Range Extension With Optimal Powertrain Operations for Multi E-Axle Based Heavy Duty Electric Vehicle

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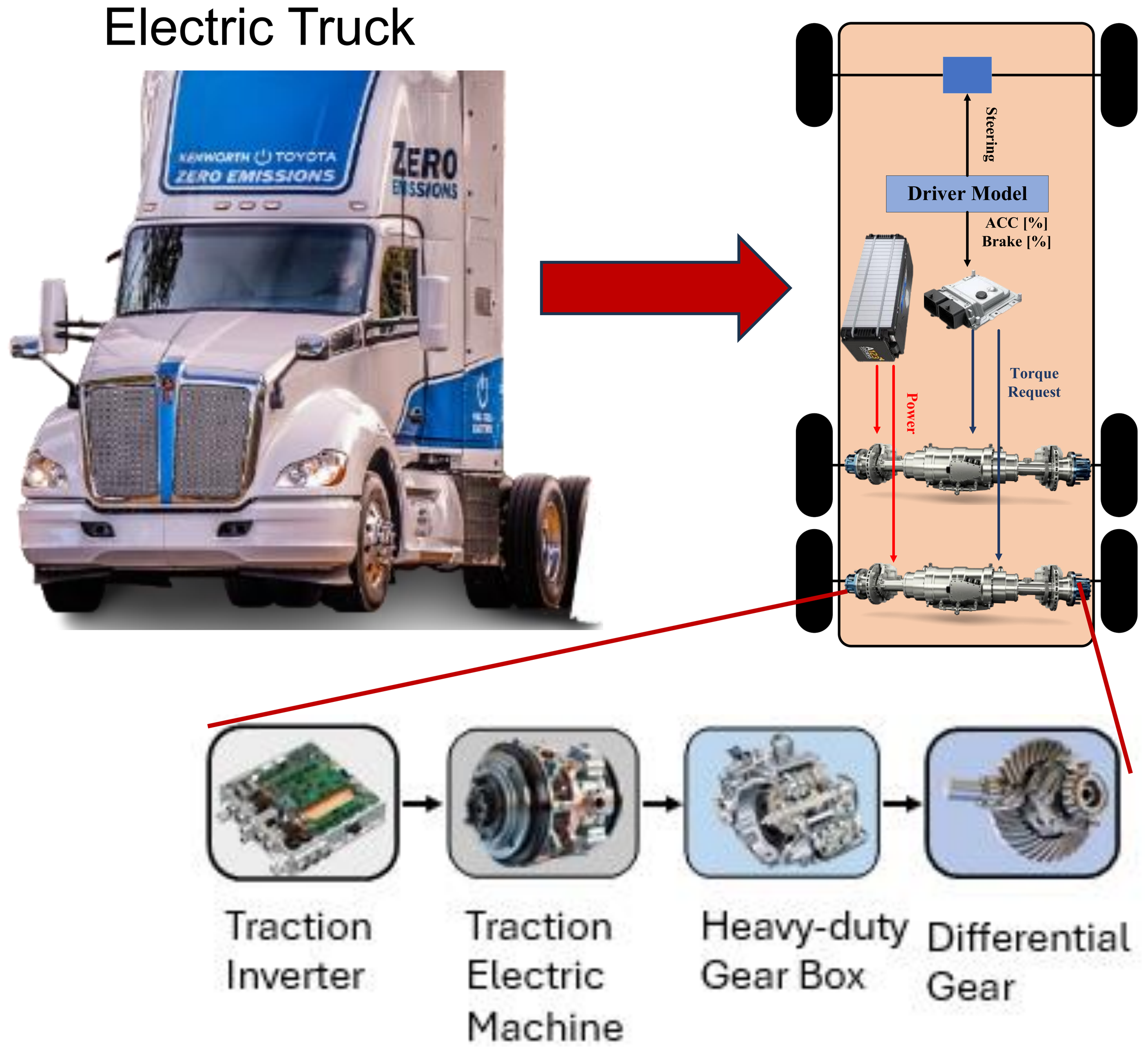
Background/Motivation

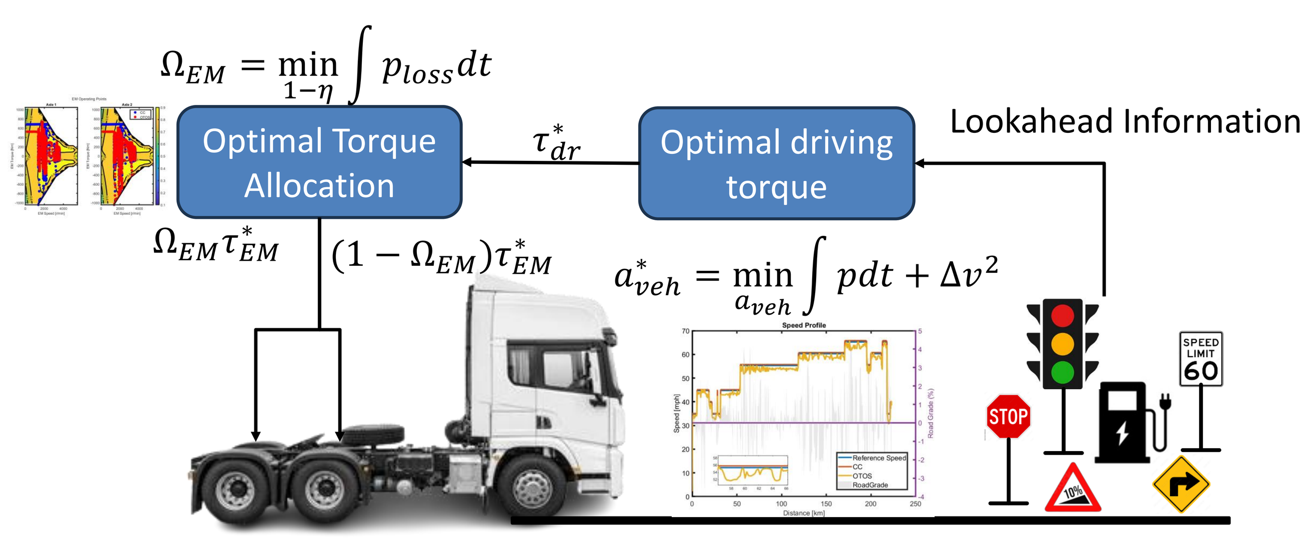
Range extension improves freight efficiency, which is critical for fully electric heavy-duty trucks



Concern: Range anxiety is the significant hurdle in the adoption of heavy duty electric vehicles.

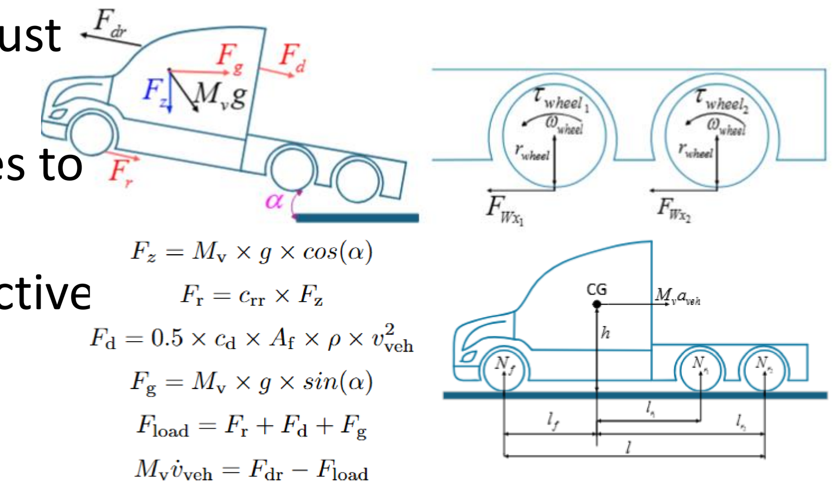
Proposed Solution:

- This research work proposes the two step energy optimal traction control.
- In step I, it uses lookahead information to generate energy optimal driving torque profile
- In Step II, it allocates the torque optimally



Vehicle Dynamics

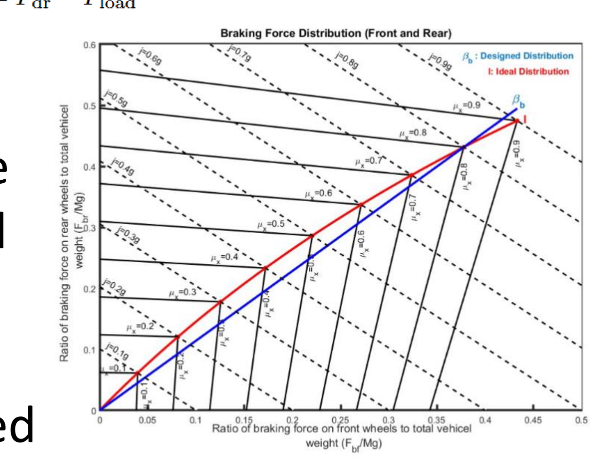
the vehicle must overcome resistive forces to generate the necessary tractive effort for acceleration.



$$F_z = M_v \times g \times cos(\alpha)$$
$$F_r = c_{rr} \times F_z$$
$$F_d = 0.5 \times c_d \times A_f \times \rho \times v_{veh}^2$$
$$F_g = M_v \times g \times sin(\alpha)$$
$$F_{load} = F_r + F_d + F_g$$
$$M_v \dot{v}_{veh} = F_{dr} - F_{load}$$

Braking Force Distribution

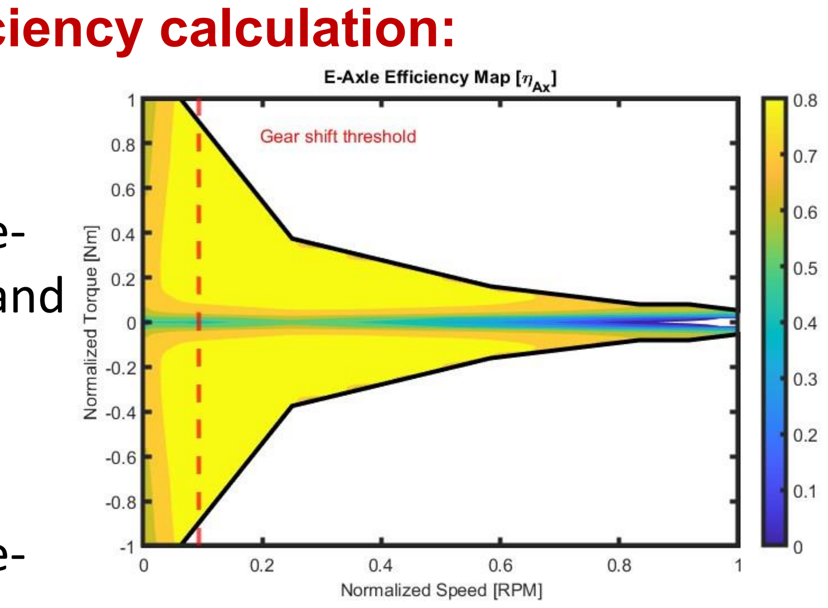
Red lines is the ideal the blue line is the designed distribution for the mechanical brakes and the area between the red and blue line is the room for regenerative braking.



$$F_{bf} = \mu_x \times N_f$$
$$F_{br} = F_{br_1} + F_{br_2} = \mu_x \times (N_{r1} + N_{r2})$$

E-axle efficiency calculation:

The X-axis represents normalized e-axle speed, and the Y-axis represents requested normalized e-axle torque.



The color contours indicate efficiency levels, where yellow regions denote high efficiency (up to 80%) and blue regions indicate low efficiency.

Optimal Driving Torque

Cost Function:

$$J_1 = \sum_{i=1}^{N} 100 \times (1-\zeta) P_{load_i} dt_i + \zeta (v_{ref_i} - v_{veh_i})^2$$

$$\begin{cases} a_{min}(M_v) \leq a_{veh} \leq a_{max}(M_v) \\ v_{min} \leq v_{veh} \leq v_{lim} \\ 0 \leq \kappa \leq \kappa_{peak} (\kappa - \mu \text{ linear region}) \end{cases}$$

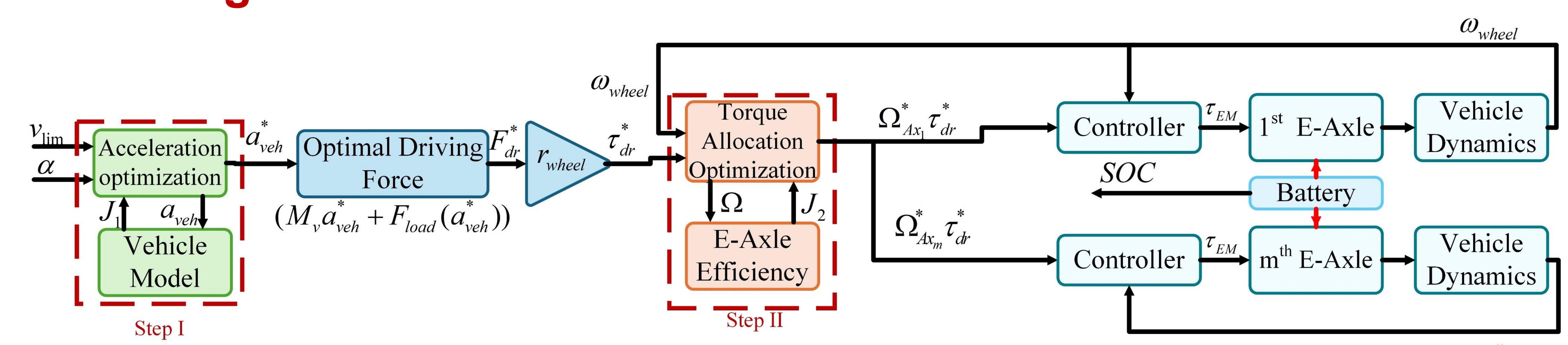
$$a_{max}(M_v) = \frac{\lambda_g \lambda_d \left(\sum_{i=1}^{m} \tau_{EM_{max_{Ax\,i}}}\right) - F_{load} r_{wheel}}{1.1 M_v r_{wheel}}$$

$$a_{min}(M_v) = \frac{\lambda_g \lambda_d \left(\sum_{i=1}^{m} \tau_{EM_{min_{Ax\,i}}}\right) - F_{load} r_{wheel}}{1.1 M_v r_{wheel}}$$

$$a_{veh}^* = \underset{a_{veh}}{\operatorname{argmin}} J_1$$

$$F_{dr}^* = M_v a_{veh}^* + F_{load}(a_{veh}^*)$$

Block Diagram



Optimal Torque Allocation

Cost Function:

$$p_{req} = \omega_{wheel} \times F_{dr}^* \times r_{wheel}$$

$$p_{out} = \sum_{i=1}^{m} \Omega_{Ax_i} \times \eta_{Ax_i} \times p_{req}$$

$$J_2 = \sum_{i=1}^{N} (1 - \eta_{total_i}) p_{req}$$

$$\eta_{total} = \frac{p_{out}}{p_{req}}$$

$$\begin{cases} 0 \leq \Omega_{Ax_i} \leq 1 \\ \sum_{i=1}^{m} \Omega_{Ax_i} \\ \lambda_{g_{Ax_1}} = \lambda_{g_{Ax_2}} = \ldots = \lambda_{g_{Ax_m}} \end{cases}$$

$$[\Omega_{Ax_1}^*, \Omega_{Ax_1}^*, \ldots, \Omega_{Ax_m}^*] = \underset{[\Omega_{Ax_1}^*, \Omega_{Ax_2}^*, \ldots, \Omega_{Ax_m}^*]}{\operatorname{argmin}} J_2$$

Optimization Techniques

Sequential Quadratic Prog. (SQP)

$$\min_{\Delta a_{veh}} \frac{1}{2} \Delta a_{veh}^\top H_k \Delta a_{veh} + \nabla J_1(a_{veh_k})^\top \Delta a_{veh}$$

subject to linearized constraints:

$$\nabla g(a_{veh_k})^\top \Delta a + g(a_{veh_k}) = 0,$$
$$\nabla h(a_{veh_k})^\top \Delta a + h(a_{veh_k}) \leq 0$$

$$\min_{\mathbf{d}} \nabla J_2(\mathbf{\Omega}^k)^T \mathbf{d} + \frac{1}{2} \mathbf{d}^T \mathbf{H}_k \mathbf{d}$$

subject to

$$\nabla h(\mathbf{\Omega}^k)^T \mathbf{d} + h(\mathbf{\Omega}^k) = 0$$
$$\nabla g(\mathbf{\Omega}^k)^T \mathbf{d} + g(\mathbf{\Omega}^k) 0$$

Interior Point (IP)

$$\phi(a_{veh}) = J_1(a_{veh}) - \mu \sum_j \ln(b_j - g_j(a_{veh}))$$

$$\mathcal{L}_\mu(\mathbf{\Omega}) = J_2(\mathbf{\Omega}) - \mu \sum_{i=1}^{m} [\ln(\Omega_{Ax_i}) + \ln(1 - \Omega_{Ax_i})]$$

Dynamic Prog. (DP)

$$a_{veh_k}^* = \arg\min_{a_{veh_k}} \left[w_1 P_{load,k} \Delta t_k + w_2 (v_{ref,k} - v_{veh_k})^2 + V_{k+1}(v_{veh_k} + a_{veh_k} \Delta t_k) \right.$$

Brute Force (BF)

$$S = \left\{ 0 + 0.05k \,\middle|\, \begin{array}{l} 0 \leq \Omega_{Axi} \leq 1, \quad \forall i = 1, \ldots, m \\ k = 0, 1, 2, \ldots, 20 \\ \sum_{i=1}^{m} \Omega_{Axi} = 1 \end{array} \right\}$$

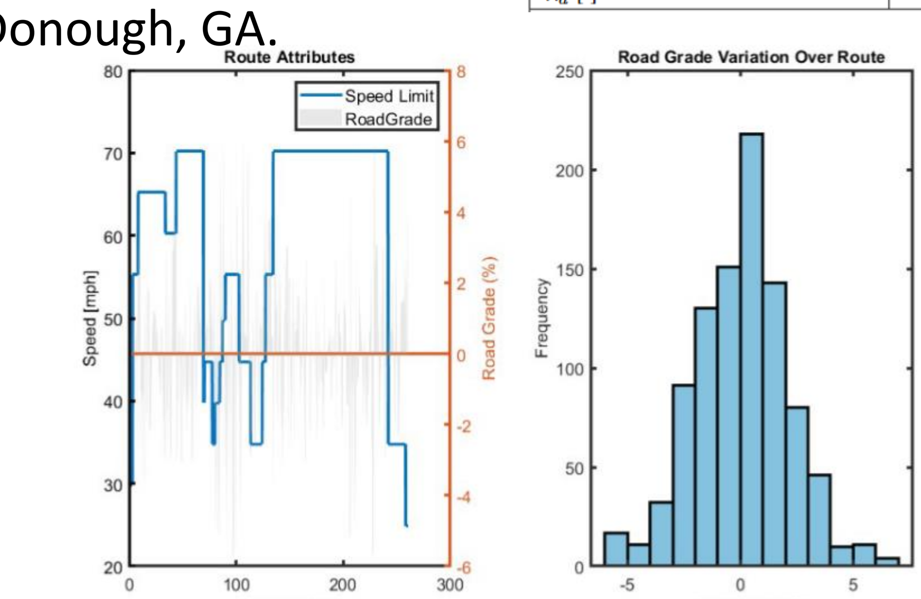
$$\mathbf{\Omega}^* = \arg\min_{\mathbf{\Omega} \in S} J_2(\mathbf{\Omega})$$

Simulation Variables	
Look-ahead horizon (d) [m]	100
Segments (N) [-]	10
dx [m]	10
Route length [km]	260
Weight factor w_1 [-]	50
Weight factor w_2 [-]	1
Vehicle Parameters	
Rolling resistance coefficient c_{rr}	0.005
Frontal area A_f [m^2]	8.48
Drag coefficient c_d [-]	0.6
Vehicle mass M_{veh} [kg] @ no load	8000
Vehicle mass M_{veh} [kg] @ 50% load	18000
Vehicle mass M_{veh} [kg] @ 100% load	36000
λ_g [-]	[2.79, 1.39]
λ_d [-]	3.91

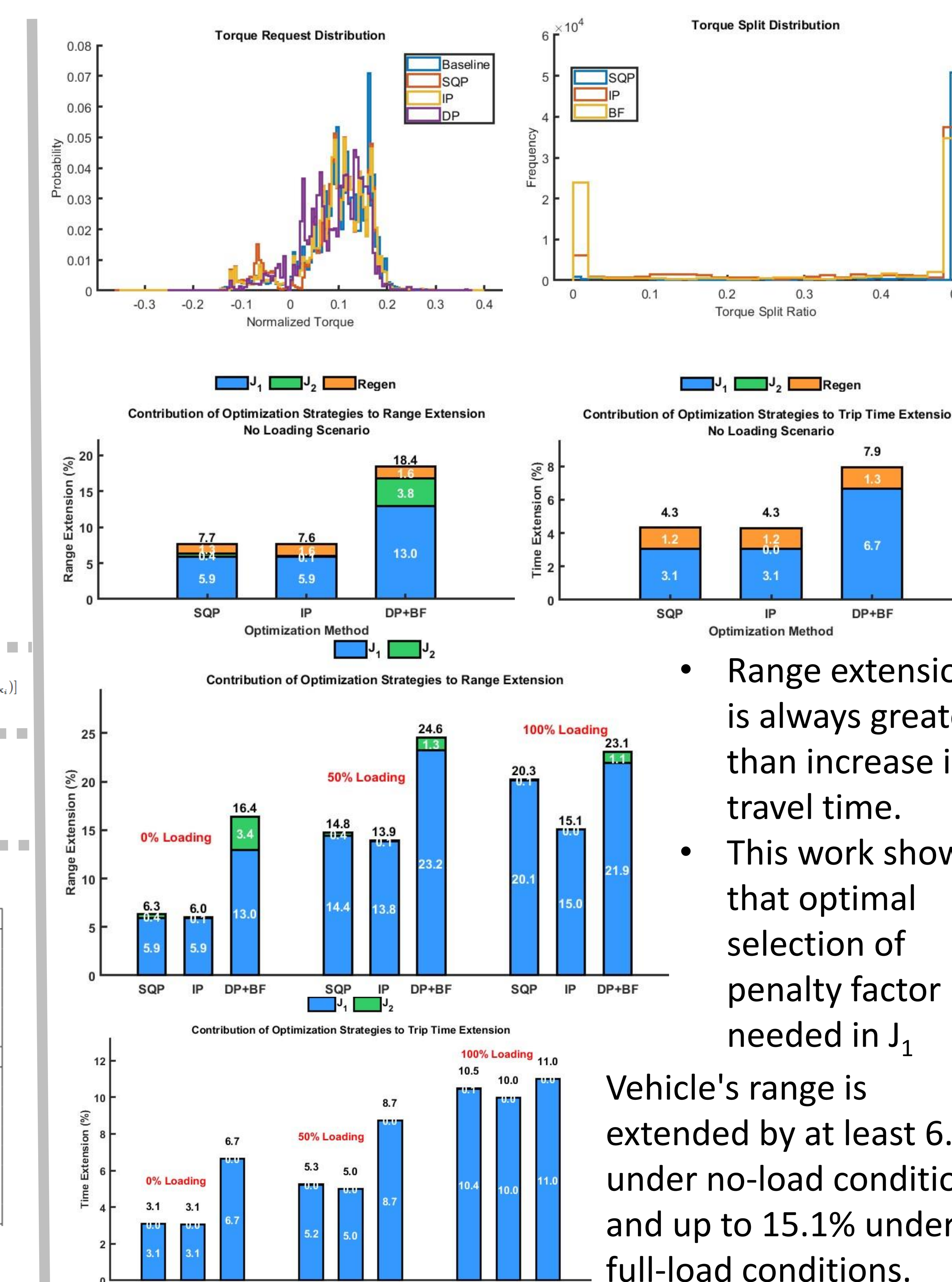
Simulation & Route

Start: Fulton Parkway, College Park, GA

End: Jodeco Road, McDonough, GA.



Results



- Range extension is always greater than increase in travel time.
- This work shows that optimal selection of penalty factor needed in J_1

Vehicle's range is extended by at least 6.0% under no-load conditions and up to 15.1% under full-load conditions.

Reference

1. A. H. Safder, A. Hanif and Q. Ahmed, "Optimal Torque Allocation for Energy Efficient Operation of Dual E-Axle Based Powertrain for Heavy Duty Electric Vehicles," 2025 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS), Anaheim, CA, USA, 2025, pp. 1-6, doi: 10.1109/ITEC63604.2025.11098060.
2. A. H. Safder, A. Hanif and Q. Ahmed, "Look Ahead Information-Based Optimal Control of Traction Electric Machine for Energy-Efficient Operations," *2024 IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, Lahore, Pakistan, 2024, pp. 1-6, doi: 10.1109/COMPEL57542.2024.10614027.