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

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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.3. It can be seen that 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. Algorithm 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 in the literature. 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 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. For the use of the PSW technique, we need to maintain *PS*=20 parallel subprocesses. Hence, any computer with at least 20 CPU cores can meet the requirements of LMM.

C. Compared Algorithms

LMM should be first compared with other simulation-free TSTO methods. In this paper, the compared simulation-free TSTO methods are UniformSample, 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. To make the comparison fair, the hyperparameters of Max-pressure and SOTL are optimized and determined by a grid search on the validation set.

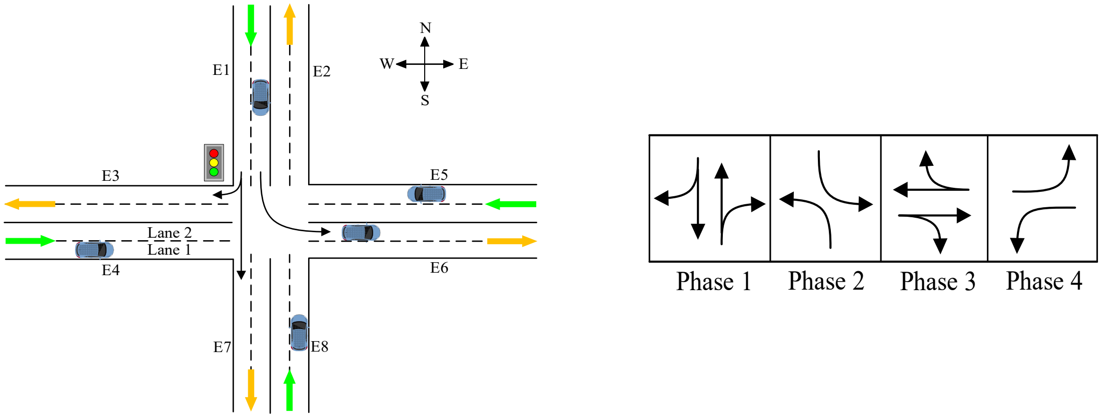
Moreover, to further verify the effectiveness of the LMM20 and LMM-PSO, we implement several state-of-the-art TSTO methods for comparison, including reinforcement learning (RL) algorithms and advanced PSO algorithms specially designed for TSTO. In particular, the RL algorithms include deep Q-networks (DQN) [S1] and proximal policy optimization (PPO) [S1] while advanced PSO algorithms include comprehensive learning PSO (CLPSO) [S2], MELPSO [S3], and REPSO [S4]. The configurations of DQN and PPO, including the state and reward design along with the hyperparameter settings, follow the traffic signal control benchmark in [S1]. The parameter settings of compared PSO algorithms are kept the same as specified in these papers.

[S1] J. Ault and G. Sharon, "Reinforcement learning benchmarks for traffic signal control," in *Proc. 35th Conf. Neural Inf. Process. Syst. Datasets Benchmarks Track (Round 1)*, 2021, pp. 1–11.

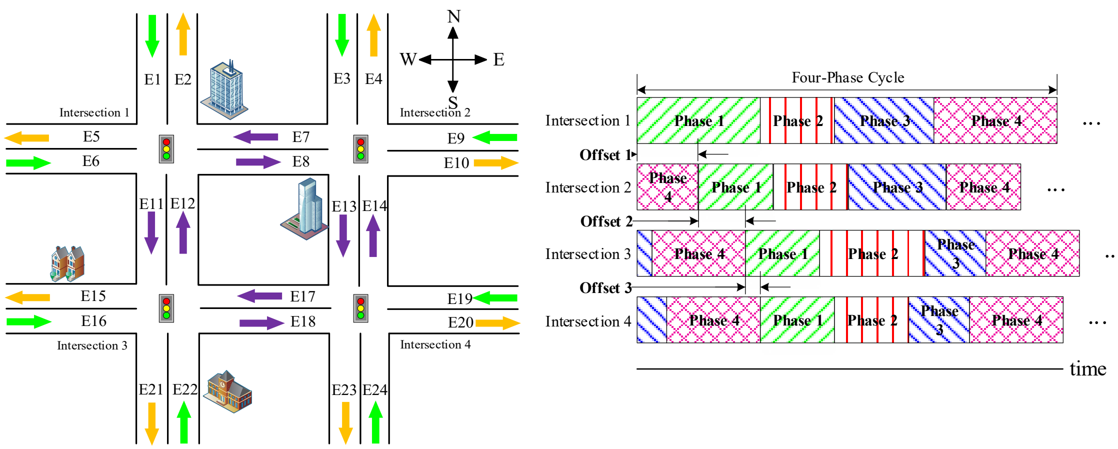
[S2] J. J. Liang, A. K. Qin, P. N. Suganthan, and S. Baskar, "Comprehensive learning particle swarm optimizer for global optimization of multimodal functions," *IEEE Trans. Evol. Comput.*, vol. 10, no. 3, pp. 281-295, June 2006.

[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.



(a) single-intersection scene (b) single-phase sequence



(c) multi-intersection scene (d) multiple phase sequences with offsets

Fig. S.1. Examples of single/multi-intersection scenes and their phase sequences.

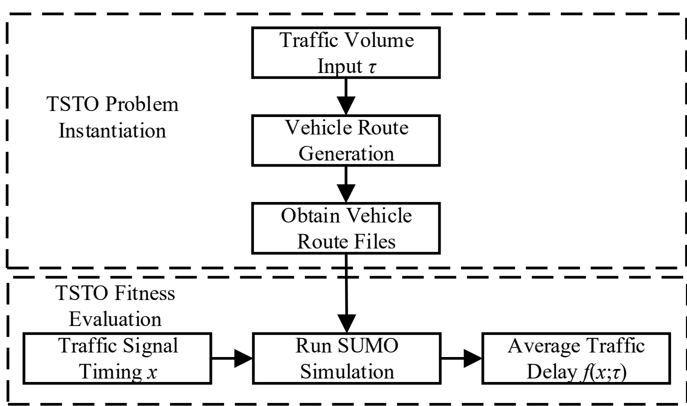
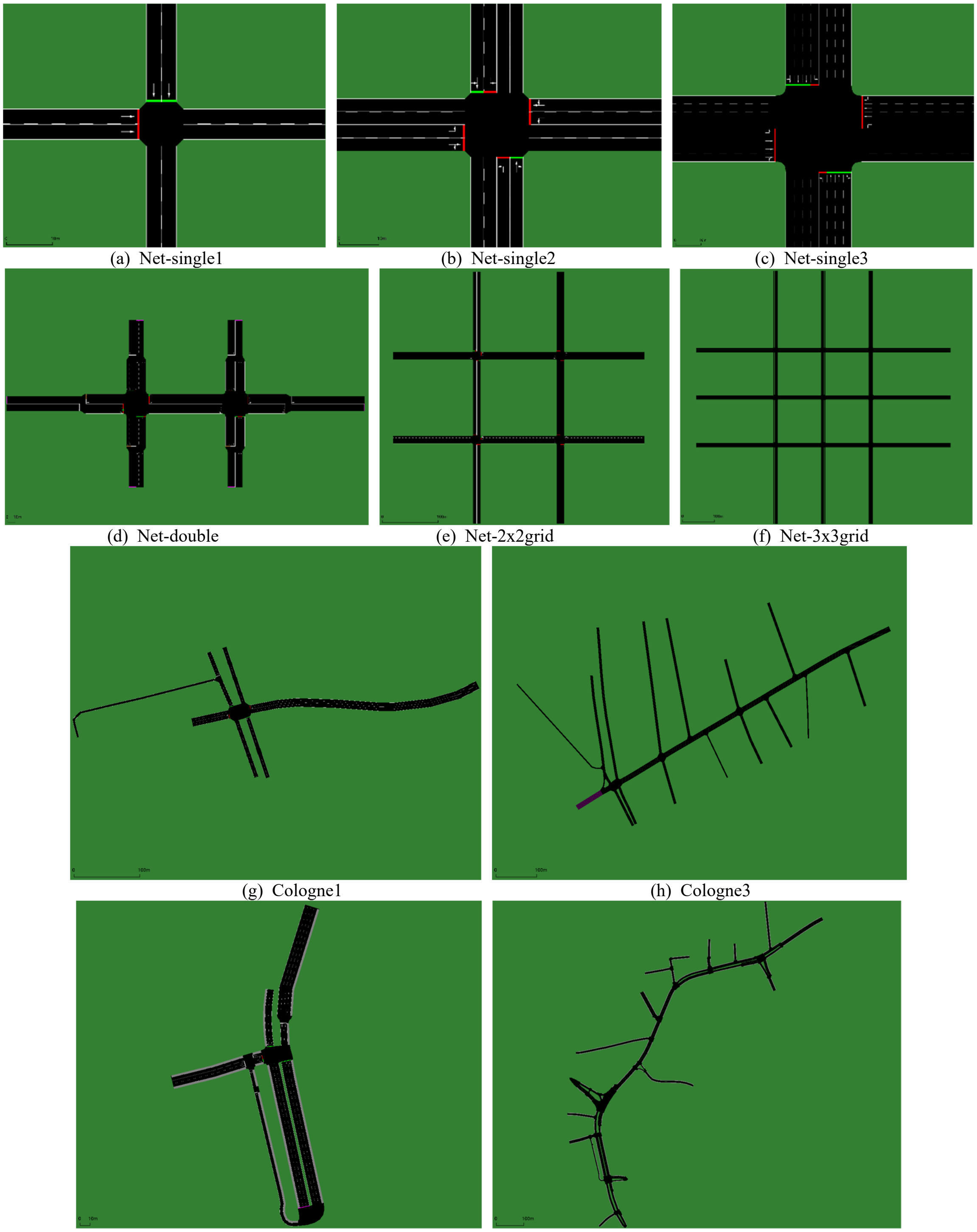


Fig. S.2. Problem instantiation and fitness evaluation.



(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.3. The geometry of the road network of 10 tested scenarios (a)-(j).

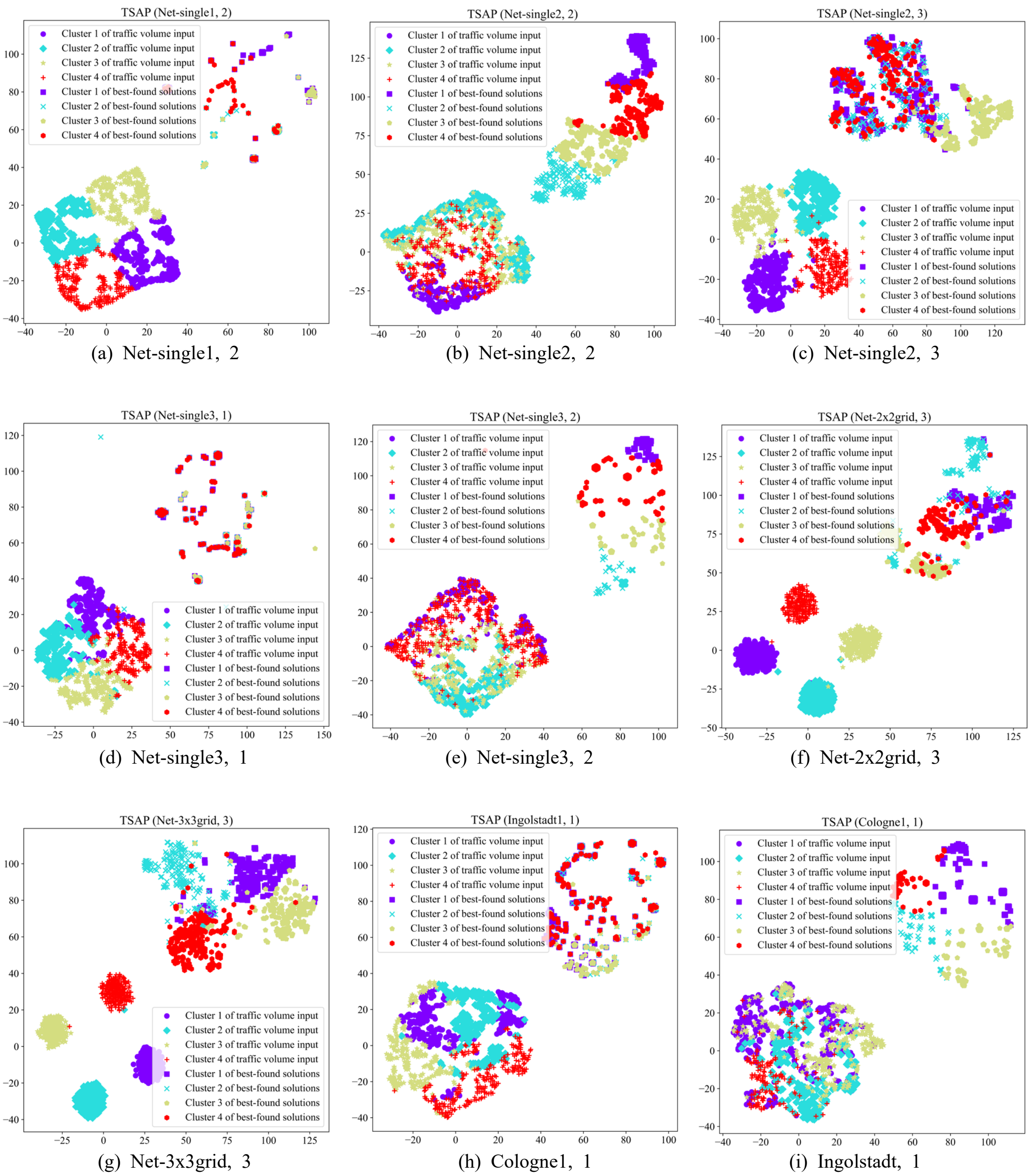
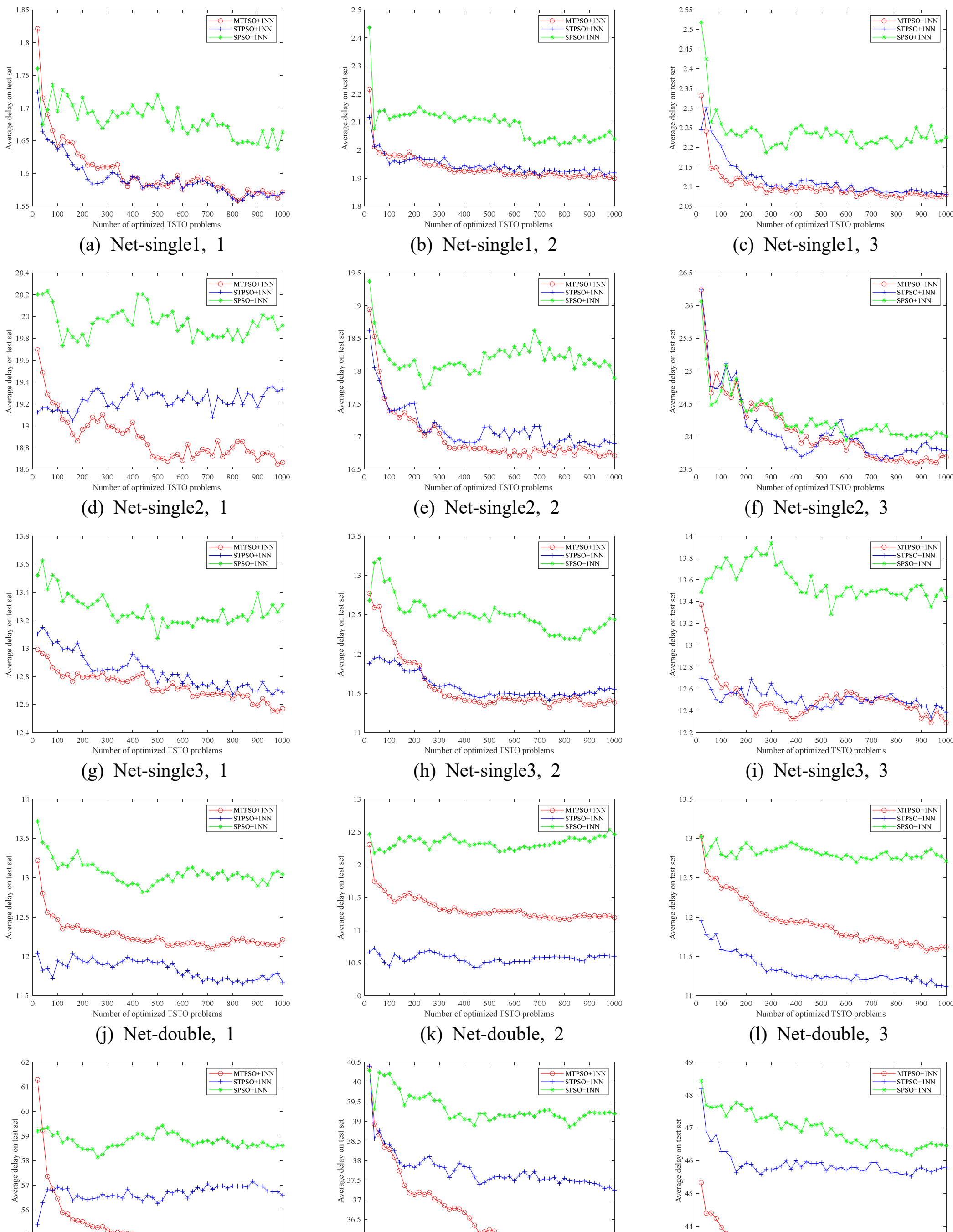


Fig. S.4. The two-dimensional visualization by t-SNE of the traffic volume inputs and their optimized signal plans after the DC stage on selected representative TSAPs (a)-(i).



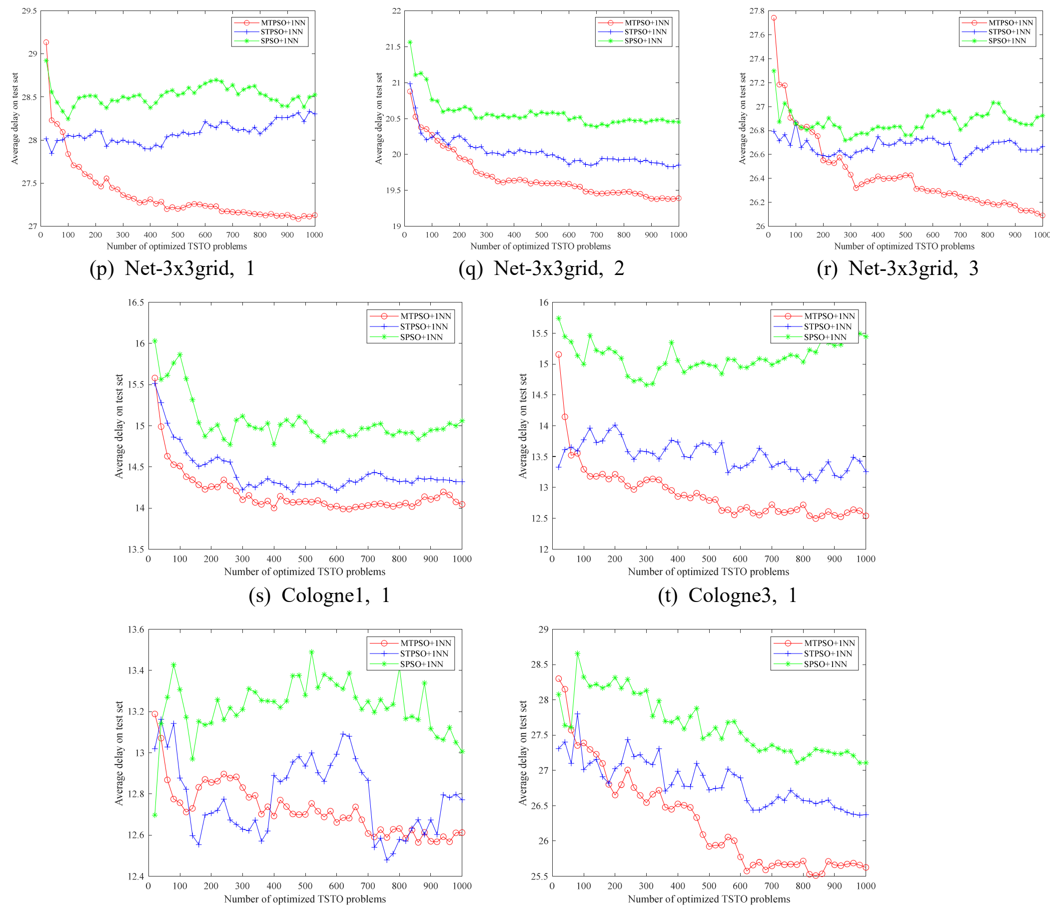
(a) Net-single1, 1 (b) Net-single1, 2 (c) Net-single1, 3

(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.5. 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	Single-intersection	2	2
Net-single2	Single-intersection	4	4
Net-single3	Single-intersection	4	4
Net-double	Two-intersection	6	10
Net-2x2grid	Four-intersection	8	20
Net-3x3grid	Nine-intersection	12	27
Cologne1	Single-intersection	5	4
Cologne3	Many-intersection	13	14
Ingolstadt1	Single-intersection	4	3
Ingolstadt7	Many-intersection	14	27

TABLE S.II

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

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

TABLE S.III
DETAILED COMPARATIVE RESULTS BETWEEN LMM AND DIFFERENT SIMULATION-FREE TSTO METHODS

Scene name	Case	LMM	UniformSample	Default30	Default60	Webster	Max-pressure	SOTL
Net-single1	1	**1.55(0.26)**	11.01(5.86)(+)	3.55(0.30)(+)	9.22(0.59)(+)	2.12(0.42)(+)	3.47(0.47)(+)	3.40(0.67)(+)
Net-single2	1	**18.66(2.57)**	70.20(11.93)(+)	87.11(6.78)(+)	50.96(10.89)(+)	20.29(3.42)(+)	56.18(16.06)(+)	120.62(7.35)(+)
Net-single3	1	**12.31(1.21)**	47.38(9.66)(+)	46.88(9.14)(+)	21.69(2.82)(+)	13.02(1.14)(+)	16.35(3.34)(+)	82.82(9.05)(+)
Net-double	1	**11.30(0.83)**	21.80(2.83)(+)	17.13(3.65)(+)	17.40(1.68)(+)	15.34(1.85)(+)	11.65(1.49)(+)	24.74(6.59)(+)
Net-2x2grid	1	**51.41(6.11)**	85.47(5.17)(+)	99.45(5.12)(+)	71.74(7.11)(+)	61.06(8.90)(+)	82.02(15.28)(+)	131.37(7.01)(+)
Net-3x3grid	1	25.81(2.76)	46.25(4.87)(+)	33.68(4.44)(+)	35.03(3.97)(+)	26.60(3.19)(+)	**18.65(2.13)(−)**	21.20(2.56)(−)
Net-single1	2	**1.91(0.47)**	8.40(4.35)(+)	3.19(0.44)(+)	7.91(1.01)(+)	2.63(0.61)(+)	4.23(1.78)(+)	5.88(4.00)(+)
Net-single2	2	**16.85(4.81)**	48.11(16.29)(+)	48.04(26.00)(+)	31.51(15.42)(+)	17.16(4.58)(+)	37.36(20.94)(+)	70.21(34.62)(+)
Net-single3	2	**11.45(1.87)**	33.76(9.48)(+)	24.02(14.27)(+)	17.99(2.74)(+)	11.52(1.71)(=)	12.10(3.17)(+)	40.20(24.22)(+)
Net-double	2	11.21(1.17)	18.27(4.00)(+)	12.77(4.39)(+)	16.12(2.07)(+)	11.97(2.43)(+)	**10.16(2.02)(−)**	20.04(5.46)(+)
Net-2x2grid	2	**35.60(8.31)**	60.73(13.35)(+)	62.68(18.99)(+)	51.18(12.22)(+)	37.59(9.92)(+)	69.09(17.30)(+)	89.06(23.94)(+)
Net-3x3grid	2	19.13(2.79)	30.36(6.87)(+)	22.28(4.07)(+)	24.57(3.65)(+)	18.62(2.45)(−)	**12.07(2.00)(−)**	15.64(1.40)(−)
Net-single1	3	**2.08(0.56)**	9.60(5.19)(+)	3.31(0.49)(+)	8.21(0.95)(+)	2.77(0.71)(+)	4.86(2.53)(+)	7.16(6.38)(+)
Net-single2	3	**23.66(7.20)**	54.01(14.86)(+)	57.93(22.03)(+)	36.32(14.69)(+)	24.30(7.41)(+)	66.29(26.83)(+)	86.46(28.76)(+)
Net-single3	3	**12.31(1.77)**	34.04(7.52)(+)	21.66(9.74)(+)	17.22(2.04)(+)	12.41(1.90)(=)	16.00(4.75)(+)	41.17(19.22)(+)
Net-double	3	**11.49(1.25)**	18.30(3.77)(+)	13.07(3.87)(+)	16.16(1.67)(+)	12.19(2.23)(+)	12.52(2.72)(+)	21.57(7.27)(+)
Net-2x2grid	3	**43.30(11.38)**	65.44(14.92)(+)	67.28(20.23)(+)	52.54(13.60)(+)	46.44(13.55)(+)	84.79(22.53)(+)	98.31(24.55)(+)
Net-3x3grid	3	25.91(6.52)	37.94(11.26)(+)	28.13(8.38)(+)	29.48(7.89)(+)	25.44(6.52)(−)	**17.63(5.24)(−)**	20.94(5.29)(−)
Cologne1	1	**14.04(4.08)**	54.66(10.39)(+)	47.92(14.43)(+)	38.28(14.59)(+)	31.60(14.90)(+)	38.28(14.59)(+)	38.28(14.59)(+)
Cologne3	1	**11.10(1.81)**	22.10(5.05)(+)	17.81(5.61)(+)	20.04(5.30)(+)	14.22(3.29)(+)	17.36(5.01)(+)	19.93(5.48)(+)
Ingolstadt1	1	**12.46(6.22)**	29.67(9.50)(+)	26.85(13.02)(+)	22.68(10.55)(+)	15.44(7.73)(+)	22.68(10.55)(+)	22.68(10.55)(+)
Ingolstadt7	1	**24.29(8.50)**	36.50(7.83)(+)	33.38(9.57)(+)	36.24(9.06)(+)	25.98(7.58)(+)	37.03(9.09)(+)	38.96(8.44)(+)
Number of best		19	0	0	0	0	3	0

TABLE S.IV

COMPARATIVE RESULTS BETWEEN THE PROPOSED LMM-BASED TSTO METHODS AND PSO WITH DIFFERENT *NFE*

Scene Name	Case	LMM-PSO	LMM	LMM20	PSO100	PSO250	PSO500	PSO1000
Net-single1	1	**1.52(0.25)**	1.55(0.26)(+)	1.52(0.25)(=)	1.70(0.26)(+)	1.63(0.27)(+)	1.63(0.27)(+)	1.63(0.27)(+)
Net-single2	1	**16.56(2.17)**	18.66(2.57)(+)	16.96(2.31)(+)	21.28(2.30)(+)	17.87(2.21)(+)	17.41(2.20)(+)	17.32(2.19)(+)
Net-single3	1	**11.50(0.93)**	12.31(1.21)(+)	11.64(1.00)(+)	14.16(1.00)(+)	11.93(0.88)(+)	11.80(0.88)(+)	11.79(0.88)(+)
Net-double	1	**10.09(0.59)**	11.30(0.83)(+)	10.95(0.64)(+)	13.04(0.69)(+)	12.00(0.57)(+)	11.46(0.57)(+)	11.10(0.56)(+)
Net-2x2grid	1	**48.75(5.75)**	51.41(6.11)(+)	50.28(6.07)(+)	60.75(6.06)(+)	54.43(6.10)(+)	51.45(5.92)(+)	49.11(5.84)(=)
Net-3x3grid	1	**24.82(2.39)**	25.81(2.76)(+)	25.10(2.51)(+)	29.47(3.03)(+)	27.07(2.54)(+)	26.14(2.37)(+)	25.41(2.29)(+)
Net-single1	2	**1.81(0.46)**	1.91(0.47)(+)	1.82(0.46)(=)	2.10(0.49)(+)	1.94(0.45)(+)	1.93(0.45)(+)	1.93(0.45)(+)
Net-single2	2	**14.08(3.34)**	16.85(4.81)(+)	14.68(3.55)(+)	17.94(3.70)(+)	15.44(3.23)(+)	15.04(3.22)(+)	14.95(3.21)(+)
Net-single3	2	**10.13(1.43)**	11.45(1.87)(+)	10.25(1.47)(+)	13.02(1.02)(+)	11.08(1.00)(+)	10.87(1.08)(+)	10.83(1.11)(+)
Net-double	2	**9.23(1.00)**	11.21(1.17)(+)	10.14(0.99)(+)	11.93(1.14)(+)	11.10(1.03)(+)	10.63(0.98)(+)	10.29(0.96)(+)
Net-2x2grid	2	**32.21(7.14)**	35.60(8.31)(+)	33.17(7.45)(+)	40.27(9.95)(+)	36.13(8.28)(+)	34.14(7.49)(+)	32.58(7.12)(+)
Net-3x3grid	2	**17.85(2.37)**	19.13(2.79)(+)	18.12(2.50)(+)	19.95(2.98)(+)	18.97(2.51)(+)	18.51(2.38)(+)	18.00(2.30)(+)
Net-single1	3	**1.95(0.54)**	2.08(0.56)(+)	1.96(0.54)(=)	2.23(0.53)(+)	2.06(0.51)(+)	2.05(0.51)(+)	2.05(0.51)(+)
Net-single2	3	**19.48(5.23)**	23.66(7.20)(+)	20.90(5.74)(+)	22.67(4.92)(+)	20.67(4.81)(+)	20.26(4.86)(+)	20.18(4.88)(+)
Net-single3	3	**10.94(1.45)**	12.31(1.77)(+)	11.15(1.58)(+)	14.06(1.15)(+)	11.96(1.22)(+)	11.63(1.23)(+)	11.56(1.25)(+)
Net-double	3	**9.60(0.99)**	11.49(1.25)(+)	10.54(0.94)(+)	12.21(1.00)(+)	11.43(0.92)(+)	11.00(0.88)(+)	10.69(0.85)(+)
Net-2x2grid	3	40.11(10.86)	43.30(11.38)(+)	40.51(10.93)(+)	45.40(11.92)(+)	42.05(10.93)(+)	40.30(10.43)(=)	**38.77(10.15)(−)**
Net-3x3grid	3	23.84(5.80)	25.91(6.52)(+)	24.53(6.06)(+)	25.92(6.93)(+)	24.64(6.17)(+)	24.10(5.90)(+)	**23.54(5.75)(−)**
Cologne1	1	**12.01(2.98)**	14.04(4.08)(+)	12.35(3.15)(+)	17.58(4.58)(+)	13.49(3.32)(+)	12.99(3.07)(+)	12.93(3.04)(+)
Cologne3	1	**8.02(0.94)**	11.10(1.81)(+)	9.64(1.32)(+)	11.13(1.53)(+)	10.21(1.32)(+)	9.64(1.22)(+)	9.14(1.15)(+)
Ingolstadt1	1	**9.86(5.15)**	12.46(6.22)(+)	10.30(5.35)(+)	11.58(5.58)(+)	10.47(5.24)(+)	10.28(5.16)(+)	10.24(5.14)(+)
Ingolstadt7	1	**20.25(4.88)**	24.29(8.50)(+)	21.61(6.24)(+)	24.37(5.89)(+)	22.74(5.50)(+)	21.89(5.23)(+)	21.12(5.05)(+)

TABLE S.V

COMPARATIVE RESULTS BETWEEN THE LMM20 AND STATE-OF-THE-ART SIMULATION-FREE TSTO METHODS

Scene Name	Case	LMM20	DQN	PPO	Webster	Max-pressure	SOTL
Net-single1	1	**1.52(0.25)**	2.90(0.66)(+)	15.59(10.90)(+)	15.25(7.36)(+)	3.47(0.47)(+)	3.40(0.67)(+)
Net-single2	1	**16.96(2.31)**	25.99(11.37)(+)	75.92(15.87)(+)	118.97(7.74)(+)	56.18(16.06)(+)	120.62(7.35)(+)
Net-single3	1	**11.64(1.00)**	41.21(25.05)(+)	44.89(14.13)(+)	86.76(8.94)(+)	16.35(3.34)(+)	82.82(9.05)(+)
Net-double	1	**10.95(0.64)**	15.40(5.70)(+)	29.58(5.40)(+)	35.79(8.10)(+)	11.65(1.49)(+)	24.74(6.59)(+)
Net-2x2grid	1	**50.28(6.07)**	61.57(34.23)(+)	53.34(10.54)(+)	131.42(5.80)(+)	82.02(15.28)(+)	131.37(7.01)(+)
Net-3x3grid	1	25.10(2.51)	**11.19(1.40)(−)**	30.96(3.16)(+)	40.42(4.87)(+)	18.65(2.13)(−)	21.20(2.56)(−)
Net-single1	2	**1.82(0.46)**	3.00(0.96)(+)	10.78(6.05)(+)	9.75(7.26)(+)	4.23(1.78)(+)	5.88(4.00)(+)
Net-single2	2	**14.68(3.55)**	19.39(10.27)(+)	53.67(22.37)(+)	71.55(31.93)(+)	37.36(20.94)(+)	70.21(34.62)(+)
Net-single3	2	**10.25(1.47)**	53.48(26.90)(+)	33.66(10.29)(+)	43.71(25.43)(+)	12.10(3.17)(+)	40.20(24.22)(+)
Net-double	2	**10.14(0.99)**	13.42(7.34)(+)	25.33(6.14)(+)	24.61(10.59)(+)	10.16(2.02)(=)	20.04(5.46)(+)
Net-2x2grid	2	**33.17(7.45)**	54.31(38.18)(+)	49.82(11.56)(+)	89.60(23.17)(+)	69.09(17.30)(+)	89.06(23.94)(+)
Net-3x3grid	2	18.12(2.50)	**7.93(1.07)(−)**	25.51(3.77)(+)	25.04(7.74)(+)	12.07(2.00)(−)	15.64(1.40)(−)
Net-single1	3	**1.96(0.54)**	3.37(1.06)(+)	10.98(5.83)(+)	13.04(8.96)(+)	4.86(2.53)(+)	7.16(6.38)(+)
Net-single2	3	**20.90(5.74)**	32.82(19.72)(+)	61.08(16.52)(+)	86.28(27.01)(+)	66.29(26.83)(+)	86.46(28.76)(+)
Net-single3	3	**11.15(1.58)**	46.44(25.40)(+)	34.64(11.24)(+)	43.15(19.19)(+)	16.00(4.75)(+)	41.17(19.22)(+)
Net-double	3	**10.54(0.94)**	17.15(11.31)(+)	25.80(5.85)(+)	24.98(9.62)(+)	12.52(2.72)(+)	21.57(7.27)(+)
Net-2x2grid	3	**40.51(10.93)**	60.24(41.77)(+)	49.17(11.95)(+)	98.15(23.35)(+)	84.79(22.53)(+)	98.31(24.55)(+)
Net-3x3grid	3	24.53(6.06)	**10.05(2.37)(−)**	29.18(5.96)(+)	30.63(10.13)(+)	17.63(5.24)(−)	20.94(5.29)(−)
Cologne1	1	12.35(3.15)	**4.80(1.46)(−)**	38.82(12.40)(+)	38.28(14.59)(+)	38.28(14.59)(+)	38.28(14.59)(+)
Cologne3	1	9.64(1.32)	**4.92(1.08)(−)**	12.29(3.18)(+)	28.29(7.90)(+)	17.36(5.01)(+)	19.93(5.48)(+)
Ingolstadt1	1	**10.30(5.35)**	12.92(8.37)(+)	28.43(12.93)(+)	22.68(10.55)(+)	22.68(10.55)(+)	22.68(10.55)(+)
Ingolstadt7	1	**21.61(6.24)**	22.03(7.00)(=)	34.38(6.84)(+)	41.78(8.49)(+)	37.03(9.09)(+)	38.96(8.44)(+)

TABLE S.VI

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

Scene Name	Case	LMM-PSO	DQN	PPO	CLPSO	MELPSO	REPSO
Net-single1	1	**1.52(0.25)**	2.90(0.66)(+)	15.59(10.90)(+)	1.64(0.25)(+)	1.56(0.20)(+)	2.08(0.32)(+)
Net-single2	1	**16.56(2.17)**	25.99(11.37)(+)	75.92(15.87)(+)	18.31(2.32)(+)	16.64(2.21)(+)	23.29(2.17)(+)
Net-single3	1	**11.50(0.93)**	41.21(25.05)(+)	44.89(14.13)(+)	12.73(0.97)(+)	11.63(0.92)(+)	17.14(1.00)(+)
Net-double	1	10.09(0.59)	15.40(5.70)(+)	29.58(5.40)(+)	12.17(0.61)(+)	**9.93(0.63)(−)**	14.12(0.84)(+)
Net-2x2grid	1	**48.75(5.75)**	61.57(34.23)(+)	53.34(10.54)(+)	58.51(5.48)(+)	50.65(5.82)(+)	63.82(6.44)(+)
Net-3x3grid	1	24.82(2.39)	**11.19(1.40)(−)**	30.96(3.16)(+)	28.19(2.78)(+)	25.59(2.42)(+)	31.09(3.51)(+)
Net-single1	2	**1.81(0.46)**	3.00(0.96)(+)	10.78(6.05)(+)	2.00(0.50)(+)	1.81(0.46)(=)	2.40(0.47)(+)
Net-single2	2	**14.08(3.34)**	19.39(10.27)(+)	53.67(22.37)(+)	16.10(3.27)(+)	14.13(3.38)(+)	19.67(3.99)(+)
Net-single3	2	**10.13(1.43)**	53.48(26.90)(+)	33.66(10.29)(+)	11.75(1.18)(+)	10.20(1.43)(+)	15.46(1.61)(+)
Net-double	2	9.23(1.00)	13.42(7.34)(+)	25.33(6.14)(+)	11.01(1.13)(+)	**8.80(1.17)(−)**	12.55(1.35)(+)
Net-2x2grid	2	**32.21(7.14)**	54.31(38.18)(+)	49.82(11.56)(+)	38.87(8.95)(+)	32.97(7.96)(+)	41.90(11.75)(+)
Net-3x3grid	2	17.85(2.37)	**7.93(1.07)(−)**	25.51(3.77)(+)	19.36(2.75)(+)	17.76(2.52)(−)	20.55(3.62)(+)
Net-single1	3	**1.95(0.54)**	3.37(1.06)(+)	10.98(5.83)(+)	2.15(0.55)(+)	1.95(0.54)(=)	2.56(0.50)(+)
Net-single2	3	**19.48(5.23)**	32.82(19.72)(+)	61.08(16.52)(+)	21.38(5.05)(+)	19.46(5.19)(=)	24.01(4.88)(+)
Net-single3	3	**10.94(1.45)**	46.44(25.40)(+)	34.64(11.24)(+)	12.77(1.40)(+)	10.99(1.42)(+)	16.02(1.41)(+)
Net-double	3	9.60(0.99)	17.15(11.31)(+)	25.80(5.85)(+)	11.54(1.03)(+)	**9.40(1.10)(−)**	12.72(1.09)(+)
Net-2x2grid	3	**40.11(10.86)**	60.24(41.77)(+)	49.17(11.95)(+)	45.30(11.47)(+)	39.87(10.89)(=)	45.47(13.31)(+)
Net-3x3grid	3	23.84(5.80)	**10.05(2.37)(−)**	29.18(5.96)(+)	25.63(6.71)(+)	23.80(6.08)(=)	26.34(7.65)(+)
Cologne1	1	12.01(2.98)	**4.80(1.46)(−)**	38.82(12.40)(+)	14.21(3.21)(+)	11.91(2.67)(=)	19.73(5.09)(+)
Cologne3	1	8.02(0.94)	**4.92(1.08)(−)**	12.29(3.18)(+)	9.88(1.27)(+)	8.16(1.10)(+)	11.50(1.69)(+)
Ingolstadt1	1	**9.86(5.15)**	12.92(8.37)(+)	28.43(12.93)(+)	10.56(5.27)(+)	9.79(5.12)(=)	13.32(6.14)(+)
Ingolstadt7	1	**20.25(4.88)**	22.03(7.00)(+)	34.38(6.84)(+)	22.81(5.14)(+)	20.01(4.45)(=)	24.18(5.23)(+)

TABLE S.VII
INVESTIGATION RESULTS ON THE USE OF DIFFERENT MACHINE LEARNING MODELS

Scene Name	Case	1NN	RS	GS	LR	NN	DT	RF
Net-single1	1	**1.56(0.27)**	2.00(0.42)(+)	2.51(0.53)(+)	2.02(0.31)(+)	1.97(0.35)(+)	1.57(0.27)(=)	1.83(0.29)(+)
Net-single2	1	**18.69(2.89)**	20.16(3.24)(+)	20.92(3.54)(+)	18.92(2.70)(=)	18.90(2.84)(=)	18.82(2.77)(=)	19.13(3.15)(+)
Net-single3	1	**12.59(1.22)**	12.96(1.09)(+)	13.49(1.17)(+)	12.85(1.14)(+)	12.78(1.19)(+)	12.71(1.29)(=)	12.76(1.29)(+)
Net-double	1	12.23(1.03)	12.46(0.71)(+)	12.44(0.77)(+)	12.26(0.93)(=)	**11.94(1.10)(−)**	12.31(0.97)(=)	12.36(1.02)(=)
Net-2x2grid	1	**54.25(6.77)**	55.02(6.61)(+)	59.24(6.60)(+)	58.01(6.68)(+)	56.69(5.73)(+)	54.84(6.68)(+)	56.69(6.66)(+)
Net-3x3grid	1	**27.13(2.79)**	27.20(2.73)(=)	28.47(2.88)(+)	28.28(2.90)(+)	27.86(2.63)(+)	27.19(3.02)(=)	28.62(2.76)(+)
Net-single1	2	**1.91(0.48)**	5.57(4.37)(+)	4.47(2.79)(+)	2.26(0.51)(+)	2.26(0.51)(+)	1.93(0.48)(=)	2.09(0.52)(+)
Net-single2	2	**16.78(4.18)**	22.06(6.09)(+)	25.69(9.27)(+)	17.22(4.17)(=)	17.23(4.17)(=)	16.81(4.34)(=)	17.15(4.56)(=)
Net-single3	2	**11.40(1.77)**	13.94(3.28)(+)	14.76(3.77)(+)	11.47(1.88)(=)	11.50(1.84)(=)	11.69(1.78)(+)	11.31(1.60)(=)
Net-double	2	**11.21(1.17)**	12.20(1.42)(+)	12.08(1.68)(+)	11.49(1.32)(+)	11.45(1.26)(=)	11.29(1.17)(=)	11.42(1.26)(=)
Net-2x2grid	2	**36.01(8.82)**	39.66(9.55)(+)	44.70(10.33)(+)	37.99(9.12)(+)	38.09(9.21)(+)	36.80(9.38)(+)	38.54(9.49)(+)
Net-3x3grid	2	**19.39(2.88)**	20.74(3.12)(+)	21.41(3.35)(+)	20.43(2.64)(+)	20.16(3.00)(+)	19.71(3.04)(+)	20.49(3.05)(+)
Net-single1	3	**2.08(0.56)**	6.73(4.99)(+)	5.40(3.13)(+)	2.30(0.63)(+)	2.31(0.66)(+)	2.07(0.56)(=)	2.25(0.61)(+)
Net-single2	3	**23.66(7.20)**	34.29(9.34)(+)	38.12(10.35)(+)	24.02(7.58)(=)	24.03(7.61)(=)	24.28(6.96)(=)	23.34(6.39)(=)
Net-single3	3	**12.31(1.77)**	15.16(3.05)(+)	15.76(3.61)(+)	12.13(1.86)(=)	12.43(2.10)(=)	12.39(2.15)(=)	12.08(1.74)(=)
Net-double	3	**11.65(1.30)**	12.36(1.27)(+)	12.52(1.53)(+)	12.11(1.36)(+)	11.76(1.47)(=)	11.76(1.30)(=)	12.14(1.47)(+)
Net-2x2grid	3	**43.21(11.42)**	45.41(11.53)(+)	50.71(12.08)(+)	45.78(11.88)(+)	45.58(11.73)(+)	43.46(11.55)(=)	44.79(12.16)(+)
Net-3x3grid	3	**26.09(6.42)**	27.39(7.00)(+)	27.99(7.16)(+)	26.50(6.52)(+)	26.40(6.40)(+)	26.34(6.82)(=)	26.71(6.38)(+)
Cologne1	1	14.04(4.08)	19.37(6.77)(+)	19.21(6.79)(+)	**13.68(3.83)(−)**	13.81(3.68)(=)	14.25(4.27)(=)	14.06(4.18)(=)
Cologne3	1	**12.56(4.22)**	12.90(2.27)(+)	12.57(2.10)(+)	12.42(2.98)(=)	12.04(3.01)(=)	12.95(4.32)(=)	12.03(2.93)(=)
Ingolstadt1	1	**12.58(6.30)**	15.28(7.53)(+)	15.87(7.47)(+)	12.76(6.27)(=)	12.76(6.16)(=)	12.49(6.17)(=)	12.53(6.29)(=)
Ingolstadt7	1	**25.61(7.64)**	26.64(7.61)(+)	27.99(8.05)(+)	26.76(8.56)(+)	26.73(7.98)(+)	26.03(7.94)(=)	26.67(8.18)(+)

TABLE S.VIII
INVESTIGATION RESULTS ON THE EFFECTS OF K-SETTING

Scene Name	Case	1NN	5NN	10NN	15NN	20NN	25NN	30NN
Net-single1	1	**1.56(0.27)**	1.84(0.36)(+)	1.82(0.29)(+)	1.81(0.28)(+)	1.82(0.27)(+)	1.85(0.29)(+)	1.85(0.32)(+)
Net-single2	1	**18.69(2.89)**	18.58(2.68)(=)	18.59(2.73)(=)	18.62(2.79)(=)	18.65(2.76)(=)	18.71(2.82)(=)	18.75(2.79)(=)
Net-single3	1	**12.59(1.22)**	12.91(1.14)(+)	12.83(1.12)(+)	12.76(1.15)(+)	12.82(1.14)(+)	12.74(1.16)(+)	12.76(1.16)(+)
Net-double	1	**12.23(1.03)**	12.44(0.93)(+)	12.42(0.97)(=)	12.43(1.05)(+)	12.42(1.00)(=)	12.40(1.00)(=)	12.42(0.96)(=)
Net-2x2grid	1	**54.25(6.77)**	55.84(6.92)(+)	56.02(6.68)(+)	56.04(6.93)(+)	56.37(6.97)(+)	56.33(6.78)(+)	56.59(6.88)(+)
Net-3x3grid	1	**27.13(2.79)**	28.19(2.91)(+)	28.46(2.86)(+)	28.49(2.90)(+)	28.54(2.71)(+)	28.55(2.76)(+)	28.56(2.84)(+)
Net-single1	2	**1.91(0.48)**	2.10(0.56)(+)	2.09(0.53)(+)	2.10(0.50)(+)	2.06(0.54)(+)	2.09(0.53)(+)	2.11(0.50)(+)
Net-single2	2	**16.78(4.18)**	16.86(4.57)(=)	16.73(4.38)(=)	16.71(4.46)(=)	16.90(4.29)(=)	16.90(4.59)(=)	16.89(4.66)(=)
Net-single3	2	**11.40(1.77)**	11.28(1.75)(=)	11.29(1.64)(=)	11.32(1.71)(=)	11.30(1.66)(=)	11.27(1.60)(=)	11.26(1.65)(=)
Net-double	2	**11.21(1.17)**	11.51(1.24)(+)	11.30(1.26)(=)	11.25(1.24)(=)	11.40(1.35)(=)	11.48(1.31)(+)	11.39(1.34)(=)
Net-2x2grid	2	**36.01(8.82)**	37.48(8.87)(+)	38.07(9.00)(+)	38.20(9.43)(+)	38.30(9.33)(+)	38.43(9.68)(+)	38.42(9.49)(+)
Net-3x3grid	2	**19.39(2.88)**	20.32(2.80)(+)	20.35(2.87)(+)	20.38(2.84)(+)	20.43(2.73)(+)	20.52(2.84)(+)	20.42(2.84)(+)
Net-single1	3	**2.08(0.56)**	2.19(0.61)(+)	2.23(0.65)(+)	2.24(0.65)(+)	2.26(0.67)(+)	2.25(0.66)(+)	2.26(0.66)(+)
Net-single2	3	**23.66(7.20)**	23.12(6.39)(=)	23.24(6.61)(=)	23.37(6.43)(=)	23.21(6.53)(=)	23.12(6.61)(=)	23.31(6.57)(=)
Net-single3	3	12.31(1.77)	12.24(1.92)(=)	**11.97(1.76)(−)**	12.10(1.67)(=)	12.20(1.71)(=)	12.19(1.76)(=)	12.18(1.68)(=)
Net-double	3	**11.65(1.30)**	11.99(1.47)(+)	11.96(1.50)(+)	12.00(1.49)(+)	12.05(1.54)(+)	12.02(1.58)(+)	12.06(1.58)(+)
Net-2x2grid	3	**43.21(11.42)**	44.24(11.50)(+)	44.21(11.76)(+)	44.65(11.66)(+)	44.90(11.94)(+)	45.12(12.01)(+)	45.03(11.93)(+)
Net-3x3grid	3	**26.09(6.42)**	26.75(6.54)(+)	26.98(6.78)(+)	27.00(6.87)(+)	26.94(6.55)(+)	26.90(6.59)(+)	26.88(6.67)(+)
Cologne1	1	**14.04(4.08)**	13.99(3.84)(=)	13.97(4.12)(=)	13.96(4.03)(=)	13.81(4.06)(=)	13.84(4.15)(=)	14.06(4.09)(=)
Cologne3	1	**12.56(4.22)**	12.57(3.24)(=)	12.38(2.75)(=)	12.22(3.09)(=)	11.99(2.47)(=)	12.06(2.48)(=)	12.48(3.13)(=)
Ingolstadt1	1	**12.58(6.30)**	12.44(6.05)(=)	12.44(6.15)(=)	12.33(6.23)(=)	12.47(6.30)(=)	12.67(6.34)(=)	12.49(6.23)(=)
Ingolstadt7	1	**25.61(7.64)**	26.92(8.49)(+)	26.71(8.53)(+)	26.95(8.17)(+)	27.02(8.59)(+)	26.72(8.15)(+)	26.79(8.68)(+)

TABLE S.IX
INVESTIGATION RESULTS ON THE EFFECTS OF DISTANCE METRIC

Scene Name	Case	L1	L2	L∞	PCC	PCA-D1	PCA-D2
Net-single1	1	**1.56(0.27)**	1.57(0.28)(=)	1.57(0.28)(=)	2.05(0.56)(+)	1.81(0.62)(+)	1.55(0.27)(=)
Net-single2	1	**18.69(2.89)**	18.61(3.03)(=)	18.68(3.05)(=)	20.24(3.86)(+)	20.23(3.75)(+)	19.59(3.69)(+)
Net-single3	1	**12.59(1.22)**	12.60(1.14)(=)	12.58(1.19)(=)	12.92(1.36)(+)	12.95(1.27)(+)	12.76(1.43)(=)
Net-double	1	**12.23(1.03)**	12.19(1.09)(=)	12.17(1.20)(=)	12.25(0.88)(=)	12.23(1.02)(=)	12.43(1.05)(=)
Net-2x2grid	1	**54.25(6.77)**	54.51(6.96)(=)	54.34(7.01)(=)	54.46(6.65)(=)	54.88(6.60)(+)	54.73(6.51)(=)
Net-3x3grid	1	**27.13(2.79)**	26.96(2.88)(=)	26.97(2.81)(=)	27.03(2.78)(=)	27.28(2.80)(=)	27.02(2.79)(=)
Net-single1	2	1.91(0.48)	**1.89(0.47)(−)**	1.89(0.48)(=)	3.21(1.47)(+)	5.29(9.38)(+)	**1.89(0.48)(−)**
Net-single2	2	**16.78(4.18)**	16.72(4.23)(=)	16.69(4.19)(=)	19.69(6.77)(+)	22.17(13.17)(+)	18.08(5.41)(+)
Net-single3	2	**11.40(1.77)**	11.31(1.75)(=)	11.29(1.75)(=)	12.62(2.87)(+)	13.15(4.22)(+)	11.58(1.84)(=)
Net-double	2	**11.21(1.17)**	11.20(1.15)(=)	11.28(1.31)(=)	11.58(1.26)(+)	12.34(2.16)(+)	11.23(1.44)(=)
Net-2x2grid	2	**36.01(8.82)**	36.23(9.02)(=)	36.29(8.72)(=)	36.46(8.76)(+)	39.51(10.20)(+)	38.17(9.44)(+)
Net-3x3grid	2	**19.39(2.88)**	19.38(2.70)(=)	19.29(2.77)(=)	19.49(2.71)(=)	20.54(3.24)(+)	20.33(3.36)(+)
Net-single1	3	**2.08(0.56)**	2.09(0.55)(=)	2.08(0.54)(=)	4.05(2.90)(+)	6.60(11.54)(+)	2.09(0.56)(=)
Net-single2	3	**23.66(7.20)**	23.66(7.02)(=)	23.83(7.16)(=)	29.80(13.77)(+)	32.40(14.71)(+)	26.12(8.72)(+)
Net-single3	3	**12.31(1.77)**	12.28(1.84)(=)	12.26(1.81)(=)	13.55(4.24)(+)	14.05(4.41)(+)	12.52(1.83)(=)
Net-double	3	**11.65(1.30)**	11.67(1.29)(=)	11.68(1.22)(=)	11.76(1.19)(=)	11.95(1.47)(+)	11.67(1.27)(=)
Net-2x2grid	3	**43.21(11.42)**	43.29(11.41)(=)	43.58(11.90)(=)	43.89(11.44)(+)	44.34(11.65)(+)	43.78(11.44)(+)
Net-3x3grid	3	**26.09(6.42)**	26.09(6.41)(=)	26.08(6.41)(=)	26.30(6.32)(=)	27.21(7.83)(+)	26.42(6.48)(+)
Cologne1	1	**14.04(4.08)**	14.11(4.23)(=)	14.29(4.53)(=)	15.37(7.59)(+)	18.09(9.34)(+)	16.98(7.48)(+)
Cologne3	1	**12.56(4.22)**	12.35(3.68)(=)	12.49(3.70)(=)	12.44(3.08)(=)	12.67(3.00)(=)	12.45(2.52)(=)
Ingolstadt1	1	12.58(6.30)	**12.33(6.20)(−)**	12.47(6.44)(=)	13.19(6.96)(=)	13.72(6.87)(+)	13.23(6.62)(+)
Ingolstadt7	1	**25.61(7.64)**	26.01(7.94)(+)	26.13(8.50)(=)	25.77(7.87)(=)	26.55(7.77)(+)	26.62(8.26)(+)

TABLE S.X

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

Scene Name	Case	LMM-φ0	STPSO1+1NN	SPSO+1NN
Net-single1	1	**1.56(0.27)(=)**	1.56(0.27)(=)	1.67(0.33)(+)
Net-single2	1	**18.69(2.89)(=)**	19.33(3.13)(+)	19.86(3.13)(+)
Net-single3	1	**12.59(1.22)(+)**	12.66(1.31)(+)	13.35(1.84)(+)
Net-double	1	**12.23(1.03)(+)**	11.68(1.12)(+)	13.03(1.41)(+)
Net-2x2grid	1	**54.25(6.77)(+)**	56.69(6.67)(+)	58.69(7.26)(+)
Net-3x3grid	1	**27.13(2.79)(+)**	28.31(3.10)(+)	28.53(3.20)(+)
Net-single1	2	**1.91(0.48)(=)**	1.91(0.47)(=)	2.04(0.50)(+)
Net-single2	2	**16.78(4.18)(=)**	16.99(4.47)(=)	18.03(4.07)(+)
Net-single3	2	**11.40(1.77)(=)**	11.57(1.97)(=)	12.38(1.73)(+)
Net-double	2	11.21(1.17)(=)	**10.59(1.62)(−)**	12.47(1.63)(+)
Net-2x2grid	2	**36.01(8.82)(=)**	37.19(8.94)(+)	39.25(9.57)(+)
Net-3x3grid	2	**19.39(2.88)(+)**	19.84(2.98)(+)	20.44(3.01)(+)
Net-single1	3	**2.08(0.56)(=)**	2.08(0.58)(=)	2.23(0.59)(+)
Net-single2	3	**23.66(7.20)(=)**	23.85(7.24)(=)	24.02(6.51)(+)
Net-single3	3	**12.31(1.77)(=)**	12.42(2.04)(=)	13.49(2.54)(+)
Net-double	3	11.65(1.30)(+)	**11.13(1.38)(−)**	12.78(1.61)(+)
Net-2x2grid	3	**43.21(11.42)(=)**	45.79(12.57)(+)	46.44(12.39)(+)
Net-3x3grid	3	**26.09(6.42)(=)**	26.67(6.87)(+)	26.92(7.03)(+)
Cologne1	1	**14.04(4.08)(=)**	14.35(4.16)(+)	15.07(4.06)(+)
Cologne3	1	**12.56(4.22)(+)**	13.19(3.78)(+)	15.44(4.48)(+)
Ingolstadt1	1	**12.58(6.30)(=)**	12.75(6.27)(=)	13.14(6.47)(+)
Ingolstadt7	1	**25.61(7.64)(+)**	26.41(8.10)(+)	27.10(7.75)(+)

TABLE S.XI

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

Scene Name	Case	LMM	LMM-φ0	LMM-φ1	LMM-φ2
Net-single1	1	**1.55(0.26)**	1.56(0.27)(=)	**1.55(0.26)(=)**	1.74(0.27)(+)
Net-single2	1	**18.66(2.57)**	18.69(2.89)(=)	19.03(3.14)(=)	**18.66(2.57)(=)**
Net-single3	1	**12.31(1.21)**	12.59(1.22)(+)	12.54(1.32)(+)	**12.31(1.21)(=)**
Net-double	1	**11.30(0.83)**	12.23(1.03)(+)	11.84(0.97)(+)	**11.30(0.83)(=)**
Net-2x2grid	1	**51.41(6.11)**	54.25(6.77)(+)	53.25(6.48)(+)	**51.41(6.11)(=)**
Net-3x3grid	1	**25.81(2.76)**	27.13(2.79)(+)	26.35(2.82)(+)	**25.81(2.76)(=)**
Net-single1	2	**1.91(0.47)**	1.91(0.48)(=)	**1.91(0.47)(=)**	2.54(1.04)(+)
Net-single2	2	**16.85(4.81)**	**16.78(4.18)(=)**	16.85(4.81)(=)	18.32(3.33)(+)
Net-single3	2	**11.45(1.87)**	**11.40(1.77)(=)**	11.45(1.87)(=)	11.92(1.25)(+)
Net-double	2	**11.21(1.17)**	11.21(1.17)(=)	**11.11(1.11)(=)**	11.39(1.50)(=)
Net-2x2grid	2	**35.60(8.31)**	36.01(8.82)(=)	**35.60(8.31)(=)**	36.79(8.79)(+)
Net-3x3grid	2	**19.13(2.79)**	19.39(2.88)(+)	**19.13(2.79)(=)**	19.62(2.80)(+)
Net-single1	3	**2.08(0.56)**	**2.08(0.56)(=)**	**2.08(0.56)(=)**	2.99(0.52)(+)
Net-single2	3	**23.66(7.20)**	**23.66(7.20)(=)**	23.73(7.03)(=)	25.87(6.70)(+)
Net-single3	3	**12.31(1.77)**	**12.31(1.77)(=)**	12.39(1.94)(=)	13.04(2.05)(+)
Net-double	3	**11.49(1.25)**	11.65(1.30)(+)	**11.49(1.25)(=)**	11.54(1.36)(=)
Net-2x2grid	3	**43.30(11.38)**	**43.21(11.42)(=)**	43.30(11.38)(=)	43.57(10.58)(=)
Net-3x3grid	3	**25.91(6.52)**	26.09(6.42)(=)	**25.91(6.52)(=)**	25.98(6.10)(=)
Cologne1	1	**14.04(4.08)**	**14.04(4.08)(=)**	14.26(4.33)(+)	15.73(4.71)(+)
Cologne3	1	**11.10(1.81)**	12.56(4.22)(+)	11.94(2.51)(+)	**11.10(1.81)(=)**
Ingolstadt1	1	**12.46(6.22)**	12.58(6.30)(=)	**12.46(6.22)(=)**	12.74(6.35)(=)
Ingolstadt7	1	**24.29(8.50)**	25.61(7.64)(+)	24.82(7.71)(+)	**24.29(8.50)(=)**

TABLE S.XII

INVESTIGATION RESULTS ON THE EFFECTS OF THE PROPOSED REGULARIZATION TERM IN THE MSR METHOD

Scene Name	Case	LMM	LMM-φ3
Net-single1	1	1.55(0.26)	1.62(0.28)(+)
Net-single2	1	18.66(2.57)	18.28(2.89)(−)
Net-single3	1	12.31(1.21)	12.36(1.22)(=)
Net-double	1	11.30(0.83)	11.23(0.79)(=)
Net-2x2grid	1	51.41(6.11)	51.43(6.32)(=)
Net-3x3grid	1	25.81(2.76)	25.90(2.66)(=)
Net-single1	2	1.91(0.47)	1.94(0.51)(+)
Net-single2	2	16.85(4.81)	16.37(4.03)(=)
Net-single3	2	11.45(1.87)	11.01(1.57)(−)
Net-double	2	11.21(1.17)	10.71(1.14)(−)
Net-2x2grid	2	35.60(8.31)	35.08(8.03)(−)
Net-3x3grid	2	19.13(2.79)	18.97(2.73)(=)
Net-single1	3	2.08(0.56)	2.23(0.65)(+)
Net-single2	3	23.66(7.20)	23.13(6.28)(=)
Net-single3	3	12.31(1.77)	12.04(1.74)(−)
Net-double	3	11.49(1.25)	11.29(1.21)(−)
Net-2x2grid	3	43.30(11.38)	42.30(10.93)(−)
Net-3x3grid	3	25.91(6.52)	25.66(6.30)(=)
Cologne1	1	14.04(4.08)	13.84(3.53)(=)
Cologne3	1	11.10(1.81)	11.38(2.16)(=)
Ingolstadt1	1	12.46(6.22)	11.84(6.01)(−)
Ingolstadt7	1	24.29(8.50)	23.92(7.72)(=)