)	25.86(6.89)(=)	26.41(6.55)(+)
Cologne1	1	13.87(3.05)	**13.83(3.02)(=)**	13.87(3.05)(=)	14.06(3.36)(=)	15.56(3.89)(+)
Cologne3	1	**10.24(2.13)**	11.00(2.41)(+)	11.20(2.67)(+)	10.24(2.13)(=)	10.49(2.21)(=)
Ingolstadt1	1	**12.85(5.66)**	13.41(5.95)(+)	13.49(6.09)(+)	12.85(5.66)(=)	13.85(6.10)(+)
Ingolstadt7	1	**22.98(6.47)**	24.66(7.55)(+)	24.32(7.23)(+)	22.98(6.47)(=)	23.22(6.44)(=)
W/T/L		NA	12/9/1	11/10/1	1/21/0	17/5/0
Number of best		16	4	1	0	1

TABLE S.XI

INVESTIGATION RESULTS ON THE EFFECTS OF K-SETTING

Scene name	Case	1NN	5NN	10NN	15NN	20NN	25NN	30NN
Net-single1	1	**1.61(0.26)**	1.79(0.27)(+)	1.84(0.28)(+)	1.83(0.26)(+)	1.84(0.26)(+)	1.85(0.26)(+)	1.86(0.24)(+)
	2	**1.96(0.46)**	2.10(0.53)(+)	2.10(0.49)(+)	2.09(0.48)(+)	2.09(0.52)(+)	2.11(0.51)(+)	2.09(0.49)(+)
	3	**2.18(0.68)**	2.32(0.67)(+)	2.36(0.72)(+)	2.37(0.70)(+)	2.38(0.71)(+)	2.40(0.76)(+)	2.35(0.73)(+)
Net-single2	1	**19.41(2.77)**	19.71(2.65)(=)	19.66(2.61)(=)	19.78(2.63)(+)	19.69(2.46)(=)	19.80(2.49)(+)	19.83(2.43)(+)
	2	17.62(4.19)	17.92(4.43)(=)	17.67(4.35)(=)	**17.47(4.34)(=)**	17.59(4.30)(=)	17.73(4.33)(=)	17.61(4.06)(=)
	3	23.26(6.71)	22.88(5.84)(=)	22.63(5.90)(=)	**22.60(6.00)(=)**	22.73(5.79)(=)	22.77(5.94)(=)	22.82(6.01)(=)
Net-single3	1	12.96(1.23)	12.93(1.20)(=)	12.94(1.14)(=)	12.96(1.16)(=)	12.88(1.09)(=)	**12.86(1.17)(=)**	12.92(1.15)(=)
	2	11.54(1.61)	11.55(1.59)(=)	11.54(1.53)(=)	**11.44(1.54)(=)**	11.47(1.49)(=)	11.51(1.58)(=)	11.56(1.53)(=)
	3	12.27(1.86)	**12.14(1.71)(=)**	12.18(1.71)(=)	12.19(1.62)(=)	12.19(1.61)(=)	12.17(1.60)(=)	12.22(1.65)(=)
Net-double	1	**11.08(1.22)**	12.32(1.49)(+)	12.44(1.33)(+)	12.32(1.33)(+)	12.21(1.17)(+)	12.22(1.22)(+)	12.13(1.06)(+)
	2	**10.23(2.12)**	11.13(2.17)(+)	11.23(2.48)(+)	11.39(2.55)(+)	11.33(2.57)(+)	11.23(2.37)(+)	11.30(2.52)(+)
	3	**10.61(1.59)**	10.99(1.97)(+)	11.04(1.80)(+)	11.07(1.90)(+)	10.91(1.75)(+)	11.12(1.72)(+)	11.16(1.95)(+)
Net-2x2grid	1	**56.31(6.45)**	56.91(6.14)(=)	56.61(5.99)(=)	56.72(6.04)(=)	56.72(6.65)(=)	56.67(6.61)(=)	56.76(6.27)(=)
	2	**38.07(9.23)**	40.67(9.47)(+)	40.24(9.12)(+)	40.32(9.33)(+)	40.24(9.55)(+)	40.27(9.60)(+)	40.45(9.58)(+)
	3	**46.46(14.32)**	47.00(13.93)(+)	47.14(13.61)(+)	46.93(13.88)(=)	47.15(13.68)(+)	46.98(13.59)(=)	46.85(13.84)(=)
Net-3x3grid	1	**28.14(2.71)**	28.92(2.86)(+)	28.79(2.96)(+)	28.70(2.95)(+)	28.72(2.72)(+)	28.67(2.71)(+)	28.79(2.98)(+)
	2	**19.73(2.83)**	20.25(2.67)(+)	20.24(2.86)(+)	20.12(2.77)(+)	20.11(2.74)(+)	20.29(2.75)(+)	20.26(2.81)(+)
	3	**26.28(6.84)**	26.43(6.91)(=)	26.51(7.03)(=)	26.46(7.03)(=)	26.40(6.84)(=)	26.51(7.08)(=)	26.52(7.03)(=)
Cologne1	1	13.83(3.02)	13.75(3.17)(=)	13.78(3.33)(=)	**13.72(3.15)(=)**	13.80(3.31)(=)	13.73(3.25)(=)	13.77(3.20)(=)
Cologne3	1	11.00(2.41)	10.81(2.43)(=)	**10.80(2.56)(=)**	11.10(2.68)(=)	10.92(2.37)(=)	11.19(2.83)(=)	10.82(2.70)(=)
Ingolstadt1	1	13.41(5.95)	13.17(5.83)(=)	13.15(5.90)(=)	13.09(5.70)(=)	13.26(5.66)(=)	**13.04(5.65)(=)**	13.14(5.71)(=)
Ingolstadt7	1	24.66(7.55)	24.36(7.27)(=)	**24.30(7.02)(=)**	24.32(7.10)(=)	24.32(6.99)(=)	24.53(7.36)(=)	24.53(7.27)(=)
W/T/L		NA	10/12/0	10/12/0	10/12/0	10/12/0	10/12/0	10/12/0
Number of best		13	1	2	4	0	2	0

TABLE S.XII

INVESTIGATION RESULTS ON THE EFFECTS OF DISTANCE METRIC

Scene name	Case	L1	L2	L∞	PCC	PCA-D1	PCA-D2
Net-single1	1	1.61(0.26)	1.61(0.26)(=)	1.62(0.27)(=)	1.97(0.75)(+)	**1.60(0.27)(=)**	1.61(0.27)(=)
	2	1.96(0.46)	**1.95(0.45)(−)**	1.96(0.48)(=)	4.05(4.46)(+)	4.75(7.04)(+)	1.96(0.45)(=)
	3	**2.18(0.68)**	2.19(0.69)(=)	2.19(0.69)(=)	3.58(2.15)(+)	5.04(6.08)(+)	2.19(0.69)(=)
Net-single2	1	**19.41(2.77)**	19.43(2.72)(=)	19.43(2.79)(=)	20.93(4.23)(+)	20.39(2.93)(+)	20.04(3.08)(+)
	2	17.62(4.19)	17.64(4.32)(=)	**17.58(4.09)(=)**	22.00(8.85)(+)	19.53(5.90)(+)	18.41(4.67)(+)
	3	23.26(6.71)	**23.18(6.08)(=)**	23.41(6.19)(=)	29.12(11.70)(+)	27.45(9.97)(+)	27.22(9.02)(+)
Net-single3	1	12.96(1.23)	**12.94(1.13)(=)**	12.95(1.16)(=)	13.16(1.35)(=)	13.12(1.39)(=)	13.03(1.30)(=)
	2	11.54(1.61)	11.56(1.63)(=)	**11.52(1.58)(=)**	14.11(6.48)(+)	12.67(2.81)(+)	11.55(1.63)(=)
	3	12.27(1.86)	**12.13(1.60)(=)**	12.15(1.60)(=)	13.18(1.89)(+)	12.61(1.99)(+)	12.61(2.18)(+)
Net-double	1	**11.08(1.22)**	11.19(1.12)(=)	11.28(1.18)(+)	11.35(1.33)(+)	11.57(1.89)(+)	11.26(1.21)(+)
	2	10.23(2.12)	**10.15(1.99)(=)**	10.21(2.05)(=)	10.59(2.25)(+)	11.02(3.14)(+)	10.20(2.03)(=)
	3	10.61(1.59)	**10.58(1.58)(=)**	10.68(1.59)(=)	11.11(1.90)(+)	11.09(2.11)(+)	10.62(1.38)(=)
Net-2x2grid	1	56.31(6.45)	**56.28(6.68)(=)**	56.93(6.75)(=)	56.45(6.64)(=)	58.05(6.07)(+)	57.21(6.46)(+)
	2	**38.07(9.23)**	38.42(8.93)(=)	38.28(8.98)(=)	38.74(9.27)(=)	45.57(11.76)(+)	42.18(10.27)(+)
	3	46.46(14.32)	46.31(14.56)(=)	**46.29(14.16)(=)**	47.82(14.08)(+)	48.85(13.98)(+)	47.39(14.18)(+)
Net-3x3grid	1	**28.14(2.71)**	28.31(2.80)(=)	28.40(2.94)(=)	28.41(2.71)(=)	28.86(3.09)(+)	28.68(2.69)(+)
	2	19.73(2.83)	**19.73(2.72)(=)**	19.86(2.89)(=)	19.91(2.84)(+)	21.50(3.65)(+)	21.24(3.61)(+)
	3	**26.28(6.84)**	26.36(6.88)(=)	26.37(6.96)(=)	26.48(6.68)(=)	27.62(7.04)(+)	26.82(6.97)(+)
Cologne1	1	**13.83(3.02)**	14.04(3.29)(=)	14.30(3.56)(+)	15.10(4.76)(+)	17.83(8.35)(+)	17.65(7.77)(+)
Cologne3	1	11.00(2.41)	**10.77(2.40)(=)**	11.12(2.81)(=)	10.95(2.49)(=)	11.65(2.62)(+)	11.71(3.09)(=)
Ingolstadt1	1	**13.41(5.95)**	13.47(5.96)(=)	13.71(5.82)(=)	14.44(6.44)(+)	16.46(8.72)(+)	14.64(6.59)(+)
Ingolstadt7	1	24.66(7.55)	**23.76(6.73)(−)**	24.37(6.98)(=)	23.90(6.51)(−)	24.87(7.26)(=)	24.95(7.06)(=)
W/T/L		NA	0/20/2	2/20/0	15/6/1	19/3/0	13/9/0
Number of best		8	10	3	0	1	0

TABLE S.XIII

INVESTIGATION RESULTS ON THE EFFECTS OF λ SETTING IN MSR

Scene name	Case	λ=1	λ=10	λ=100	λ=1000	λ=10000	p-value
Net-single1	2	2.03(0.53)	1.97(0.50)	2.03(0.52)	2.04(0.54)	1.99(0.51)	0.024
Net-single2	2	17.20(3.90)	17.30(3.95)	17.20(3.90)	17.42(3.91)	17.12(3.87)	0.693
Net-single3	2	11.38(1.49)	11.40(1.48)	11.46(1.56)	11.40(1.53)	11.39(1.53)	0.911
Net-double	2	9.86(1.76)	9.88(1.75)	9.84(1.73)	9.88(1.75)	9.85(1.79)	0.97
Net-2x2grid	2	37.32(9.31)	36.94(9.15)	37.11(9.15)	37.16(9.27)	37.19(9.27)	0.905
Net-3x3grid	2	19.76(2.78)	19.67(2.77)	19.64(2.76)	19.71(2.74)	19.70(2.79)	0.865
Cologne1	1	14.05(3.53)	13.92(3.33)	14.01(3.41)	13.91(3.30)	14.04(3.46)	0.973
Cologne3	1	10.37(2.12)	10.30(2.04)	10.27(2.02)	10.35(2.14)	10.38(2.13)	0.886
Ingolstadt1	1	13.15(5.78)	13.12(5.81)	13.14(5.74)	13.11(5.82)	13.13(5.91)	1
Ingolstadt7	1	22.95(6.33)	23.06(6.44)	22.95(6.28)	22.93(6.31)	22.93(6.25)	0.998

TABLE S.XIV

TRAVEL DELAY OF LMM-RL AND RL-BASED TRAFFIC SIGNAL CONTROLLERS ON SYNTHETIC SCENES WITH CASE 2AND REAL-WORLD SCENES WITH CASE 1

Scene name	Case	LMM-RL	IDQN	IPPO	MPLight	FMA2C
Net-single1	2	2.13(0.47)	**2.09(0.64)(=)**	2.13(0.52)(=)	3.19(0.54)(+)	5.06(1.06)(+)
Net-single2	2	13.77(5.16)	33.84(47.06)(+)	**0.04(0.05)(−)**	15.66(4.23)(+)	17.67(3.97)(+)
Net-single3	2	**7.91(1.38)**	45.50(76.25)(+)	10.46(1.19)(+)	9.89(1.04)(+)	11.93(1.51)(+)
Net-double	2	**7.23(1.11)**	7.68(1.34)(+)	8.49(1.04)(+)	8.77(1.11)(+)	14.11(1.28)(+)
Net-2x2grid	2	28.24(9.86)	**15.71(19.15)(−)**	42.91(8.89)(+)	31.84(8.05)(+)	35.25(6.67)(+)
Net-3x3grid	2	52.28(9.02)	10.90(1.56)(−)	**7.91(0.97)(−)**	27.01(3.43)(−)	15.13(1.01)(−)
Cologne1	1	**4.60(1.37)**	5.37(3.30)(+)	4.91(1.66)(+)	6.40(1.34)(+)	6.51(1.74)(+)
Cologne3	1	3.99(1.09)	10.21(15.18)(=)	**1.90(0.53)(−)**	5.52(6.78)(=)	7.48(1.29)(+)
Ingolstadt1	1	13.05(6.64)	12.85(7.03)(=)	**2.92(4.22)(−)**	4.18(8.41)(−)	19.55(8.29)(+)
Ingolstadt7	1	12.83(3.57)	15.03(14.45)(=)	25.18(6.72)(+)	**1.55(0.80)(−)**	27.14(5.95)(+)
W/T/L		NA	4/4/2	5/1/4	6/1/3	9/0/1
Number of best (↑)		3	2	4	1	0
Number of worst (↓)		1	3	1	0	5

TABLE S.XV

ARRIVAL RATE OF LMM-RL AND RL-BASED TRAFFIC SIGNAL CONTROLLERS ON SYNTHETIC SCENES WITH CASE 2AND REAL-WORLD SCENES WITH CASE 1

Scene name	Case	LMM-RL	IDQN	IPPO	MPLight	FMA2C
Net-single1	2	**1.00(0.00)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**
Net-single2	2	**1.00(0.00)**	0.21(0.07)(+)	0.19(0.06)(+)	0.99(0.01)(+)	**1.00(0.00)(=)**
Net-single3	2	**1.00(0.00)**	0.34(0.17)(+)	**1.00(0.00)(=)**	0.99(0.00)(+)	**1.00(0.00)(=)**
Net-double	2	**1.00(0.00)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**	**1.00(0.00)(=)**
Net-2x2grid	2	**1.00(0.00)**	0.12(0.04)(+)	0.49(0.10)(+)	**1.00(0.00)(=)**	**1.00(0.00)(=)**
Net-3x3grid	2	0.96(0.02)	0.97(0.05)(−)	**1.00(0.00)(−)**	0.99(0.00)(−)	**1.00(0.00)(−)**
Cologne1	1	**1.00(0.00)**	1.00(0.01)(=)	1.00(0.03)(=)	1.00(0.03)(+)	**1.00(0.00)(=)**
Cologne3	1	**0.93(0.10)**	0.43(0.07)(+)	0.77(0.04)(+)	0.25(0.03)(+)	**0.93(0.10)(=)**
Ingolstadt1	1	1.00(0.01)	**1.00(0.00)(=)**	0.60(0.08)(+)	0.61(0.10)(+)	1.00(0.01)(+)
Ingolstadt7	1	0.79(0.05)	0.31(0.03)(+)	0.98(0.03)(−)	0.32(0.04)(+)	**1.00(0.00)(−)**
W/T/L		NA	5/4/1	4/4/2	6/3/1	1/7/2
Number of best (↑)		7	3	4	3	9
Number of worst (↓)		1	3	3	2	0

TABLE S.XVI

TIME LOSS OF LMM-RL AND RL-BASED TRAFFIC SIGNAL CONTROLLERS ON SYNTHETIC SCENES WITH CASE 2AND REAL-WORLD SCENES WITH CASE 1

Scene name	Case	LMM-RL	IDQN	IPPO	MPLight	FMA2C
Net-single1	2	9.47(1.15)	9.23(1.51)(−)	**9.15(1.38)(−)**	10.83(1.13)(+)	12.56(1.52)(+)
Net-single2	2	24.09(6.62)	40.42(49.33)(=)	**4.32(0.18)(−)**	26.72(5.42)(+)	28.45(5.36)(+)
Net-single3	2	**21.37(1.91)**	57.61(78.28)(=)	24.33(1.49)(+)	23.73(1.29)(+)	25.55(1.85)(+)
Net-double	2	**16.70(1.52)**	17.16(1.78)(+)	18.09(1.39)(+)	18.57(1.48)(+)	23.88(1.49)(+)
Net-2x2grid	2	46.12(12.96)	**22.49(21.00)(−)**	58.03(10.21)(+)	50.27(10.16)(+)	52.46(8.77)(+)
Net-3x3grid	2	83.77(11.43)	28.76(2.63)(−)	**25.74(1.88)(−)**	50.83(5.54)(−)	33.18(1.76)(−)
Cologne1	1	**16.35(2.57)**	17.23(4.07)(+)	16.91(2.98)(+)	19.28(2.41)(+)	18.34(2.89)(+)
Cologne3	1	14.43(1.62)	18.08(16.55)(=)	**10.63(0.91)(−)**	13.26(7.34)(−)	18.45(1.85)(+)
Ingolstadt1	1	27.60(10.62)	26.95(10.81)(=)	**8.43(4.75)(−)**	9.87(9.56)(−)	33.93(11.36)(+)
Ingolstadt7	1	29.21(4.58)	25.81(14.85)(−)	49.69(9.52)(+)	**10.05(1.20)(−)**	51.31(8.29)(+)
W/T/L		NA	2/4/4	5/0/5	6/0/4	9/0/1
Number of best (↑)		3	1	5	1	0
Number of worst (↓)		1	2	0	2	5