Appendix of Vulnerability Assessment of Charging Stations in the Electrified Road Network

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Nomenclature

Indices

a	index of links
t	index of time steps
s	index of destinations
e	index of energy levels for EVs

Sets

$\mathcal{A}$	set of arcs
$\mathcal{N}$	set of nodes
$\mathcal{N}_{SR}$	set of origin and destination nodes
$A(i)(B(i))$	set of links whose tail(head) node is i
$A^{-1}(a)(B^{-1}(a))$	set of nodes whose tail/head link is a
$\mathcal{A}_R$	set of source arcs
$\mathcal{A}_S$	set of sink arcs

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$\mathcal{A}_G$	set of general arcs
$\mathcal{A}_C$	set of charging arcs
$\mathcal{T}$	set of time steps
$\mathcal{E}_c$	set of energy levels for the EVs belong to class c
$\mathcal{C}$	set of classes
$\mathcal{M}$	set of attack strategies

Parameters

$NC_a(t)$	number of chargers at charging link a during time step t
$N_a(t)$	capacity of link a during time step t
δ	time step length
L_a	physical length of link a
$k_{jam}/q_{max}/v_f$	jam density/ maximum flow/ free-flow speed
w	backward shock-wave speed, $w = q_{max} \cdot v_f/(q_{max} - k_{jam} \cdot v_f)$
α_a^t	average charging speed for charging link a during time step t, $\alpha_a^t = p_a^{ev}/(\eta \cdot v_f)$
$f_a^I(t)$	inflow capacity of link a during time step t
$f_a^O(t)$	outflow capacity of link a during time step t
$DG_a^s(t)$	cumulative gasoline vehicle travel demand between the entry of origin link a and destination s, at the end of time step t
$DE_a^{s,e}(t)$	cumulative electric power travel demand between the entry of origin link a and destination s with energy level e at the end of time step t
ν_a	free-flow travel time on link a, $\nu_a = L_a/(\delta \cdot v_f)$
β_a	travel time required by the backward shock wave from the exit to the entry of link a, $\beta_a = L_a/(\delta \cdot w)$

ρ_a	energy levels consumed to traverse link a
n	attack resources, i.e., number of charging stations that are allowed to damage
M	preset negative constant representing the lower bound of variable $\pi_a^4(t)$

Variables

$UG_a^s(t)$	cumulative number of GVs that enter link a to destination s by the end of time step t
$VG_a^s(t)$	cumulative number of GVs that leave link a to destination s by the end of time step t
$UE_a^{s,e}(t)$	cumulative number of EVs with energy level e that enter link a to destination s by the end of time step t
$VE_a^{s,e}(t)$	cumulative number of EVs with energy level e that leave link a to destination s by the end of time step t
μ_a	binary variable equal to 0 when charging station a is damaged and 1 otherwise

Dual Variables

$\pi_a^1(t)$	dual variable of the constraint (1)
$\pi_a^2(t)$	dual variable of the constraint (2)
$\pi_a^3(t)$	dual variable of the constraint (3)
$g\psi_a^s(t)$	dual variable of the constraint (4)
$e\psi_a^{s,e}(t)$	dual variable of the constraint (5)
$g\lambda_a^s(t)$	dual variable of the constraint (6a)
$e\lambda_a^{s,e}(t)$	dual variable of the constraint (6b)
$g\varphi_i^s(t)$	dual variable of the constraint (7a)
$e\varphi_i^{s,e}(t)$	dual variable of the constraint (7b)
$\upsilon_a^{s,e}(t)$	dual variable of the constraint (9)
$g\chi_a^{s,1}(t)$	dual variable of the constraint (10a)

$g\chi_a^{s,2}(t)$	dual variable of the constraint (10b)
$e\chi_a^{s,e,1}(t)$	dual variable of the constraint (11a)
$e\chi_a^{s,e,2}(t)$	dual variable of the constraint (11b)
$g\kappa_a^{s,1}(t)$	dual variable of the constraint that enforces variable $UG_a^s(t)$ zero
$g\kappa_a^{s,2}(t)$	dual variable of the constraint that enforces variable $VG_a^s(t)$ zero
$e\kappa_a^{s,e,1}(t)$	dual variable of the constraint that enforces variable $UE_a^{s,e}(t)$ zero
$e\kappa_a^{s,e,2}(t)$	dual variable of the constraint that enforces variable $VE_a^{s,e}(t)$ zero
$\pi_a^4(t)$	dual variable of the constraint (15)
$L_a^1(t)$	dual variable of the constraint (19a)
$L_a^2(t)$	dual variable of the constraint (19b)
$L_a^3(t)$	dual variable of the constraint (19c)
$L_a^4(t)$	dual variable of the constraint (19d)

Vectors and matrices

$\boldsymbol{x}$	vector of a mixed flow pattern, $\boldsymbol{x} = [[UG_a^s(t), VG_a^s(t), a \in \mathcal{A}/\{\mathcal{A}_C\}, s \in \mathcal{N}_{SR}, t \in \mathcal{T}], [UE_a^{s,e}(t), UE_a^{s,e}(t), a \in \mathcal{A}, s \in \mathcal{N}_{SR}, e \in \mathcal{E}, t \in \mathcal{T}]]$.
$\boldsymbol{y}$	vector of dual variables for problem (18)
$\bar{\boldsymbol{x}}$	vector of variables consisting of $\boldsymbol{x}$ and dual variables of linearization constraint (19) for problem (20)
$\boldsymbol{\mu}$	attack strategy
$\boldsymbol{A}$	coefficient matrix related to $\boldsymbol{x}$ in problem (20)
$\boldsymbol{B}$	coefficient matrix related to $\boldsymbol{\mu}$ in problem (20)
$\boldsymbol{b}$	right-hand parameters in problem (20)
$\boldsymbol{c}$	cost coefficient vector in problem (20)

Performance indices

$P(t)$ satisfaction rate of cumulative traffic demand up to time step t

$VI(t)$ relative system performance loss up to time step t, compared to normal scenario

$\mathcal{U}_a(t)$ utilization rate of FCS a during time step t under normal scenario

$\mathcal{U}_a^{\mu}(t)$ utilization rate of FCS a during time step t under attack strategy $\boldsymbol{\mu}$

$\Delta\mathcal{U}_a^{\mu}(t)$ utilization rate variation of FCS a during time step t after attack strategy $\boldsymbol{\mu}$

$GATT_s/EATT_s$ average travel time of GVs/EVs with destination s under normal scenario

$GATT_s^{\mu}/EATT_s^{\mu}$ average travel time of GVs/EVs with destination s under attack strategy $\boldsymbol{\mu}$

$\Delta GATT_s^{\mu}/\Delta EATT_s^{\mu}$ changed ratio of average travel time of GVs/EVs with destination s after attack strategy $\boldsymbol{\mu}$

Appendix A. Problem Formulation

Appendix A.1. Exact form of Ω^{-1}

$$\begin{aligned} g\lambda_a^s(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^s(t+\nu_a) - g\chi_a^{s,1}(t+1) + g\kappa_a^{s,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, t = 0 \end{aligned} \tag{A.1a}$$

$$\begin{aligned} g\lambda_a^s(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^r(t+\nu_a) + g\chi_a^{s,1}(t) - g\chi_a^{s,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall t \in \{1, \ldots, T_{max}-1\} \end{aligned} \tag{A.1b}$$

$$\begin{aligned} g\lambda_a^s(t) + \pi_a^2(t) - \pi_a^3(t) - g\psi_a^r(t+\nu_a) + g\chi_a^{s,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, t = T_{max} \end{aligned} \tag{A.1c}$$

$$\begin{aligned} -g\varphi_i^s(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) - g\chi_a^{s,2}(t+1) + g\kappa_a^{s,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), t = 0 \end{aligned} \tag{A.2a}$$

$$-g\varphi_i^s(t) + \pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t) - g\chi_a^{s,2}(t+1) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), \forall t \in \{1, \ldots, T_{max}-1\} \tag{A.2b}$$

$$-g\varphi_i^s(t) + \pi_a^1(t) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), t = T_{max} \tag{A.2c}$$

$$e\lambda_a^{s,e}(t) - \pi_a^2(t+1) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) - e\chi_a^{s,e,1}(t+1) + e\kappa_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = 0 \tag{A.3a}$$

$$e\lambda_a^{s,e}(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, \forall t \in \{1, \ldots, T_{max}-1\} \tag{A.3b}$$

$$e\lambda_a^{s,e}(t) + \pi_a^2(t) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) + e\chi_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} \tag{A.3c}$$

$$-e\varphi_i^{s,e}(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) - e\chi_a^{s,e,2}(t+1) + e\kappa_a^{s,e,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), t = 0 \tag{A.4a}$$

$$-e\varphi_i^{s,e}(t) + \pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), \forall t \in \{1, \ldots, T_{max}-1\} \tag{A.4b}$$

$$-e\varphi_i^{s,e}(t) + \pi_a^1(t) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) + e\chi_a^{s,e,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_R, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), t = T_{max} \tag{A.4c}$$

$$g\varphi_i^s(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^s(t+\nu_a) - g\chi_a^{s,1}(t+1) + g\kappa_a^{s,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), t = 0 \tag{A.5a}$$

$$g\varphi_i^s(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^r(t+\nu_a) + g\chi_a^{s,1}(t) - g\chi_a^{s,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), \forall t \in \{1, \ldots, T_{max}-\nu_a\} \tag{A.5b}$$

$$g\varphi_i^s(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) + g\chi_a^{s,1}(t) - g\chi_a^{s,1}(t+1)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), \forall t \in \{T_{max} - \nu_a + 1, \dots, T_{max} - 1\} \tag{A.5c}$$

$$g\varphi_i^s(t) + \pi_a^2(t) - \pi_a^3(t) - g\psi_a^r(t + \nu_a) + g\chi_a^{s,1}(t)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), t = T_{max} \tag{A.5d}$$

$$-g\varphi_i^s(t) - \pi_a^1(t+1) + \pi_a^3(t + \beta_a) + g\psi_a^s(t) - g\chi_a^{s,2}(t+1) + g\kappa_a^{s,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), t = 0 \tag{A.6a}$$

$$-g\varphi_i^s(t) + \pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t + \beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t) - g\chi_a^{s,2}(t+1)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), \forall t \in \{1, \dots, T_{max} - \beta_a\} \tag{A.6b}$$

$$-g\varphi_i^s(t) + \pi_a^1(t) - \pi_a^1(t+1) + g\psi_a^s(t) + g\chi_a^{s,2}(t) - g\chi_a^{s,2}(t+1)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), \forall t \in \{T_{max} - \beta_a + 1, \dots, T_{max} - 1\} \tag{A.6c}$$

$$-g\varphi_i^s(t) + \pi_a^1(t) + \pi_a^3(t + \beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, i = B^{-1}(a), t = T_{max} \tag{A.6d}$$

$$e\varphi_i^{s,e}(t) - \pi_a^2(t+1) - \pi_a^3(t) - e\psi_a^{s,e-\rho_a}(t + \nu_a) - e\chi_a^{s,e,1}(t+1) + e\kappa_a^{s,e,1}(t)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = 0 \tag{A.7a}$$

$$e\varphi_i^{s,e}(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t)(-e\psi_a^{s,e-\rho_a}(t + \nu_a)) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, e < \rho_a (e \geq \rho_a), \forall t \in \{1, \dots, T_{max} - \nu_a\} \tag{A.7b}$$

$$e\varphi_i^{s,e}(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, \forall t \in \{T_{max} - \nu_a + 1, \dots, T_{max} - 1\} \tag{A.7c}$$

$$e\varphi_i^{s,e}(t) + \pi_a^2(t) - \pi_a^3(t) + e\chi_a^{s,e,1}(t)$$
$$\leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} \tag{A.7d}$$

$$-e\varphi_i^{s,e}(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t)(e\kappa_a^{s,e,2}) - e\chi_a^{s,e,2}(t+1) + e\kappa_a^{s,e,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, e \leq E_c - \rho_a(e > E_c - \rho_a), i = B^{-1}(a), t = 0 \tag{A.8a}$$

$$-e\varphi_i^{s,e}(t) + \pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t)(e\kappa_a^{s,e,2}) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) \leq -1,$$
$$\forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, e \leq E_c - \rho_a(e > E_c - \rho_a), i = B^{-1}(a), \forall t \in \{1, \ldots, T_{max} - \beta_a\} \tag{A.8b}$$

$$-e\varphi_i^{s,e}(t) + \pi_a^1(t) - \pi_a^1(t+1) + e\psi_a^{s,e}(t)(e\kappa_a^{s,e,2}) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) \leq -1, \forall a \in \mathcal{A}_G,$$
$$\forall s \in \mathcal{N}_{SR}, e \leq E_c - \rho_a(e > E_c - \rho_a), i = B^{-1}(a), \forall t \in \{T_{max} - \beta_a + 1, \ldots, T_{max} - 1\} \tag{A.8c}$$

$$-e\varphi_i^{s,e}(t) + \pi_a^1(t) + e\psi_a^{s,e}(t)(e\kappa_a^{s,e,2}(t)) + e\chi_a^{s,e,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, e \leq E_c - \rho_a(e > E_c - \rho_a), i = B^{-1}(a), t = T_{max} \tag{A.8d}$$

$$g\varphi_i^s(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^s(t+\nu_a) - g\chi_a^{s,1}(t+1) + g\kappa_a^{s,1}(t)$$
$$\leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), t = 0 \tag{A.9a}$$

$$g\varphi_i^s(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) - g\psi_a^r(t+\nu_a) + g\chi_a^{s,1}(t) - g\chi_a^{s,1}(t+1)$$
$$\leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), \forall t \in \{1, \ldots, T_{max} - 1\} \tag{A.9b}$$

$$g\varphi_i^s(t) + \pi_a^2(t) - \pi_a^3(t) - g\psi_a^r(t+\nu_a) + g\chi_a^{s,1}(t)$$
$$\leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, i = A^{-1}(a), t = T_{max} \tag{A.9c}$$

$$-\pi_a^1(t+1) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) - g\chi_a^{s,2}(t+1) + g\kappa_a^{s,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, t = 0 \tag{A.10a}$$

$$\pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t) - g\chi_a^{s,2}(t+1) + g\kappa_a^{s,2}(t)$$
$$\leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall t \in \{1, \ldots, T_{max} - 1\} \tag{A.10b}$$

$$\pi_a^1(t) + \pi_a^3(t+\beta_a) + g\psi_a^s(t) + g\chi_a^{s,2}(t) + g\kappa_a^{s,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, t = T_{max} \tag{A.10c}$$

$$e\varphi_i^{s,e}(t) - \pi_a^2(t+1) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) - e\chi_a^{s,e,1}(t+1) + e\kappa_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = 0 \tag{A.11a}$$

$$e\varphi_i^{s,e}(t) + \pi_a^2(t) - \pi_a^2(t+1) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, e < \rho_a(e \geq \rho_a), \forall t \in \{1, \ldots, T_{max}-1\} \tag{A.11b}$$

$$e\varphi_i^{s,e}(t) + \pi_a^2(t) - \pi_a^3(t) - e\psi_a^{s,e}(t+\nu_a) + e\chi_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} \tag{A.11c}$$

$$-\pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) - e\chi_a^{s,e,2}(t+1) + e\kappa_a^{s,e,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = 0 \tag{A.12a}$$

$$\pi_a^1(t) - \pi_a^1(t+1) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) + e\kappa_a^{s,e,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, \forall t \in \{1, \ldots, T_{max}-1\} \tag{A.12b}$$

$$\pi_a^1(t) + \pi_a^3(t+\beta_a) + e\psi_a^{s,e}(t) + e\chi_a^{s,e,2}(t) + e\kappa_a^{s,e,2}(t) \\ \leq -1, \forall a \in \mathcal{A}_S, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} \tag{A.12c}$$

$$e\varphi_i^{s,e}(t) + \eta_a^{s,e}(t+2) + \pi_a^3(t) - e\chi_a^{s,e,1}(t+1) + e\kappa_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = 0 \tag{A.13a}$$

$$e\varphi_i^{s,e}(t) + \eta_a^{s,e}(t+2) - \eta_a^{s,e}(t+1) + \pi_a^4(t) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, e < \rho_a (e \geq \rho_a), \forall t \in \{1, \ldots, T_{max} - 2\} \tag{A.13b}$$

$$e\varphi_i^{s,e}(t) - \eta_a^{s,e}(t+1) + \pi_a^4(t) + e\chi_a^{s,e,1}(t) - e\chi_a^{s,e,1}(t+1) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} - 1 \tag{A.13c}$$

$$e\varphi_i^{s,e}(t) + \pi_a^4(t) + e\chi_a^{s,e,1}(t) \\ \leq 1, \forall a \in \mathcal{A}_G, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, t = T_{max} \tag{A.13d}$$

$$-e\varphi_i^{s,e}(t) - \eta_a^{s,e}(t+2) - \pi_a^4(t) - e\chi_a^{s,e,2}(t+1) - \upsilon_a^{s,e}(t) + e\kappa_a^{s,e,2}(t+1) \\ \leq -1, \forall a \in \mathcal{A}_C, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), t = 0 \tag{A.14a}$$

$$-e\varphi_i^{s,e}(t) - \eta_a^{s,e}(t+2) + \eta_a^{s,e}(t+1) - \pi_a^4(t) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) + \upsilon_a^{s,e}(t) - \upsilon_a^{s,e}(t+1) \\ \leq -1, \forall a \in \mathcal{A}_C, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), \forall t \in \{1, \ldots, T_{max} - 2\} \tag{A.14b}$$

$$-e\varphi_i^{s,e}(t) + \eta_a^{s,e}(t+1) - \pi_a^4(t) + e\chi_a^{s,e,2}(t) - e\chi_a^{s,e,2}(t+1) + \upsilon_a^{s,e}(t) - \upsilon_a^{s,e}(t+1) \\ \leq -1, \forall a \in \mathcal{A}_C, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), t = T_{max} - 1 \tag{A.14c}$$

$$-e\varphi_i^{s,e}(t) - \pi_a^4(t) + e\chi_a^{s,e,2}(t) + \upsilon_a^{s,e}(t) \\ \leq -1, \forall a \in \mathcal{A}_C, \forall s \in \mathcal{N}_{SR}, \forall e \in \mathcal{E}, i = B^{-1}(a), t = T_{max} \tag{A.14d}$$

Based on the above constraints, we can write Ω^{-1} as:

$$\Omega^{-1} = \{\boldsymbol{y} | \text{Subject to (A.1) - (A.14)}\} \tag{A.15}$$

Appendix A.2. Exact form of Ω_L^{-1}

The form of Ω_L^{-1} is similar to Ω^{-1}:

$$\Omega_L^{-1} = \{(\boldsymbol{y}, \boldsymbol{\mu}) | \boldsymbol{y} \text{ subject to (A.1) - (A.14) and } (19a) - (19d) \text{ in the main text}, \boldsymbol{\mu} \in \mathcal{M}\} \tag{A.16}$$

Appendix A.3. Exact form of the dual subproblem and master problem

The objective function of the dual subproblem is formulated as follows:

$$\min_{\bar{\boldsymbol{x}}\in\Omega_{DSP}} \boldsymbol{\varpi} = \sum_{s\in\mathcal{N}_{SR}}\sum_{t\in\mathcal{T}}\sum_{a\in\mathcal{A}/\{\mathcal{A}_C,\mathcal{A}_S\}}[UG_a^s(t)-VG_a^s(t)] + \sum_{s\in\mathcal{N}_{SR}}\sum_{t\in\mathcal{T}}\sum_{a\in\mathcal{A}/\mathcal{A}_S}\sum_{e\in\mathcal{E}}[UE_a^{s,e}(t)-VE_a^{s,e}(t)]$$
$$+M\sum_{a\in\mathcal{A}_C}\sum_{t\in\mathcal{T}}[\mu_a\cdot L_a^2(t)+L_a^3(t)\cdot(1-\mu_a)+L_a^4(t)] \tag{A.17}$$

where $L_a^1(t), L_a^2(t), L_a^3(t), L_a^4(t)$ are the dual variables of the linearization constraints, corresponding to (19a)-(19b) in the main text. $\bar{\boldsymbol{x}} = [[UG_a^s(t), VG_a^s(t), a\in\mathcal{A}/\{\mathcal{A}_C\}, s\in\mathcal{N}_{SR}, t\in\mathcal{T}], [UE_a^{s,e}(t), UE_a^{s,e}(t), a\in\mathcal{A}, s\in\mathcal{N}_{SR}, e\in\mathcal{E}, t\in\mathcal{T}], [L_a^1(t), L_a^2(t), L_a^3(t), L_a^4(t), a\in\mathcal{A}_C, \forall t\in\mathcal{T}]]$ is the basic feasible solution of the dual subproblem.

$$L_a^1(t)+L_a^2(t)+L_a^3(t)+L_a^4(t)\geq -NC_a(t), \forall a\in\mathcal{A}_C, \forall t \tag{A.18}$$

$$\sum_{s\in\mathcal{N}_{SR}}\sum_{e\in\mathcal{E}}[UE_a^{s,e}(t)-VE_a^{s,e}(t)]\leq L_a^1(t)-L_a^3(t), \forall a\in\mathcal{A}_C, \forall t \tag{A.19}$$

$$\Omega_{DSP} = \{\bar{\boldsymbol{x}}|\text{Subject to (A.18) - (A.19), (1) - (7), (9) - (12) in the main text}\} \tag{A.20}$$

Appendix B. Data Description

The experimental electrified road network is selected from [1]. The used parameters of this studied network are listed in Tables B.1 and B.2. The node ID, its corresponding town or city name and its population within this area are listed in Table B.3. The cities or towns connected source-sink nodes are those whose population is more than 11000. Considering their geographic distances among these nodes and their population, the gravity model is used to generate the daily traffic demand. The generic form of the gravity model [2] is usually written as $f_{od} = P_o^\alpha P_d^\beta / D_{od}^\gamma$, where P_o and P_d are the population sizes of origin a and destination d, respectively, D_{od} is the shortest distance between them, α, β and γ are fitting parameters. We set $\alpha=\beta=0.92$ and $\gamma=1$, in this study. To consider the worst-case scenario, the traffic volumes at 17:00 and 18:00 are adopted, which is the peak of traffic and accounts for approximately 15.3% of the whole daily traffic, in the basic time-of-day patterns [3]. The traffic volumes usually show the directional differences and it is difficult to get the applicable statistics for time-of-day travel by direction for each O-D pair [3]. For simplicity, only one direction is randomly selected for each O-D pair and traffic volumes in the other direction are ignored. The obtained traffic demand is shown in Table B.4.

According to Ref. [4], the electricity demand in U.S. has peak hours similar to traffic volumes, and the demand does not change a lot during this period. For simplicity, it is assumed that the base load at each bus is constant during this period and follows the standard test data [5].

References

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Table B.1: Parameters of the studied highway network

Link ID	Start	End	ν_a	β_a	ρ_a	Type	$L_a k_{jam}$	f_a^I / f_a^O	Lanes
1/101	2/1	1/2	5	10	5	G	13910	500	2
2/102	2/3	3/2	3	6	3	G	8346	500	2
3/103	3/8	8/3	4	8	4	G	5564	250	1
4/104	1/5	5/1	3	6	3	G	8346	500	2
5/105	2/5	5/2	3	6	3	G	8346	500	2
6/106	2/6	6/2	3	6	3	G	8346	500	2
7/107	3/4	4/3	1	2	1	G	1391	250	1
8/108	5/6	6/5	1	2	1	G	2782	500	2
9/109	4/6	6/4	3	6	3	G	4173	250	1
10/110	4/7	7/4	2	4	2	G	2782	250	1
11/111	4/8	8/4	3	6	3	G	4173	250	1
12/112	6/7	7/6	5	10	5	G	13910	500	2
13/113	6/7	7/6	5	10	5	G	6955	250	1
14/114	7/8	8/7	2	4	2	G	5564	500	2
15/115	7/8	8/7	2	4	2	G	2782	250	1
16/116	1/10	10/1	4	8	4	G	11128	500	2
17/117	10/14	14/10	3	6	3	G	8346	500	2
18/118	5/15	14/5	5	10	5	G	6955	250	1
19/119	11/14	14/11	2	4	2	G	5564	500	2
20/120	5/9	9/5	2	4	2	G	5564	500	2
21/121	6/9	9/6	2	4	2	G	5564	500	2
22/122	9/11	11/9	2	4	2	G	5564	500	2
23/123	11/9	9/11	2	4	2	G	5564	500	2
24/124	11/12	12/11	4	4	4	G	11128	500	2
25/125	6/12	12/6	4	4	4	G	11128	500	2
26/126	12/13	13/12	3	6	3	G	4173	250	1
27/127	7/13	13/7	2	4	2	G	2782	250	1
29/129	2/201	201/2	0	0	0	S/R	inf	inf	
30/130	10/202	202/10	0	0	0	S/R	inf	inf	
36/136	5/203	203/5	0	0	0	S/R	inf	inf	
31/131	11/204	204/11	0	0	0	S/R	inf	inf	
32/132	12/205	205/12	0	0	0	S/R	inf	inf	
33/133	14/206	206/14	0	0	0	S/R	inf	inf	
34/134	8/207	207/8	0	0	0	S/R	inf	inf	
35/135	3/208	208/3	0	0	0	S/R	inf	inf	

Table B.2: Parameters of the studied traffic-power system

Parameters	Values
v_f (m/h)	65
k_{jam}(veh/m)	214
δ (min)	6
q_{max} (veh/h/lane)	2500
p_a^{ev} (kW)	80
η (kMh/mile)	0.4
ϕ (\$/h)	13
C	1
E_c	10
α_a^t (ELs/δ)	3
Initial EL of EV	3

Table B.3: Population of the towns and cities

Node ID	Name	Population	Node ID	Name	Population
1	Zebulon	4526	2	Rocky Mount	56650
3	Tarboro	11255	4	Pinetops	1351
5 & 6	Wilson	49436	7	Farmville	4695
8	Greenville	86142	9	Kenly	1344
10	Raleigh	418099	11	Selma & Smithfield	17901
12	Goldsboro	35609	13	Snow Hill	1611
14	Clayton	16529			

Table B.4: O-D pairs and their traffic demand

Link ID	Node ID	Demand	Link ID	Node ID	Demand
130	203	6460	136	204	620
129	202	5700	129	208	620
130	206	5500	133	203	460
134	202	5380	131	205	460
130	205	3720	133	204	460
131	202	3560	131	201	400
136	201	2400	134	204	380
129	207	1720	129	206	320
136	207	1520	136	208	320
134	205	1120	133	205	280
130	208	960	134	206	260
132	203	940	132	208	160
132	201	760	135	204	100
135	207	680	135	206	60