Online-Appendix zu

„Designing and Scheduling Cost-Efficient Tours by Using the Concept of Truck Platooning“

Florian Stehbeck
Technische Universität München

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List of Abbreviations

ACAM	Alternative Cost Avoided Method
CACC	Cooperative Adaptive Cruise Control
ECM	Equal Charge Method
EU	European Union
EU-TPP	EU-Truck Platooning Problem
GPS	Global Positioning System
HCT	Hypothetical Cost of Trailing
HDV	Heavy-Duty Vehicle
ILP	Integer Linear Program(ming)
Lidar	Light detection and ranging
LP	Linear Program(ming)
MILP	Mixed-Integer Linear Program(ming)
MIP	Mixed-Integer Program(ming)
ORP	Orchestrated Platooning
OTFP	On-The-Fly-Platooning
PER	Platoon Exploitation Rate
PF	Platoon Follower
PL	Platoon Leader
PP	Platooning Problem
PRH	Platoon Routing Heuristic
PSP	Platooning Service Provider
Radar	Radio detection and ranging
SNSC	Separable and Non-Separable Cost
SOS	Self-Organized Scheduling
SPH	Shortest Path Heuristic
SV	Shapley Value
TCO	Total Cost of Ownership
TSP	Travelling Salesman Problem
UPP	Unlimited Platooning Problem
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem with Time Windows
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WC	Weighted Cost

List of Symbols

Symbols for the exact *EU-Truck Platooning Problem* (*EU-TPP*) formulation as well as for the hierarchical planning-based *Shortest Path Heuristic* (*SPH*) and the *Platoon Routing Heuristic* (*PRH*)

Sets

M	Manning (single vs. double)
N	Nodes / Locations
T	Planning horizon (time steps)
V	Vehicles / Trucks

Parameters

BIG	Sufficiently large number (often referred to as '*Big-M*')
$brp1_m$	Duration of shorter first part of a split required break with $m \in M$ truck drivers
c	Fuel and AdBlue cost per liter
$d_{i,j}$	Required driving time between two nodes $i \in N$ and $j \in N$
$dbr_{v,i,m}$	Duration of the full or second part of the mandatory break of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers (only applies to step 2 of matheuristics)
$ddr_{v,i,m}$	Duration of the full or second part of the mandatory daily rest period of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers (only applies to step 2 of matheuristics)
des_v	Destination node of truck $v \in V$
$drp1_m$	Duration of shorter first part of a split required daily rest period with $m \in M$ truck drivers
ed_v	Earliest possible departure time for truck $v \in V$
f_v	Fuel consumption of truck $v \in V$ per unit distance
la_v	Latest possible arrival time for truck $v \in V$
$max1_m$	Maximum accumulated driving time with $m \in M$ truck drivers between two breaks or between a daily rest period and a break
$max2_m$	Maximum accumulated driving time with $m \in M$ truck drivers between two daily rest periods

$min1_m$	Minimum required break time with $m \in M$ truck drivers after a maximum accumulated driving time $max1_m$
$min2_m$	Minimum required daily rest period with $m \in M$ truck drivers after a maximum accumulated driving time of $max2_m$
ori_v	Origin node of truck $v \in V$
p_m	Personnel cost per time step with $m \in M$ truck drivers
pen	Penalty cost per time step of later arrival at destination
$redbr_m$	Reduction factor for the calculation of the second part of a split required break with $m \in M$ truck drivers
$reddr_m$	Reduction factor for the calculation of the second part of a split required daily rest period with $m \in M$ truck drivers
$share$	Share of granted task relief for followers in a platoon
$short_v$	Length of shortest path for truck $v \in V$
$y_{v,i,j,m}$	Indicates if truck $v \in V$ traverses the edge between two nodes $i \in N$ and $j \in N$ with $m \in M$ truck drivers (only applies to step 2 of matheuristics)
η	Platooning cost factor for followers in a platoon

Decision variables

$a_{v,i,m}$	Integer: Arrival time of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers
$br_{v,i,m}$	Binary: 1 if truck $v \in V$ takes a mandatory break after arriving at node $i \in N$ with $m \in M$ truck drivers; 0 otherwise
$brClock_{v,i,m}$	Integer (real for qualitative sensitivity analysis relating to a task relief): Auxiliary variable for truck $v \in V$ to indicate the driving time status of its $m \in M$ truck drivers at node $i \in N$ with regard to the necessity of a mandatory break
$dbr_{v,i,m}$	Integer: Required time for the full or second part of the mandatory break of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers (does not apply to step 2 of matheuristics)
$ddr_{v,i,m}$	Integer: Required time for the full or second part of the mandatory daily rest period of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers (does not apply to step 2 of matheuristics)
$dr_{v,i,m}$	Binary: 1 if truck $v \in V$ takes a mandatory daily rest period after arriving at node $i \in N$ with $m \in M$ truck drivers; 0 otherwise

$drClock_{v,i,m}$	Integer (real for qualitative sensitivity analysis relating to a task relief): Auxiliary variable for truck $v \in V$ to indicate the driving time status of its $m \in M$ truck drivers at node $i \in N$ with regard to the necessity of a mandatory daily rest period
$FIF_{v,i,m}$	Binary: 1 if truck $v \in V$ has already taken a first part of a mandatory break at some location before node $i \in N$ with its $m \in M$ truck drivers until its associated second part is taken; 0 otherwise (only applies to *EU*-TPP)
$fifmin_{v,i,m}$	Binary: 1 if truck $v \in V$ takes the first part of a split mandatory break after arriving at node $i \in N$ with $m \in M$ truck drivers; 0 otherwise (only applies to *EU*-TPP)
$late_{v,m}$	Integer: Delay of truck $v \in V$ at its destination with $m \in M$ truck drivers
$pl_{v,u,i,j,t}$	Binary: 1 if truck $v \in V$ and $u \in V$ traverse the edge between two nodes $i \in N$ and $j \in N$ together in a platoon, starting at the same time $t \in T$; 0 otherwise
$THR_{v,i,m}$	Binary: 1 if truck $v \in V$ has already taken a first part of a mandatory daily rest period at some location before node $i \in N$ with its $m \in M$ truck drivers until its associated second part is taken; 0 otherwise (only applies to *EU*-TPP)
$thrhour_{v,i,m}$	Binary: 1 if truck $v \in V$ takes the first part of a split mandatory daily rest period after arriving at node $i \in N$ with $m \in M$ truck drivers; 0 otherwise (only applies to *EU*-TPP)
$w_{v,i,m}$	Integer: Optional waiting time of truck $v \in V$ at node $i \in N$ with $m \in M$ truck drivers
$x_{v,i,j,t,m}$	Binary: 1 if truck $v \in V$ traverses the edge between two nodes $i \in N$ and $j \in N$ with $m \in M$ truck drivers, starting at time $t \in T$; 0 otherwise
$y_{v,i,j,m}$	Binary: 1 if truck $v \in V$ traverses the edge between two nodes $i \in N$ and $j \in N$ with $m \in M$ truck drivers; 0 otherwise (only applies to step 1 of matheuristics)
$\alpha_{v,i,j,t,m}$	Binary: 1 if truck $v \in V$ traverses the edge between two nodes $i \in N$ and $j \in N$ with $m \in M$ truck drivers as a leader of a platoon or alone, starting at time $t \in T$; 0 otherwise

Symbols for mutual compensation mechanisms between the leader and its followers in a platooning-based application

Weighted Cost (WC)

$C(\{p\})$	Stand-alone costs of player p (if working independently)
$C(Z)$	Jointly achieved costs of the coalition Z
p	Individual player
Y_p	Costs which are assigned to player p if he collaborates with members of the coalition Z
Z	Coalition of collaborating players

Shapley Value (SV) – additionally required symbols

S	Sub-coalition of the (grand) coalition Z
$\lvert * \rvert$	Number of players in the respective coalition S or Z

Separable and Non-Separable Cost (SNSC) – additionally required symbols

G_Z	Non-separable cost of coalition Z as the difference between the total cost of the grand coalition and the sum of the individual players' marginal cost
M_p	Separable (i.e. marginal) cost of player p
W_p	Weight which is defined as the individual benefit of joining the grand coalition in contrast to operating alone

Hypothetical Cost of Trailing (HCT) – additionally required symbols

F_p	Reduced fuel cost rate of player p if he followed a preceding truck (at least hypothetically)
R_Z	Non-separable cost of coalition Z as the difference between the total cost of the grand coalition and the sum of the individual players' reduced fuel cost rates (at least hypothetically)

Appendices

Appendix A Overview of appended files (with explanations)

The following information is meant to guide the reader of this thesis step-by-step through the digitally appended folders with their respective data files.

Chapter 4 – Basic model files and input / output data templates

Next to the respective *Xpress* files, each of the subsequent folders contains the input data file *Input* as well as the output file *Output* in order to be able to test the respective models instantly. The input file is subdivided into 5 sheets with the distance matrix of our network, a time window generator, information about the shortest path for each origin-destination pair, the database with all 120 instances (30 for each coordination problem) and finally a sheet, where miscellaneous other parameter values can be found and modified. Moreover, the respective instances can be inserted on this latter sheet. Run 30 of the different-start coordination problem with the fully available planning horizon and 12 trucks to be managed is set as default.

Folder *01_EU-TPP_Single* – includes the single manning version of the *EU-TPP*

Folder *02_EU-TPP_Multi* – includes the multi manning version of the *EU-TPP*

Folder *03_SPH_Single* – includes the single manning version of the *SPH*

Folder *04_SPH_Multi* – includes the multi manning version of the *SPH*

Folder *05_PRH_Single* – includes the single manning version of the *PRH*

Folder *06_PRH_Multi* – includes the multi manning version of the *PRH*

Folder *07_Standard_Single* – includes the single manning version of the standard planning model in the *EU* (benchmark model 1)

Folder *08_Standard_Multi* – includes the multi manning version of the standard planning model in the *EU* (benchmark model 1)

Folder *09_PlatooningNoEU_Single* – includes the single manning version of the mere platooning model without the consideration of mandatory driving time restrictions in the *EU* (benchmark model 2)

Folder *10_PlatooningNoEU_Multi* – includes the multi manning version of the mere platooning model without the consideration of mandatory driving time restrictions in the *EU* (benchmark model 2)

Chapter 5 – Validation scenarios and pruning-related output analysis

Folder *01_Validation_Scenarios* – includes the respectively required *Xpress* files *(EU-TPP_Single, EU-TPP_Multi, SPH_Single, PRH_Single)* as well as the input data file *Input* with scenario 1 as default (scenarios 2 and 3 are provided) and the output file *Output*

Folder *02_Validation_Pruning* – includes the respectively required *Xpress* files *(EU-TPP_Single, EU-TPP_Multi;* both with and without the auxiliary constraint*)* as well as the input data file *Input* with run 1 of the unrestricted different-start coordination problem as default, the output file *Output* and the separately created analysis file *Efficiency_Pruning*

Chapter 6 – Experimental input / output data, performance indicator analysis and scenarios / results of sensitivity analysis

Folder *01_Experimental_Data* – includes the files *Data_Different_Full, Data_Different_TW20, Data_Same_Full and Data_Same_TW20* which contain the respective coordination problems' results for the various model runs within our numerical experiments (single manning)

File *02_Performance_Analysis* – includes the respective performance indicator calculations along with associated analyses and graphical representations

Folder *03_Sensitivity_Analysis* – includes the respectively required *Xpress* files *(EU-TPP_Single, EU-TPP_Multi)* as well as the input data file *Input* with scenario 1 as default (scenarios 2 and 3 are provided), the output file *Output* and the separately created analysis file *Sensitivity_Analysis*

Chapter 7 – Conceptual application of mutual compensation mechanisms

File *Compensation_Mechanisms* – includes the major calculations of the following benefit / cost sharing approaches: *WC*, *SV*, *SNSC* (*ACAM & ECM*) and *HCT*

Miscellaneous – Further figures and tables

File *01_Figures* – includes figures of the thesis, which have not been created within the framework of our performance analysis

File *02_Tables* – includes all tables regarding the review of literature and research

Appendix B Exact EU-TPP model (compact)

The following *ILP*-based formulation represents the exact *EU-TPP* model in its compact double manning version, i.e. manning options can be considered. In order to derive its single manning variant that we used for our extensive numerical experiments in chapter 6, it is just necessary remove all manning indices $m \in M$ as well as constraint (B.34) from the formulation. Further changes are not required.

<u>*Objective*</u>

$$\text{Minimize } Z = \sum_{v \in V} \sum_{i \in N} \sum_{j \in N \setminus \{i\}} \sum_{t \in T} \sum_{m \in M} c \cdot f_v \cdot d_{i,j} \cdot \left(\alpha_{v,i,j,t,m} + \eta \cdot (x_{v,i,j,t,m} - \alpha_{v,i,j,t,m})\right) + \sum_{v \in V} \sum_{m \in M} p_m \cdot (a_{v,des_v,m} - \sum_{j \in N \setminus \{ori_v\}} \sum_{t \in T} x_{v,ori_v,j,t,m} \cdot t) + \sum_{v \in V} \sum_{m \in M} pen \cdot late_{v,m} \tag{B.1}$$

<u>*subject to*</u>

$$\sum_{i \in N \setminus \{des_v\}} \sum_{t=ed_v}^{la_v} x_{v,i,j,t,m} = \sum_{i \in N \setminus \{ori_v\}} \sum_{t=ed_v}^{la_v} x_{v,j,i,t,m} \quad \forall v \in V; j \in N \setminus \{ori_v, des_v\}; i \neq j; m \in M \tag{B.2}$$

$$\sum_{j \in N \setminus \{ori_v\}} \sum_{t=ed_v}^{la_v} \sum_{m \in M} x_{v,ori_v,j,t,m} = 1 \quad \forall v \in V \tag{B.3}$$

$$\sum_{i \in N \setminus \{des_v\}} \sum_{t=ed_v}^{la_v} \sum_{m \in M} x_{v,i,des_v,t,m} = 1 \quad \forall v \in V \tag{B.4}$$

$$\sum_{i \in N} \sum_{j \in N \setminus \{i\}} \sum_{t \in T} x_{v,i,j,t,m} \cdot d_{i,j} \leq Short_v \cdot \frac{c \cdot f_v + p_m}{c \cdot f_v \cdot \eta + p_m} \quad \forall v \in V; m \in M \tag{B.5}$$

$$ed_v \leq \sum_{j \in N \setminus \{ori_v\}} \sum_{t \in T} \sum_{m \in M} x_{v,ori_v,j,t,m} \cdot t \quad \forall v \in V \tag{B.6}$$

$$a_{v,des_v,m} - late_{v,m} \leq la_v \quad \forall v \in V, m \in M \tag{B.7}$$

$$\sum_{i \in N} \sum_{t \in T} x_{v,i,j,t,m} \cdot (t + d_{i,j}) \leq a_{v,j,m} \quad \forall v \in V; j \in N; i \neq j; m \in M \tag{B.8}$$

$$a_{v,i,m} + dbr_{v,i,m} + ddr_{v,i,m} + brp1_m \cdot fifmin_{v,i,m} + drp1_m \cdot thrhour_{v,i,m} + w_{v,i,m} \leq \sum_{j \in N \setminus \{ori_v\}} \sum_{t \in T} x_{v,i,j,t,m} \cdot t \quad \forall v \in V; i \in N \setminus \{ori_v, des_v\}; i \neq j; m \in M \tag{B.9}$$

$$2 \cdot pl_{v,u,i,j,t} - (\sum_{m \in M} x_{v,i,j,t,m} + \sum_{n \in M} x_{u,i,j,t,n}) \leq 0 \quad \forall v, u \in V; u < v; i, j \in N; i \neq j; t \in T \tag{B.10}$$

$$\sum_{m \in M} \alpha_{v,i,j,t,m} \geq pl_{u,v,i,j,t} \quad \forall v, u \in V; v < u; i, j \in N; i \neq j; t \in T \tag{B.11}$$

$$\sum_{m \in M} \alpha_{v,i,j,t,m} + \sum_{u=1}^{v-1} pl_{v,u,i,j,t} \geq \sum_{m \in M} x_{v,i,j,t,m} \quad \forall v \in V; i, j \in N; i \neq j; t \in T \tag{B.12}$$

$$\alpha_{v,i,j,t,m} \leq x_{v,i,j,t,m} \quad \forall v \in V; i, j \in N; i \neq j; t \in T; m \in M \tag{B.13}$$

$$brClock_{v,i,m} + d_{i,j} \cdot \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share \cdot \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m}\right)\right) - BIG \cdot \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) - BIG \cdot br_{v,j,m} - BIG \cdot dr_{v,j,m} \leq brClock_{v,j,m} \quad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{B.14}$$

$$drClock_{v,i,m} + d_{i,j} \cdot \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share \cdot \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m}\right)\right) - BIG \cdot \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) - BIG \cdot dr_{v,j,m} \leq drClock_{v,j,m} \quad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{B.15}$$

$$max1_m - brClock_{v,i,m} - d_{i,j} \cdot \sum_{t \in T} (\alpha_{v,i,j,t,m} + share \cdot \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m}\right)) \geq 0 \quad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{B.16}$$

$$max2_m - drClock_{v,i,m} - d_{i,j} \cdot \sum_{t \in T} (\alpha_{v,i,j,t,m} + share \cdot (x_{v,i,j,t,m} - \alpha_{v,i,j,t,m})) \geq 0 \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.17}$$

$$FIF_{v,i,m} + fifmin_{v,i,m} + BIG \cdot \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) \geq FIF_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.18}$$

$$FIF_{v,j,m} \leq (1 - \sum_{t \in T} x_{v,i,j,t,m}) + (1 - br_{v,i,m}) \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.19}$$

$$FIF_{v,j,m} \leq (1 - \sum_{t \in T} x_{v,i,j,t,m}) + (1 - dr_{v,i,m}) \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.20}$$

$$THR_{v,i,m} + thrhour_{v,i,m} + BIG \cdot \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) \geq THR_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.21}$$

$$THR_{v,j,m} \leq (1 - \sum_{t \in T} x_{v,i,j,t,m}) + (1 - dr_{v,i,m}) \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{B.22}$$

$$min1_m \leq dbr_{v,i,m} + BIG \cdot (1 - br_{v,i,m}) + redbr_m \cdot FIF_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.23}$$

$$min2_m \leq ddr_{v,i,m} + BIG \cdot (1 - dr_{v,i,m}) + reddr_m \cdot THR_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.24}$$

$$fifmin_{v,i,m} \leq 1 - br_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.25}$$

$$fifmin_{v,i,m} \leq 1 - dr_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.26}$$

$$thrhour_{v,i,m} \leq 1 - br_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.27}$$

$$thrhour_{v,i,m} \leq 1 - dr_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.28}$$

$$thrhour_{v,i,m} \leq 1 - fifmin_{v,i,m} \quad \forall v \in V; i \in N; m \in M \tag{B.29}$$

$$brClock_{v,ori_v,m}, drClock_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{B.30}$$

$$br_{v,ori_v,m}, br_{v,des_v,m}, dr_{v,ori_v,m}, dr_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{B.31}$$

$$FIF_{v,ori_v,m}, THR_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{B.32}$$

$$fifmin_{v,ori_v,m}, fifmin_{v,des_v,m}, thrhour_{v,ori_v,m}, thrhour_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{B.33}$$

$$FIF_{v,i,2}, fifmin_{v,i,2}, THR_{v,i,2}, thrhour_{v,i,2} = 0 \quad \forall v \in V; i \in N \tag{B.34}$$

$$x_{v,i,j,t,m}, \alpha_{v,i,j,t,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; t \in T; m \in M \tag{B.35}$$

$$pl_{v,u,i,j,t} \in \{0,1\} \quad \forall v,u \in V; v \neq u; i,j \in N; i \neq j; t \in T \tag{B.36}$$

$$br_{v,i,m}, dr_{v,i,m}, fifmin_{v,i,m}, thrhour_{v,i,m}, FIF_{v,i,m}, THR_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{B.37}$$

$$a_{v,i,m}, w_{v,i,m}, dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \tag{B.38}$$

$$late_{v,m} \in \mathbb{Z}_+ \quad \forall v \in V, m \in M \tag{B.39}$$

Appendix C Matheuristic 1: SPH (compact)

The following mathematical model represents the hierarchical planning-based *SPH* in its compact double manning version, i.e. manning options can be considered. In order to derive its single manning variant that we used for our extensive numerical experiments in chapter 6, it is just necessary to remove all manning indices $m \in M$ from the formulation. Moreover, the objective function of stage 1 can be reduced by the personnel cost factor p_m. Further changes are not required.

<u>Stage 1</u>

<u>Objective</u>

$$\text{Minimize } Z = \sum_{v \in V} \sum_{i \in N} \sum_{m \in M} p_m \cdot (dbr_{v,i,m} + ddr_{v,i,m} + \sum_{j \in N \setminus \{i\}} d_{i,j} \cdot y_{v,i,j,m}) \tag{C.1}$$

<u>subject to</u>

$$\sum_{i \in N \setminus \{des_v\}} y_{v,i,j,m} = \sum_{i \in N \setminus \{ori_v\}} y_{v,j,i,m} \quad \forall v \in V; j \in N \setminus \{ori_v, des_v\}; i \neq j; m \in M \tag{C.2}$$

$$\sum_{j \in N \setminus \{ori_v\}} \sum_{m \in M} y_{v,ori_v,j,m} = 1 \quad \forall v \in V \tag{C.3}$$

$$\sum_{i \in N \setminus \{des_v\}} \sum_{m \in M} y_{v,i,des_v,m} = 1 \quad \forall v \in V \tag{C.4}$$

$$brClock_{v,i,m} + d_{i,j} \cdot y_{v,i,j,m} - BIG \cdot (1 - y_{v,i,j,m}) - BIG \cdot br_{v,j,m} - BIG \cdot dr_{v,j,m} \leq brClock_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.5}$$

$$drClock_{v,i,m} + d_{i,j} \cdot y_{v,i,j,m} - BIG \cdot (1 - y_{v,i,j,m}) - BIG \cdot dr_{v,j,m} \leq drClock_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.6}$$

$$max1_m - brClock_{v,i,m} - d_{i,j} \cdot y_{v,i,j,m} \geq 0 \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.7}$$

$$max2_m - drClock_{v,i,m} - d_{i,j} \cdot y_{v,i,j,m} \geq 0$$
$$\forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.8}$$

$$min1_m \leq dbr_{v,i,m} + BIG \cdot \left(1 - br_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{C.9}$$

$$min2_m \leq ddr_{v,i,m} + BIG \cdot \left(1 - dr_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{C.10}$$

$$brClock_{v,ori_v,m}, drClock_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{C.11}$$

$$br_{v,ori_v,m}, br_{v,des_v,m}, dr_{v,ori_v,m}, dr_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{C.12}$$

$$y_{v,i,j,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.13}$$

$$br_{v,i,m}, dr_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{C.14}$$

$$dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+$$
$$\forall v \in V; i \in N; m \in M \tag{C.15}$$

<u>Stage 2</u>

<u>Objective</u>

$$\text{Minimize } Z =$$
$$\sum_{v \in V} \sum_{i \in N} \sum_{j \in N \setminus \{i\}} \sum_{t \in T} \sum_{m \in M} c \cdot f_v \cdot d_{i,j} \cdot \left(\alpha_{v,i,j,t,m} + \eta \cdot \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m}\right)\right)$$
$$+ \sum_{v \in V} \sum_{m \in M} p_m \cdot (a_{v,des_v,m} - \sum_{j \in N \setminus \{ori_v\}} \sum_{t \in T} x_{v,ori_v,j,t,m} \cdot t)$$
$$+ \sum_{v \in V} \sum_{m \in M} pen \cdot late_{v,m} \tag{C.16}$$

<u>subject to</u>

$$\sum_{t \in T} x_{v,i,j,t,m} = y_{v,i,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{C.17}$$

$$\sum_{i \in N \setminus \{des_v\}} \sum_{t=ed_v}^{la_v} x_{v,i,j,t,m} = \sum_{i \in N \setminus \{ori_v\}} \sum_{t=ed_v}^{la_v} x_{v,j,i,t,m}$$
$$\forall v \in V; j \in N \setminus \{ori_v, des_v\}; i \neq j; m \in M \tag{C.18}$$

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,ori_v,j,t,m} = 1 \quad \forall v \in V \tag{C.19}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,i,des_v,t,m} = 1 \quad \forall v \in V \tag{C.20}$$

$$ed_v \le \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T}\sum_{m\in M} x_{v,ori_v,j,t,m}\cdot t \quad \forall v \in V \tag{C.21}$$

$$a_{v,des_v,m} - late_{v,m} \le la_v \quad \forall v \in V, m \in M \tag{C.22}$$

$$\sum_{i\in N}\sum_{t\in T} x_{v,i,j,t,m}\cdot (t + d_{i,j}) \le a_{v,j,m} \quad \forall v \in V; j \in N; i \ne j; m \in M \tag{C.23}$$

$$a_{v,i,m} + dbr_{v,i,m} + ddr_{v,i,m} + w_{v,i,m} \le \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,i,j,t,m}\cdot t$$
$$\forall v \in V; i \in N \setminus \{ori_v, des_v\}; i \ne j; m \in M \tag{C.24}$$

$$2\cdot pl_{v,u,i,j,t} - \Big(\sum_{m\in M} x_{v,i,j,t,m} + \sum_{n\in M} x_{u,i,j,t,n}\Big) \le 0$$
$$\forall v,u \in V; u < v; i,j \in N; i \ne j; t \in T \tag{C.25}$$

$$\sum_{m\in M} \alpha_{v,i,j,t,m} \ge pl_{u,v,i,j,t} \quad \forall v,u \in V; v < u; i,j \in N; i \ne j; t \in T \tag{C.26}$$

$$\sum_{m\in M} \alpha_{v,i,j,t,m} + \sum_{u=1}^{v-1} pl_{v,u,i,j,t} \ge \sum_{m\in M} x_{v,i,j,t,m}$$
$$\forall v \in V; i,j \in N; i \ne j; t \in T \tag{C.27}$$

$$\alpha_{v,i,j,t,m} \le x_{v,i,j,t,m} \quad \forall v \in V; i,j \in N; i \ne j; t \in T; m \in M \tag{C.28}$$

$$x_{v,i,j,t,m}, \alpha_{v,i,j,t,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \ne j; t \in T; m \in M \tag{C.29}$$

$$pl_{v,u,i,j,t} \in \{0,1\} \quad \forall v,u \in V; v \ne u; i,j \in N; i \ne j; t \in T \tag{C.30}$$

$$late_{v,m} \in \mathbb{Z}_+ \quad \forall v \in V, m \in M \tag{C.31}$$

$$a_{v,i,m}, w_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \tag{C.32}$$

Appendix D Matheuristic 2: PRH (compact)

The following mathematical model represents the hierarchical planning-based *PRH* in its compact double manning version, i.e. manning options can be considered. In order to derive its single manning variant that we used for our extensive numerical experiments in chapter 6, it is just necessary to remove all manning indices $m \in M$ from the formulation. Further changes are not required.

Stage 1

Objective

$$\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\backslash\{i\}}\sum_{m\in M} c\cdot f_v\cdot d_{i,j}\cdot\left(\alpha_{v,i,j,m}+\eta\cdot\left(y_{v,i,j,m}-\alpha_{v,i,j,m}\right)\right) + \sum_{v\in V}\sum_{i\in N}\sum_{m\in M} p_m\cdot(dbr_{v,i,m}+ddr_{v,i,m} + \sum_{j\in N\backslash\{i\}} d_{i,j}\cdot y_{v,i,j,m}) \tag{D.1}$$

subject to

$$\sum_{i\in N\backslash\{des_v\}} y_{v,i,j,m} = \sum_{i\in N\backslash\{ori_v\}} y_{v,j,i,m} \quad \forall v\in V; j\in N\setminus\{ori_v,des_v\}; i\neq j; m\in M \tag{D.2}$$

$$\sum_{j\in N\backslash\{ori_v\}}\sum_{m\in M} y_{v,ori_v,j,m} = 1 \quad \forall v\in V \tag{D.3}$$

$$\sum_{i\in N\backslash\{des_v\}}\sum_{m\in M} y_{v,i,des_v,m} = 1 \quad \forall v\in V \tag{D.4}$$

$$\sum_{i\in N}\sum_{j\in N\backslash\{i\}}\sum_{t\in T} x_{v,i,j,t,m}\cdot d_{i,j} \le Short_v\cdot\frac{c\cdot f_v+p_m}{c\cdot f_v\cdot\eta+p_m} \quad \forall v\in V; m\in M \tag{D.5}$$

$$2\cdot pl_{v,u,i,j} - (\sum_{m\in M} y_{v,i,j,m} + \sum_{n\in M} y_{u,i,j,n}) \le 0 \quad \forall v,u\in V; u<v; i,j\in N; i\neq j \tag{D.6}$$

$$\sum_{m\in M}\alpha_{v,i,j,m} + \sum_{u=1}^{v-1} pl_{v,u,i,j} \ge \sum_{m\in M} y_{v,i,j,m} \quad \forall v\in V; i,j\in N; i\neq j \tag{D.7}$$

$$\alpha_{v,i,j,m} \leq y_{v,i,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{D.8}$$

$$\sum_{m \in M} \alpha_{v,i,j,m} \geq pl_{u,v,i,j} \quad \forall v,u \in V; v < u; i,j \in N; i \neq j \tag{D.9}$$

$$\begin{gathered} brClock_{v,i,m} + d_{i,j} \cdot y_{v,i,j,m} - \\ BIG \cdot \left(1 - y_{v,i,j,m}\right) - BIG \cdot br_{v,j,m} - BIG \cdot dr_{v,j,m} \leq brClock_{v,j,m} \\ \forall v \in V; i,j \in N; i \neq j; m \in M \end{gathered} \tag{D.10}$$

$$\begin{gathered} drClock_{v,i,m} + d_{i,j} \cdot y_{v,i,j,m} - \\ BIG \cdot \left(1 - y_{v,i,j,m}\right) - BIG \cdot dr_{v,j,m} \leq drClock_{v,j,m} \\ \forall v \in V; i,j \in N; i \neq j; m \in M \end{gathered} \tag{D.11}$$

$$\begin{gathered} max1_m - brClock_{v,i,m} - d_{i,j} \cdot y_{v,i,j,m} \geq 0 \\ \forall v \in V; i,j \in N; i \neq j; m \in M \end{gathered} \tag{D.12}$$

$$\begin{gathered} max2_m - drClock_{v,i,m} - d_{i,j} \cdot y_{v,i,j,m} \geq 0 \\ \forall v \in V; i,j \in N; i \neq j; m \in M \end{gathered} \tag{D.13}$$

$$min1_m \leq dbr_{v,i,m} + BIG \cdot \left(1 - br_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{D.14}$$

$$min2_m \leq ddr_{v,i,m} + BIG \cdot \left(1 - dr_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{D.15}$$

$$brClock_{v,ori_v,m}, drClock_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{D.16}$$

$$br_{v,ori_v,m}, br_{v,des_v,m}, dr_{v,ori_v,m}, dr_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{D.17}$$

$$y_{v,i,j,m}, \alpha_{v,i,j,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{D.18}$$

$$pl_{v,u,i,j} \in \{0,1\} \quad \forall v,u \in V; v \neq u; i,j \in N; i \neq j \tag{D.19}$$

$$br_{v,i,m}, dr_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{D.20}$$

$$\begin{gathered} dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+ \\ \forall v \in V; i \in N; m \in M \end{gathered} \tag{D.21}$$

Stage 2

Objective

$$\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus\{i\}}\sum_{t\in T}\sum_{m\in M} c\cdot f_v\cdot d_{i,j}\cdot\left(\alpha_{v,i,j,t,m}+\eta\cdot\left(x_{v,i,j,t,m}-\alpha_{v,i,j,t,m}\right)\right) + \sum_{v\in V}\sum_{m\in M} p_m\cdot\left(a_{v,des_v,m}-\sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,ori_v,j,t,m}\cdot t\right) + \sum_{v\in V}\sum_{m\in M} pen\cdot late_{v,m} \tag{D.22}$$

subject to

$$\sum_{t\in T} x_{v,i,j,t,m} = y_{v,i,j,m} \quad \forall v\in V; i,j\in N; i\neq j; m\in M \tag{D.23}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v} x_{v,i,j,t,m} = \sum_{i\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v} x_{v,j,i,t,m} \quad \forall v\in V; j\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{D.24}$$

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,ori_v,j,t,m} = 1 \quad \forall v\in V \tag{D.25}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,i,des_v,t,m} = 1 \quad \forall v\in V \tag{D.26}$$

$$ed_v \le \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T}\sum_{m\in M} x_{v,ori_v,j,t,m}\cdot t \quad \forall v\in V \tag{D.27}$$

$$a_{v,des_v,m} - late_{v,m} \le la_v \quad \forall v\in V, m\in M \tag{D.28}$$

$$\sum_{i\in N}\sum_{t\in T} x_{v,i,j,t,m}\cdot\left(t+d_{i,j}\right) \le a_{v,j,m} \quad \forall v\in V; j\in N; i\neq j; m\in M \tag{D.29}$$

$$a_{v,i,m} + dbr_{v,i,m} + ddr_{v,i,m} + w_{v,i,m} \le \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,i,j,t,m}\cdot t \quad \forall v\in V; i\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{D.30}$$

$$2 \cdot pl_{v,u,i,j,t} - (\sum_{m \in M} x_{v,i,j,t,m} + \sum_{n \in M} x_{u,i,j,t,n}) \leq 0$$
$$\forall v, u \in V; u < v; i, j \in N; i \neq j; t \in T \quad \text{(D.31)}$$

$$\sum_{m \in M} \alpha_{v,i,j,t,m} \geq pl_{u,v,i,j,t} \quad \forall v, u \in V; v < u; i, j \in N; i \neq j; t \in T \quad \text{(D.32)}$$

$$\sum_{m \in M} \alpha_{v,i,j,t,m} + \sum_{u=1}^{v-1} pl_{v,u,i,j,t} \geq \sum_{m \in M} x_{v,i,j,t,m}$$
$$\forall v \in V; i, j \in N; i \neq j; t \in T \quad \text{(D.33)}$$

$$\alpha_{v,i,j,t,m} \leq x_{v,i,j,t,m} \quad \forall v \in V; i, j \in N; i \neq j; t \in T; m \in M \quad \text{(D.34)}$$

$$x_{v,i,j,t,m}, \alpha_{v,i,j,t,m} \in \{0,1\} \quad \forall v \in V; i, j \in N; i \neq j; t \in T; m \in M \quad \text{(D.35)}$$

$$pl_{v,u,i,j,t} \in \{0,1\} \quad \forall v, u \in V; v \neq u; i, j \in N; i \neq j; t \in T \quad \text{(D.36)}$$

$$late_{v,m} \in \mathbb{Z}_+ \quad \forall v \in V, m \in M \quad \text{(D.37)}$$

$$a_{v,i,m}, w_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \quad \text{(D.38)}$$

Appendix E Standard planning model (compact)

The following formulation represents the standard planning model in the *EU* in its compact double manning version, i.e. manning options can be considered. In order to derive its single manning variant that we used as a benchmark for our extensive numerical experiments in chapter 6, it is just necessary to remove all manning indices $m \in M$ from the formulation. Further changes are not required.

Objective

$$\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus\{i\}}\sum_{m\in M} c \cdot f_v \cdot d_{i,j} \cdot x_{v,i,j,m} + \sum_{v\in V}\sum_{i\in N}\sum_{m\in M} p_m \cdot (dbr_{v,i,m} + ddr_{v,i,m} + \sum_{j\in N\setminus\{i\}} d_{i,j} \cdot x_{v,i,j,m}) \tag{E.1}$$

subject to

$$\sum_{i\in N\setminus\{des_v\}} x_{v,i,j,m} = \sum_{i\in N\setminus\{ori_v\}} x_{v,j,i,m} \quad \forall v \in V; j \in N \setminus \{ori_v, des_v\}; i \neq j; m \in M \tag{E.2}$$

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{m\in M} x_{v,ori_v,j,m} = 1 \quad \forall v \in V \tag{E.3}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{m\in M} x_{v,i,des_v,m} = 1 \quad \forall v \in V \tag{E.4}$$

$$brClock_{v,i,m} + d_{i,j} \cdot x_{v,i,j,m} - BIG \cdot (1 - x_{v,i,j,m}) - BIG \cdot br_{v,j,m} - BIG \cdot dr_{v,j,m} \leq brClock_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{E.5}$$

$$drClock_{v,i,m} + d_{i,j} \cdot x_{v,i,j,m} - BIG \cdot (1 - x_{v,i,j,m}) - BIG \cdot dr_{v,j,m} \leq drClock_{v,j,m} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{E.6}$$

$$max1_m - brClock_{v,i,m} - d_{i,j} \cdot x_{v,i,j,m} \geq 0 \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{E.7}$$

$$max2_m - drClock_{v,i,m} - d_{i,j} \cdot x_{v,i,j,m} \geq 0 \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{E.8}$$

$$min1_m \leq dbr_{v,i,m} + BIG \cdot \left(1 - br_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{E.9}$$

$$min2_m \leq ddr_{v,i,m} + BIG \cdot \left(1 - dr_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{E.10}$$

$$brClock_{v,ori_v,m}, drClock_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{E.11}$$

$$br_{v,ori_v,m}, br_{v,des_v,m}, dr_{v,ori_v,m}, dr_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{E.12}$$

$$x_{v,i,j,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{E.13}$$

$$br_{v,i,m}, dr_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{E.14}$$

$$dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \tag{E.15}$$

Appendix F Basic platooning model (compact)

The following formulation represents the mere platooning model without *EU* driving time restrictions in its compact double manning version, i.e. manning options can be considered. In order to derive its single manning variant that we used as a benchmark for our extensive numerical experiments in chapter 6, it is just necessary to remove all manning indices $m \in M$ from the formulation. Further changes are not required.

<u>Objective</u>

$$\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus\{i\}}\sum_{t\in T}\sum_{m\in M} c\cdot f_v\cdot d_{i,j}\cdot\left(\alpha_{v,i,j,t,m}+\eta\cdot\left(x_{v,i,j,t,m}-\alpha_{v,i,j,t,m}\right)\right) + \sum_{v\in V}\sum_{m\in M} p_m\cdot\left(a_{v,des_v,m}-\sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,ori_v,j,t,m}\cdot t\right) + \sum_{v\in V}\sum_{m\in M} pen\cdot late_{v,m} \tag{F.1}$$

<u>subject to</u>

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v} x_{v,i,j,t,m} = \sum_{i\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v} x_{v,j,i,t,m} \quad \forall v\in V; j\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{F.2}$$

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,ori_v,j,t,m} = 1 \quad \forall v\in V \tag{F.3}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,i,des_v,t,m} = 1 \quad \forall v\in V \tag{F.4}$$

$$\sum_{i\in N}\sum_{j\in N\setminus\{i\}}\sum_{t\in T} x_{v,i,j,t,m}\cdot d_{i,j} \leq Short_v\cdot\frac{c\cdot f_v+p_m}{c\cdot f_v\cdot\eta+p_m} \quad \forall v\in V; m\in M \tag{F.5}$$

$$ed_v \leq \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T}\sum_{m\in M} x_{v,ori_v,j,t,m}\cdot t \quad \forall v\in V \tag{F.6}$$

$$a_{v,des_v,m} - late_{v,m} \leq la_v \quad \forall v\in V, m\in M \tag{F.7}$$

$$\sum_{i\in N}\sum_{t\in T} x_{v,i,j,t,m}\cdot(t+d_{i,j}) \le a_{v,j,m} \quad \forall v\in V; j\in N; i\neq j; m\in M \tag{F.8}$$

$$a_{v,i,m}+w_{v,i,m} \le \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,i,j,t,m}\cdot t \quad \forall v\in V; i\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{F.9}$$

$$2\cdot pl_{v,u,i,j,t}-\left(\sum_{m\in M} x_{v,i,j,t,m}+\sum_{n\in M} x_{u,i,j,t,n}\right)\le 0 \quad \forall v,u\in V; u<v; i,j\in N; i\neq j; t\in T \tag{F.10}$$

$$\sum_{m\in M}\alpha_{v,i,j,t,m} \ge pl_{u,v,i,j,t} \quad \forall v,u\in V; v<u; i,j\in N; i\neq j; t\in T \tag{F.11}$$

$$\sum_{m\in M}\alpha_{v,i,j,t,m}+\sum_{u=1}^{v-1} pl_{v,u,i,j,t} \ge \sum_{m\in M} x_{v,i,j,t,m} \quad \forall v\in V; i,j\in N; i\neq j; t\in T \tag{F.12}$$

$$\alpha_{v,i,j,t,m}\le x_{v,i,j,t,m} \quad \forall v\in V; i,j\in N; i\neq j; t\in T; m\in M \tag{F.13}$$

$$x_{v,i,j,t,m}, \alpha_{v,i,j,t,m}\in\{0,1\} \quad \forall v\in V; i,j\in N; i\neq j; t\in T; m\in M \tag{F.14}$$

$$pl_{v,u,i,j,t}\in\{0,1\} \quad \forall v,u\in V; v\neq u; i,j\in N; i\neq j; t\in T \tag{F.15}$$

$$a_{v,i,m}, w_{v,i,m}\in\mathbb{Z}_+ \quad \forall v\in V; i\in N; m\in M \tag{F.16}$$

$$late_{v,m}\in\mathbb{Z}_+ \quad \forall v\in V, m\in M \tag{F.17}$$

Appendix G Further explanations on performance indicators

The following remarks are dedicated to the generated solutions' maturity levels from our model runs that are required for a proper calculation and comparison of the defined performance indicators. This refers to the respectively achieved optimality gaps within the preset runtime limit of 3600 s and is important in order to derive correct conclusions with regard to the research questions at hand. Please note that the standard benchmark model is always solved to optimality within a few seconds for our problem sizes due to its inherent computational simplicity.

a) **Percentage fuel cost savings:** This key figure will at worst exhibit a value of 0% and thus never become negative. Hence, the respective instances of the *EU* platooning model (basic *EU-TPP*, *SPH* or *PRH*) do not necessarily have to be solved to optimality after the given runtime limit for a comparison with the optimal fuel cost solution of the standard benchmark model. The generated overall savings level with either approach thus represents a lower bound for the considered instances and would just increase if all of them were solved to optimality. Instances with an optimality gap of 100% have to be excluded though.

b) **Percentage change of fuel cost:** The extra consideration of a task relief or of mandatory idle times can lead to more or less consumed fuel than with the basic *EU-TPP* or the mere platooning model. Consequently, all of the considered models' instances have to be solved to optimality within the preset runtime limit as this key figure could theoretically exhibit both positive and negative values.

c) **Share of maximum fuel cost savings:** Unlike the approximate *SPH* and *PRH* approaches' instances, the basic *EU-TPP*'s cases need to be solved to optimality within the preset runtime limit in order to derive proper statements about the matheuristics' respective solution quality. The generated overall savings level of the heuristics thus represents a lower bound for the considered instances and would just increase if all of them were solved to optimality.

d) **Percentage personnel cost savings:**
Both exact *EU-TPP* versions' instances must be solved to optimality within the given runtime limit to draw the correct conclusions from this performance indicator. Otherwise, potentially redundant but scheduled extra waiting times from an interim solution would still be included and thus falsify the results. This key figure only exhibits positive or zero values as wage expenses in the presence of a task relief would generally be lower than in the case without a task relief. The only exception is given by a situation where the task relief arranges for an extended travel range and thus allows to exploit new platooning opportunities by means of additional waiting.

e) **Percentage increase of personnel cost:**
Platooning would never lead to less personnel cost in the absence of a task relief than with the standard benchmark model due to possibly scheduled extra waiting times for the sake of platooning. The respective *EU* platooning models' instances (basic *EU-TPP*, *SPH*, *PRH*) must be solved to optimality within the preset runtime limit to avoid considering unnecessarily scheduled idle times from an interim solution in a comparison with the optimal personnel cost solution of the standard benchmark model. These would falsify the results.

f) **Percentage total cost savings:**
All of the involved models' instances have to be solved to optimality within the preset runtime limit in order to avoid considering unnecessarily scheduled idle times or redundant penalty cost from an interim solution. These would falsify the results. In the end, platooning would only improve the overall cost structure and never lead to more cost in total when aggregating its fuel, personnel and penalty cost effects.

g) ***Platoon Exploitation Rate* (*PER*):** There is no need for a certain maturity level as long as there is no comparison between instances from different models. However, this is done with the next key figure.

h) **Change of *Platoon Exploitation Rate* (*PER*):**
All models' instances except from those of the *SPH* and the *PRH* must be solved to optimality within the preset runtime limit for our purposes as the heuristics' performance could just improve even further with optimal solutions. Their *PER* thus represents a lower bound for the considered instances. The extra consideration of a task relief or of mandatory idle times, on the contrary, can lead to more or less slipstream-exploiting edge traversals than with the basic *EU-TPP* or the mere platooning model.

i) **Processing time:** There is no need for a certain maturity level as this indicator represents a simple output figure from the optimization software.

j) **Share of *EU-TPP* processing time:** There is no need for a certain maturity level. Even if some instances are not solved to optimality yet before reaching the maximum runtime limit of 3600 s, we can still use these instances to demonstrate the temporal performance of our matheuristics as a fraction of the *EU-TPP*'s processing time within this predefined time frame.

Please note that we need to exclude instances with an optimality gap of 100% from our trade-off analysis between solution quality and processing time performance for a comparison of the matheuristics with the exact model. In the end, the evaluation of computational efficiency should be based on the same instances.

Appendix H Computational efficiency: single graphs

The following figures illustrate the single platooning models' computational efficiency graphs for each type of coordination problem based on the trade-off between solution quality and temporal performance.

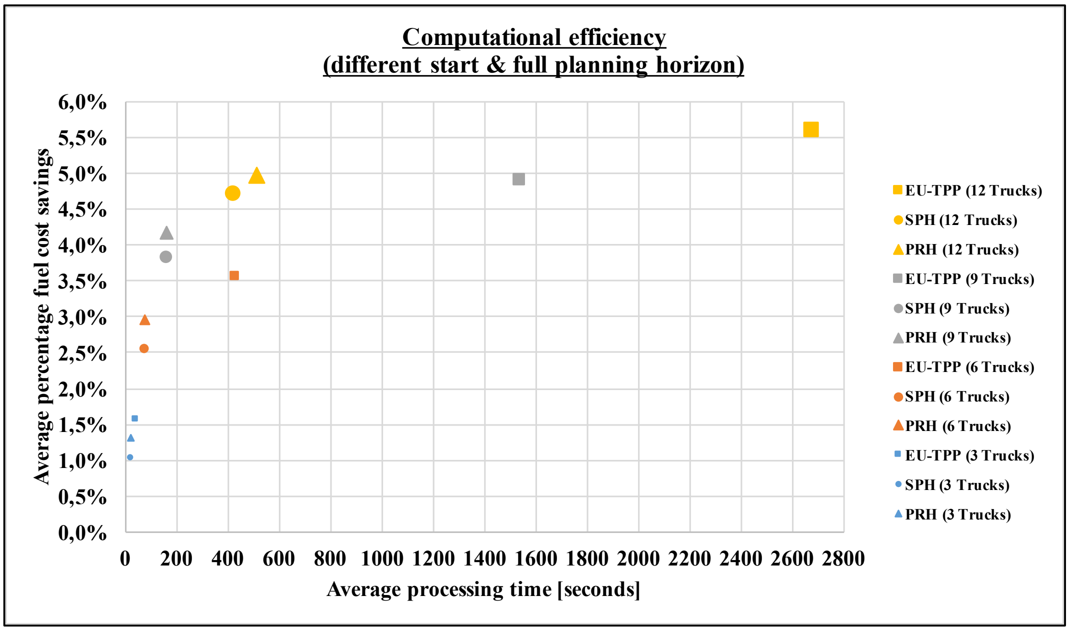

Figure 23: Computational efficiency – unrestricted different-start problem

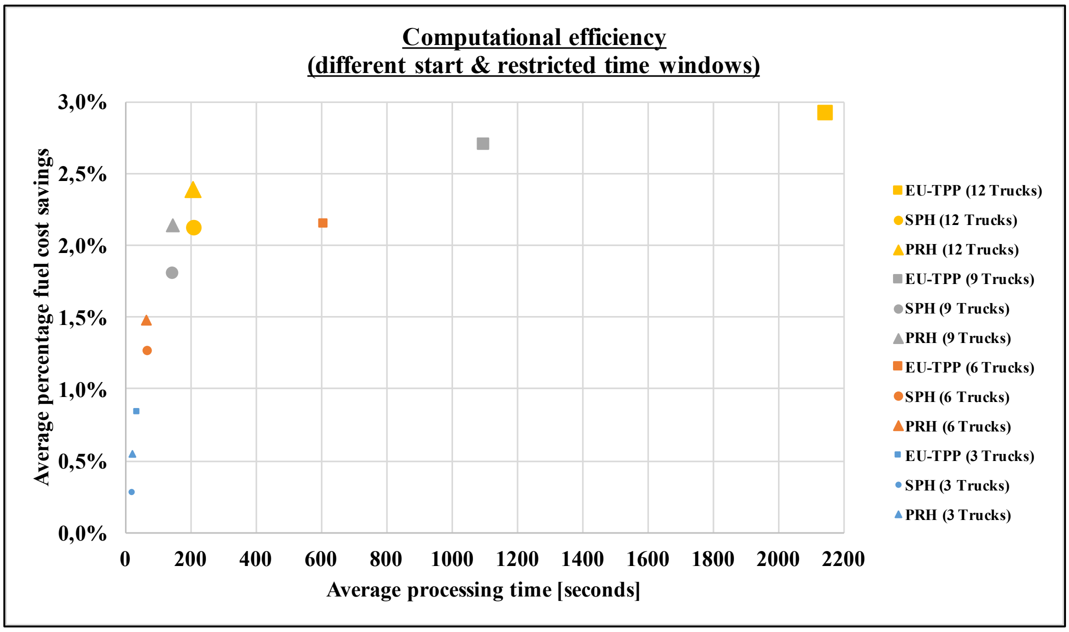

Figure 24: Computational efficiency – restricted different-start problem

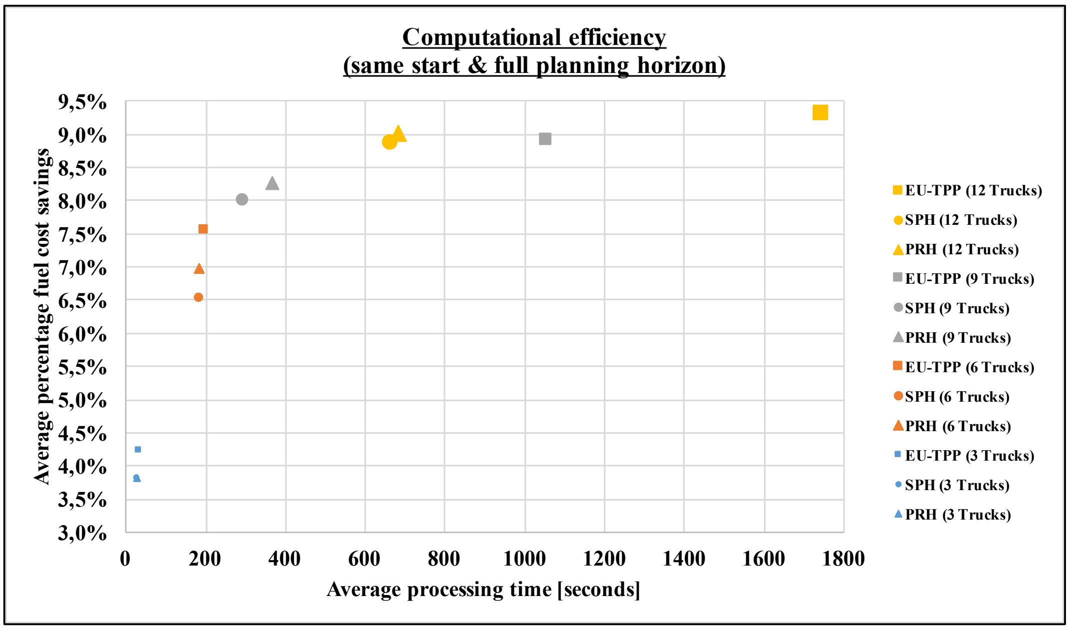

Figure 25: Computational efficiency – unrestricted same-start problem

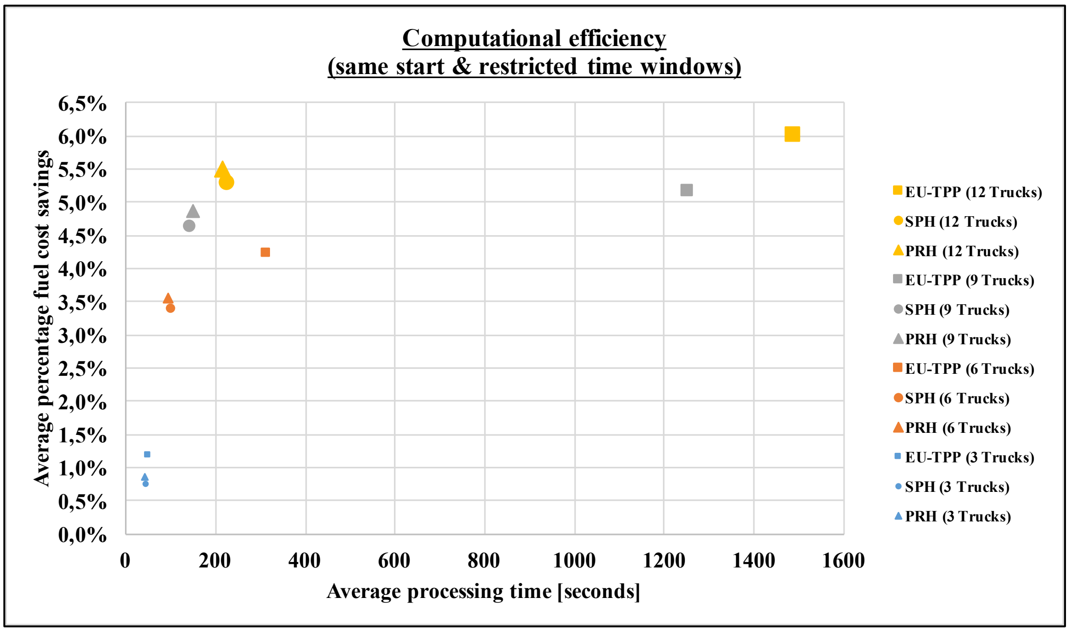

Figure 26: Computational efficiency – restricted same-start problem