Follow the Sun and Go with the Wind: Carbon-Footprint Optimized Timely E-Truck Transportation

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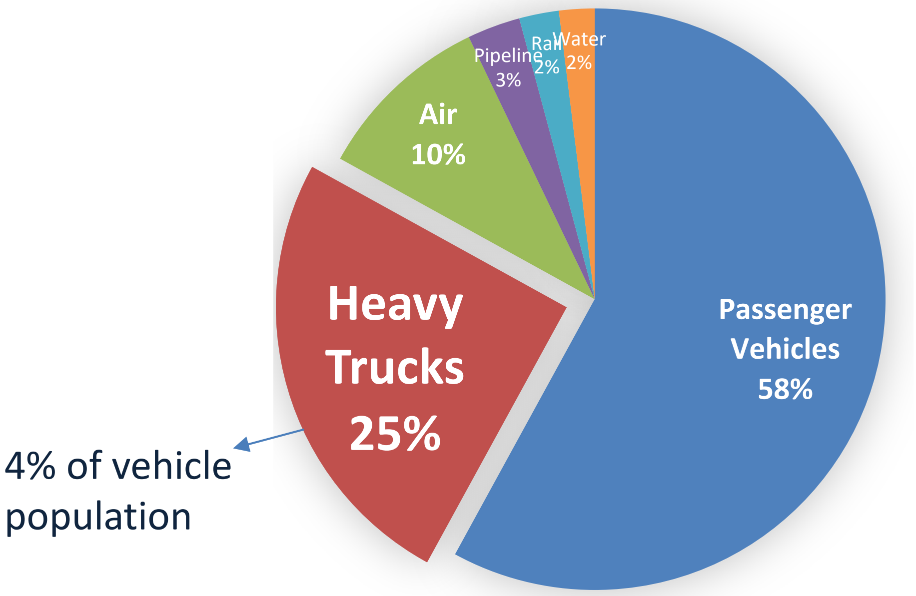
US Trucking Industry: A Top-20 Economy with High Environmental Impact

- U.S. freight tonnage: 11B (72% of all freight)
- U.S. freight revenue: **$875.5B**

Rank	Country	GDP (USD billion)
1	United States	23,315
2	China	17,734
3	Japan	4,940
…	….	…
18	Saudi Arabia	833
19	Turkey	815
20	Switzerland	812

GDP rank in 2021
source: world bank

- Carbon emission of U.S. heavy trucks: 456.6M
- 25% of transportation sector (8.8% of whole U.S.)

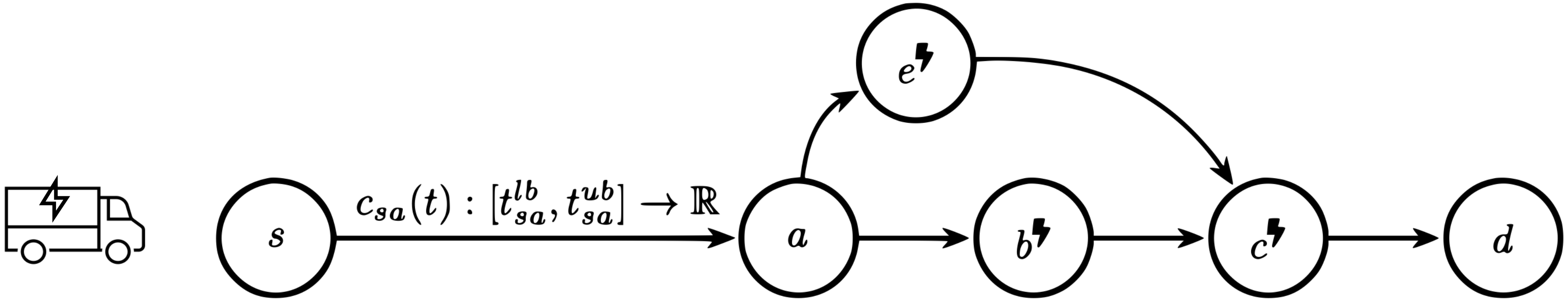


Carbon emissions of U.S. transportation secto
source: transportation energy data book

E-Truck: Future Towards Net-Zero

- □ High energy efficiency
  - – Electric motor: ~95%
  - – Internal combustion engine (ICE): ~35%
- □ Improve the air quality
- □ Carbon optimized truck operation saves 28% carbon.

Carbon Footprint Optimized Timely Transportation



- **Objective**
  - Minimize the carbon footprint incurred at each charging stop
- **Constraints**
  - State of Charge (SoC) constraints
  - Deadline constraint
- **Design space**
  - Path planning, speed planning, and charge planning

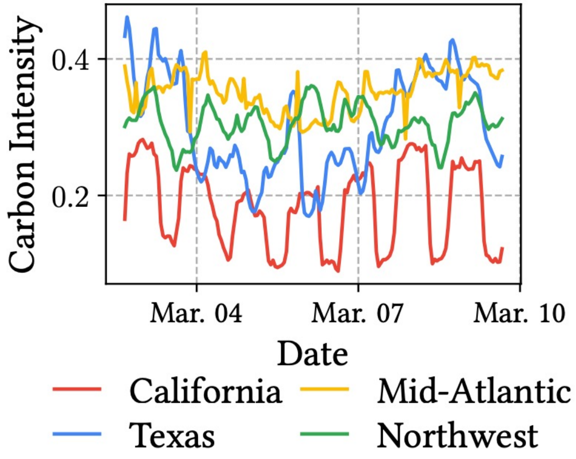
Design Space

Charge planning
- When, where, and how long to charge
- Carbon intensity is diverse geographically and temporally
- Carbon footprint = carbon intensity × charged energy

Path Planning
- Energy-related factors: distance, congestion, road type…

Speed Planning
- A faster speed means more energy consumption

	Carbon intensity (kg/kWh)
Coal	1.02
Natural gas	0.39
Petroleum	0.91
Renewable	**0**



Research Landscape

	Charge planning	Path planning	Speed planning	Hard deadline	Truck type
[1,2,3]	N/A	✓	✓	✓	ICE
[4]	N/A	✗	✓	✗	ICE
[5]	✓	✓	✓	✗	Electric
[6]	✗	✗	✓	✓	Electric
Current practice			**Human intelligence**		
This work	✓	✓	✓	✓	Electric

[1] L. Deng, et al, Energy-Efficient Timely Transportation of Long-Haul Heavy-Duty Trucks. IEEE Transactions on Intelligent Transportation Systems, 2017.
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[3] W. Xu, et al, Ride the Tide of Traffic Conditions: Opportunistic Driving Improves Energy Efficiency of Timely Truck Transportation. IEEE Transactions on Intelligent Transportation Systems, 2023.
[4] E, Hellström, at al, Look-ahead control for heavy trucks to minimize trip time and fuel consumption. Control Engineering Practice, 2009.
[5] M. Strehler, et al, Energy-efficient shortest routes for electric and hybrid vehicles. Transportation Research Part B: Methodological, 2017.
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Our Contributions

Important and challenging problem

- We identify and study an important and challenging problem, namely the carbon footprint optimization problem for e-trucks

Efficient algorithm

- Performance guarantee:
  - Convergence rate,
  - Polynomial run time per iteration
  - Performance bound

Novel formulation

- It reveals an elegant problem structure with low model complexity
- It is widely applicable beyond this work

Extensive simulation

- Based on real-world traces
- Carbon-optimized solutions achieve up to 28% carbon reduction

The Carbon Footprint Optimization (CFO) Problem

Input
- ❑ Graph $G = (V, E)$, speed limits
- ❑ Origin s, destination d, deadline T
- ❑ The e-truck parameters
- ❑ Charge functions $\phi(t)$
- ❑ Carbon intensity functions $\pi(\tau)$

Output
- ❑ Path selection $\vec{x}$
- ❑ Travel time $\vec{t}$
- ❑ Wait time $\vec{t}^w$, charge time $\vec{t}^c$

Objective

Minimize carbon footprint

Constraints
- ❑ Ensure positive state of charge (SoC) at each road segment
- ❑ Arrive the destination before deadline

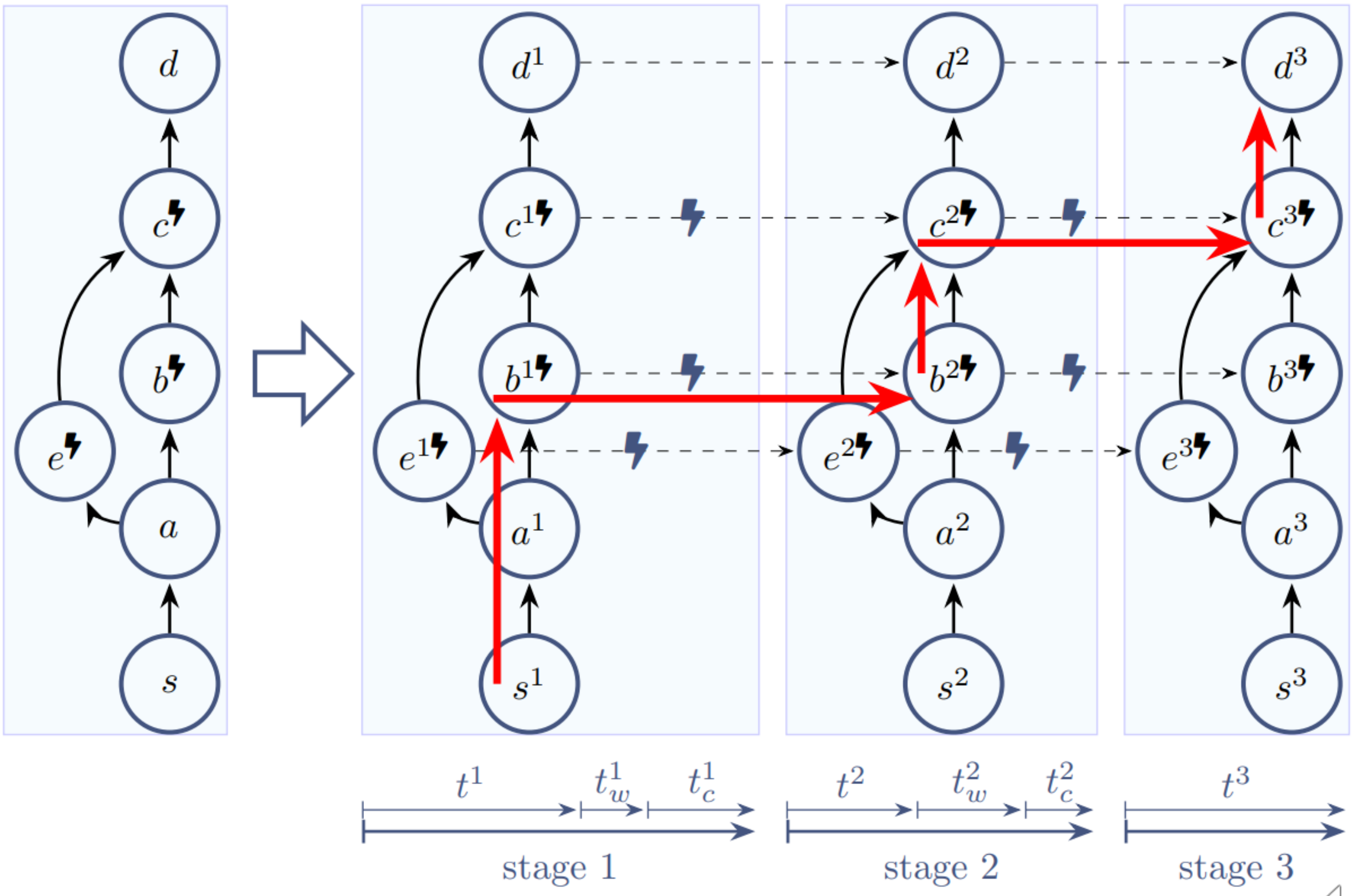
Remark
- ❑ The CFO problem is NP-hard.
- ❑ Common approaches (e.g., branch and bound) incur a large time complexity

Explore Problem Structure: Stage-Expanded Graph

Key observation: Given the charging planning, we can efficiently solve subproblems between charging stops.

Benefits: It reveals an elegant problem structure with low model complexity

Result: The CFO problem is a *Generalized Restricted Shortest Path (GRSP)* problem on the stage-expanded graph



The Dual Subgradient Approach

$$\max_{\vec{\lambda}\geq 0} D(\vec{\lambda}) = \max_{\vec{\lambda}\geq 0} \boxed{\min_{\substack{(\vec{x},\vec{y})\in\mathcal{P},\\ \vec{\beta}\in\mathcal{S}_{\alpha},\vec{\tau}\in\mathcal{T}_{\tau},\vec{t}\in\mathcal{T}}} L(\vec{x},\vec{y},\vec{t},\vec{\beta},\vec{\tau},\vec{\lambda})} \leftarrow D(\lambda)$$

- At the iteration k
  - Compute the dual function $D(\vec{\lambda}_k)$
    - Solve the easy subproblems in parallel
      - (Single-variable problem) determine the speed planning for each road segment
      - (4-variable problem) determine the charge scheduling for each charging station
    - (An integer problem) solve the path and charging location selection problem
  - Update $\vec{\lambda}$ via the subgradient direction: $\vec{\lambda}_{k+1} = \left[\vec{\lambda}_k + \theta_k \frac{\partial D}{\partial \lambda}(\lambda_k)\right]_+$

Solve the Integer Problem

At the iteration k

- Compute the dual function $D(\vec{\lambda}_k)$
  - Solve the easy subproblems in parallel
    - (Single-variable problem) determine the speed planning for each road segment
    - (4-variable problem) determine the charge scheduling for each charging station
  - (An integer problem) solve the path and charging location selection problem
- Update $\vec{\lambda}$ via the subgradient direction: $\vec{\lambda}_{k+1} = \left[\vec{\lambda}_k + \theta_k \frac{\partial D}{\partial \lambda}(\lambda_k)\right]_+$

Theorem: The problem of determining path and charge locations is equivalent to a shortest path problem on an extended charging station graph

Intuition: The optimal values of the subproblems are the cost for each road segment and charging station

Performance Analysis

Theorem [convergence rate]: Let D^* be the optimal dual objective and let $\overline{D_K}$ be the maximum dual value over K iterations. For some constant C, we have

$$D^* - \overline{D_K} \leq \frac{C}{\sqrt{K}}$$

Convergence rate of $\frac{1}{\sqrt{K}}$.

Theorem [time complexity]: The time complexity per iteration is $\tilde{O}(|V|^2|E|)$

Polynomial run time per iteration

Theorem [posterior bound]: Let OPT be the optimal objective. If our algorithm produces a feasible solution at iteration k with objective ALG, then $ALG - OPT$ is bounded by $(-\vec{\lambda}^T\vec{\delta})$. Here $\vec{\delta}$ is the value of constraint functions.

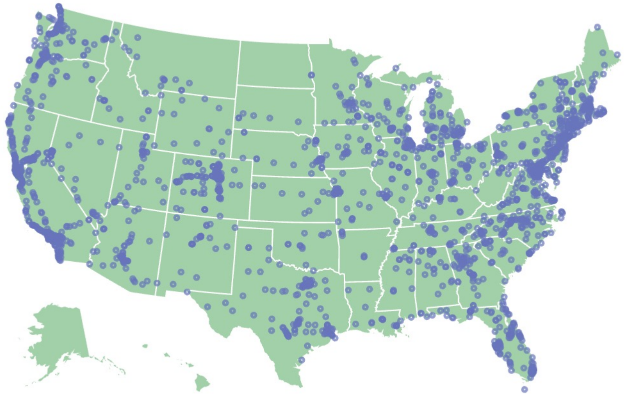
When the solution is active at all constraints (i.e., $\vec{\delta} = 0$), then we find the optimal solution

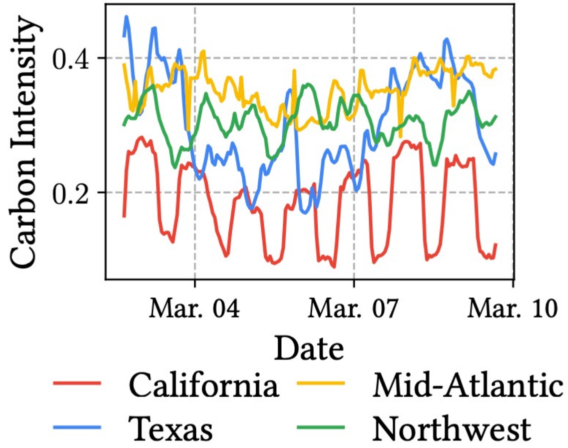
Simulation Setup

- ❑ Highway network: U.S. national highway network
  - ❑ 84,505 nodes and 178,238 edges
  - ❑ 2,555 charging stations

- ❑ 500 origin-destination pairs longer than 800 miles from Freight Analysis Framework (FAF)

- ❑ Carbon intensity data from U.S. Energy Information Administration (EIA)





Simulation Results

Compared to the fastest path

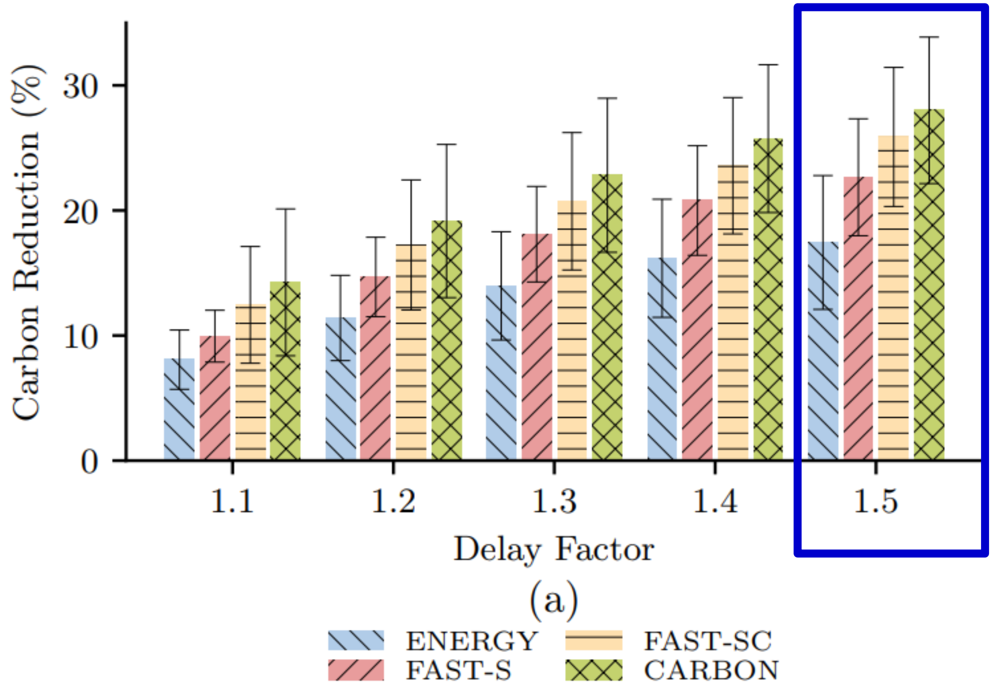
- ❑ The carbon-optimized solutions save up to 28% carbon footprint

Compared to energy-efficient solution

- ❑ The carbon-optimized solutions save up to 9% carbon footprint

Compared to ICE truck

- ❑ E-truck saves up to 59% carbon as compared to ICE trucks



Conclusion and Future Work

Summary

- ❑ Important and Challenging CFO problem
- ❑ Novel formulation and efficient approach which is widely applicable beyond CFO
- ❑ Simulation results: 28% carbon reduction

Future work

- ❑ Explore the potential of our approach in other applications
- ❑ Explore the problem with uncertainty

Thank you!

https://sujunyan.github.io/cfo-page/