Table 1. Sets, decision variables and parameters used for the formulation of the linear program.

Notation	Description	Unit
$y \in \mathcal{Y}$	year	
$p \in \mathcal{M}$	product type (incl. passengers)	p/T
$m \in \mathcal{M}$	mode	
$r \in \mathcal{R}$	O-D pair	
$k \in \mathcal{K}$	route	
$v \in \mathcal{V}$	vehicle	
$t \in \mathcal{T}$	drive-train technology	
$l \in \mathcal{L}_t$	fuel supply options for technology t	
$e \in \mathcal{E}$	edge	
$n \in \mathcal{N}$	node	
$a \in \mathcal{A}^p$	trip purpose for the transport of product type p	
$b \in \mathcal{B}_{kmtg}$	subset defined for each route k and technology t for year y	
$g \in \mathcal{G}$	age of vehicle fleet	
$\mathcal{V}_k$	$(e_1, e_2, e_3, \ldots, e_I)$	
$\mathcal{O}_k$	$(n_1, n_2, n_3, \ldots, n_I)$	
$\mathcal{U}_k$	$\{(i, e_i) \mid e_i \in \mathcal{V}_k, 1 \leq i \leq I\}$	
$\mathcal{Z}_k$	$\{(j, n_j) \mid n_j \in \mathcal{O}_k, 1 \leq j \leq J\}$	
$\mathcal{Y}_y$	$\{0, \ldots, y\}$	
$\mathcal{E}_k$	edge along route k	
$\mathcal{E}_{kmtgb}$	subset of edges within the driving range of technology t in year y along route k	
f_{ypkmtg}	transport volumes transported using technology t on mode m along route k in year y	T
h_{yprmtg}	vehicle fleet for mode m with technology t	#
h^{+}_{yprmtg}	vehicle fleet growth for mode m with technology t	#
h^{-}_{yprmtg}	vehicle fleet reduction for mode m with technology t	#
$s_{ypkmtle}$	fueling demand during annual peak hour covered at edge e of technology t with fuel supplied with supply option l along route k in year y	kWh
$s_{ypkmtln}$	fueling demand during annual peak hour covered at node n of technology t with fuel supplied with supply option l along route k in year y	kWh
$q^{+,mode\_infr}_{yet}$	installed mode infrastructure for technology t along edge e in year y	kW
$q^{+,mode\_infr}_{ynt}$	installed mode infrastructure for technology t along node n in year y	kW
$q^{+,fuel\_infr}_{yet}$	installed fueling infrastructure for technology t along edge e in year y	kW
$q^{+,fuel\_infr}_{ynt}$	installed fueling infrastructure for technology t along node n in year y	kW
$q^{+,supply\_infr}_{yle}$	capacity of supply infrastructure l installed along edge e in year y	kW
$q^{+,supply\_infr}_{yln}$	capacity of supply infrastructure l installed along node n in year y	kW
F_{yrp}	transport demand between O-D pair r for product p in year y	T
D^{spec}_{yt}	specific energy consumption of drive-train technology t in year y	kWh/km
W_{gmt}	average load of a vehicle of technology t bought in year g	T
A_{mt}	maximum age of vehicle	a
L_{gmt}	maximum annual mileage of vehicle	km
L_e	length of edge e	km
L_{nk}	distance of path k within node n	km
$Q^{mode\_infr}_{et}$	initial transport capacity for edge e on mode m	T
$Q^{fuel\_infr}_{et}$	initial fueling capacity for technology t at edge e	kW
$Q^{supply\_infr}_{le}$	inital capacity for supply l at edge e	kW
Q^{tank}_{gmt}	tank size	kWh
δ	maximum substitution rate	
α	Bass diffusion coefficient	
β	Bass diffusion coefficient	

1. Methodology and Data

$$minimize_x z \tag{1}$$

$$z = \mathrm{C}^{fueling,total} + \mathrm{C}^{vehiclestock,total} + \mathrm{C}^{transportactivity,total} + \mathrm{C}^{intangiblecosts,total} + \mathrm{C}^{paneltycosts,total} \tag{2}$$

$$\begin{aligned}\mathrm{C}^{fueling,total} = \sum_t \sum_y \left(\sum_e C^{fuel\_infr}_{yte} q^{+,fuel\_infr}_{yte} + C^{fuel\_infr}_{ytn} q^{+,fuel\_infr}_{ytn} \right) \\ + \sum_t \sum_y \left(\sum_e \sum_{kmvtl} C^{fuel}_{vtle} s_{ypkmvtle} + \sum_n \sum_{kmvtl} C^{fuel}_{vtln} \right) \\ + \sum_l \sum_y \left(\sum_e C^{supply\_infr}_{yle} q^{+,supply\_infr}_{yle} + C^{supply\_infr}_{yln} q^{+,supply\_infr}_{yln} \right)\end{aligned} \tag{3}$$

$$\mathrm{C}^{vehiclestock,total} = \sum_y \sum_v \sum_t \sum_g \left(C^{CAPEX}_{yvtg} h^{+}_{yprvtg} + C^{OM,fix}_{yvtg} h_{yprvtg} + C^{sell}_{yvtg} h^{-}_{yprvtg} + C^{OM,var} L_k \sum_k f_{y,prkmvtg} \right) \tag{4}$$

$$\mathrm{C}^{transportactivity,total} = \sum_y C^{levelized,var}_{mvt} \sum_k L_k f_{y,prkmvtg} \tag{5}$$

$$\mathrm{C}^{intangiblecosts,total} = \sum_y \sum_r \sum_{kvt} LoS_{ykvt} * VoT_{ykvt,ic} * L_k * f_{y,prkmvtg} \tag{6}$$

$$\mathrm{C}^{paneltycosts,total} = \sum_{y} \sum_{p} \sum_{r} penalty_{pry}^{budget} \tag{7}$$

$$LoS_k = \frac{L_k}{speed_v mt} + fueling\_time_{kvmt} \tag{8}$$

$C^{transport,total}$ ... Fuel costs, vehicle purchase, vehicle operation
$C^{infr,total}$ ... Investments and operational costs for fueling and mode infrastructure

$$\sum_{k \in \mathcal{K}_r} \sum_{m \in M} \sum_{t \in \mathcal{T}_m} \sum_{g \in \mathcal{G}} f_{ypakmvtg} = F_{yrp} \quad : \forall y \in \mathcal{Y}, r \in \mathcal{R}, p \in \mathcal{P} \tag{9}$$

$$h_{yprmvtg} \geq \sum_{k \in \mathcal{K}_r} \sum_{e \in \mathcal{E}_k} \sum_{n \in \mathcal{N}_k} \sum_{a \in \mathcal{A}^p} \frac{L_e + L_{nk}}{W_{ymvtg} L_{ymvtg}^{a}} f_{ypakmvtg} : \forall y \in \mathcal{Y}, r \in \mathcal{R}, p \in \mathcal{P}, m \in \mathcal{M}, v \in \mathcal{V}, t \in \mathcal{T}, g \in \mathcal{G} \tag{10}$$

$$h_{yprmvtg} = h_{(y-1)prmvt(g-1)} + h_{yprmvtg}^{+} - h_{yprmvtg}^{-} : \forall y \in \mathcal{Y}, r \in \mathcal{R}, p \in \mathcal{P}, m \in \mathcal{M}, v \in \mathcal{V}, t \in \mathcal{T}, g \in \mathcal{G} \tag{11}$$

$$h_{yprmvtg}^{-} = h_{(y-A_{mvt})prmvt(g=0)} \quad : \forall y - A_{mvt} > 0 \tag{12}$$

$$\sum_{l\in\mathcal{L}_t}\left(\sum_{e\in\mathcal{E}_{kmvtbg}} s_{ypkmvtle} + \sum_{n\in\mathcal{N}_{kmvtbg}} s_{ypkmvtln}\right) \geq \sum_{g\in\mathcal{G}}\sum_{e\in\mathcal{E}_{pkmvtbg}}\sum_{n\in\mathcal{N}_{pkmvtbg}} \gamma \frac{D^{spec}_{gmt}}{W_{gmvt}(L_e+L_{nk})} f_{ypkmvtg}$$
$$: \forall y \in \mathcal{Y}, p\in\mathcal{P}, k\in\mathcal{K}, m\in\mathcal{M}, t\in\mathcal{T}_m, b\in\mathcal{B}_{kmvtg} \quad (13)$$

$$\sum_{l\in\mathcal{L}_t}\left(\sum_{e\in\mathcal{E}_k} s_{ypkmvtle} + \sum_{n\in\mathcal{N}_k} s_{ypkmvtln}\right) = \sum_{g\in\mathcal{G}}\sum_{a\in\mathcal{A}^p}\sum_{e\in\mathcal{E}_k}\sum_{n\in\mathcal{N}_k} \gamma \frac{D^{spec}_{yt}}{W_{ymvt}(L_e+L_{nk})} f_{ypakmvtg} : \forall y \in \mathcal{Y}, p\in\mathcal{P}, k\in\mathcal{K}, m\in\mathcal{M}, t\in\mathcal{T}_m \quad (14)$$

$$\sum_{l\in\mathcal{L}_t}\left(\sum_{e\in\mathcal{U}_{ke}} s_{ypkmvtle} + \sum_{e\in\mathcal{Z}_{ke}} s_{ypkmvtln}\right) \leq \gamma \sum_{g\in\mathcal{G}} \frac{1}{W_{gmvt}} f_{ypkmvtg} * Q^{tank}_{gmvt} : \forall y, p, k, m, t, (i, e_i) \in \mathcal{V}_k, (j, n_j) \in \mathcal{Z}_k \quad (15)$$

$$Q^{mode\_infr}_{me} + \sum_{y\in\mathcal{Y}_y} q^{+,mode\_infr}_{yme} \geq \gamma \sum_{e\in\mathcal{K}_e}\sum_{p\in\mathcal{P}}\sum_{t\in T_m} f_{ypkmtg} : \forall y \in \mathcal{Y}, m\in\mathcal{M}, e\in\mathcal{E} \quad (16)$$

$$Q^{mode\_infr}_{mn} + \sum_{y\in\mathcal{Y}_y} q^{+,mode\_infr}_{ymn} \geq \gamma \sum_{n\in\mathcal{K}_n}\sum_{p\in\mathcal{P}}\sum_{t\in T_m} f_{ypkmtg} : \forall y \in \mathcal{Y}, m\in\mathcal{M}, n\in\mathcal{N} \quad (17)$$

$$Q^{fuel\_infr}_{te} + \sum_{y\in\mathcal{Y}_y} q^{+,fuel\_infr}_{yte} \geq \sum_{k\in\mathcal{K}_e}\sum_{p\in\mathcal{P}}\sum_{m\in\mathcal{M}}\sum_{l\in\mathcal{L}_t} s_{ypkmtle} : \forall y \in \mathcal{Y}, t\in\mathcal{T}, e\in\mathcal{E} \quad (18)$$

$$Q_{tn}^{fuel\_infr} + \sum_{y \in \mathcal{Y}_y} q_{ytn}^{+,fuel\_infr} \geq \sum_{k \in \mathcal{K}_n} \sum_{p \in \mathcal{P}} \sum_{m \in \mathcal{M}} \sum_{l \in \mathcal{L}_t} s_{ypkmtln} : \forall y \in \mathcal{Y}, t \in \mathcal{T}, n \in \mathcal{N} \tag{19}$$

$$Q_{le}^{supply\_infr} + \sum_{y \in \mathcal{Y}_y} q_{yle}^{+,supply\_infr} \geq \sum_{e \in \mathcal{K}_e} \sum_{p \in \mathcal{P}} \sum_{m \in M} \sum_{t \in \mathcal{T}_l} s_{ypkmtle} : \forall y \in \mathcal{Y}, l \in \mathcal{L}, e \in \mathcal{E} \tag{20}$$

$$Q_{ln}^{supply\_infr} + \sum_{y \in \mathcal{Y}_y} q_{yln}^{+,supply\_infr} \geq \sum_{e \in \mathcal{K}_n} \sum_{p \in \mathcal{P}} \sum_{m \in M} \sum_{t \in \mathcal{T}_l} s_{ypkmtln} : \forall y \in \mathcal{Y}, l \in \mathcal{L}, n \in \mathcal{N} \tag{21}$$

In addition, constraints for limiting the maximum technology substitution between time steps are introduced:

$$\pm \left(h_{yprmvt} - h_{(y-1)prmvt}\right) \leq \alpha F_{yrp} + \beta h_{(y-1)prmvt} : \forall y \in \mathcal{Y}, r \in \mathcal{R}, m \in \mathcal{M}, v \in \mathcal{V}, t \in \mathcal{T}_m \tag{22}$$

Limitations for capacity expansions:

$$Q_{me}^{mode\_infr} + \sum_{y \in \mathcal{Y}_y} q_{ymn}^{+,mode\_infr} \leq Q_{me}^{max,mode\_infr} : \forall y, m, e \tag{23}$$

$$Q_{mn}^{mode\_infr} + \sum_{y \in \mathcal{Y}_y} q_{ymn}^{+,mode\_infr} \leq Q_{mn}^{max,mode\_infr} : \forall y, m, n \tag{24}$$

$$Q_{te}^{fuel\_infr} + \sum_{y \in \mathcal{Y}_y} q_{yte}^{+,fuel\_infr} \leq Q_{yte}^{max,fuel\_infr} : \forall y, t, e \tag{25}$$

$$Q_{tn}^{fuel\_infr} + \sum_{y \in \mathcal{Y}_y} q_{ytn}^{+,fuel\_infr} \leq Q_{ytn}^{max,fuel\_infr} : \forall y, t, n \tag{26}$$

$$Q_{le}^{supply\_infr} + \sum_{y \in \mathcal{Y}_y} q_{yle}^{+,supply\_infr} \leq Q_{yte}^{max,supply\_infr} : \forall y, t, e \tag{27}$$

$$Q_{ln}^{supply\_infr} + \sum_{y \in \mathcal{Y}_y} q_{yln}^{+,supply\_infr} \leq Q_{ytn}^{max,exp,supply\_infr} : \forall y, t, n \tag{28}$$

$$\sum_{y \in \mathcal{Y}_y} q_{ymn}^{+,mode\_infr} \leq Q_{me}^{max,exp,mode\_infr} : \forall y, m, e \tag{29}$$

$$\sum_{y \in \mathcal{Y}_y} q_{ymn}^{+,mode\_infr} \leq Q_{mn}^{max,exp,mode\_infr} : \forall y, m, n \tag{30}$$

$$\sum_{y \in \mathcal{Y}_y} q_{yte}^{+,fuel\_infr} \leq Q_{yte}^{max,exp,fuel\_infr} : \forall y, t, e \tag{31}$$

$$\sum_{y \in \mathcal{Y}_y} q_{ytn}^{+,fuel\_infr} \leq Q_{ytn}^{max,exp.fuel\_infr} : \forall y, t, n \tag{32}$$

$$\sum_{y \in \mathcal{Y}_y} q_{yle}^{+,supply\_infr} \leq Q_{yte}^{max,+,supply\_infr} : \forall y, t, e \tag{33}$$

$$\sum_{y \in \mathcal{Y}_y} q_{yln}^{+,supply\_infr} \leq Q_{ytn}^{max,exp,supply\_infr} : \forall y, t, n \tag{34}$$

Monetary budget constraint:

$$\sum_{y} C_{yvtg}^{CAPEX} * h_{yr}^{+} \leq Budget_{ic} + penalty^{+,invbudget} \tag{35}$$

$$\sum_{y} C_{yvtg}^{CAPEX} * h_{yr}^{+} \geq Budget_{ic} - penalty^{-,invbudget} \tag{36}$$