Energy-Efficient Timely Transportation of Long-Haul Heavy-Duty Trucks

Lei Deng[1] Mohammad H. Hajiesmaili[1]
Minghua Chen[1] Haibo Zeng[2]

[1]Department of Information Engineering
The Chinese University of Hong Kong, Hong Kong

[2]Department of Electrical and Computer Engineering
Virginia Tech, Blacksburg, VA, USA

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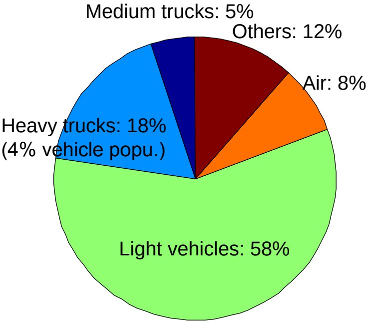
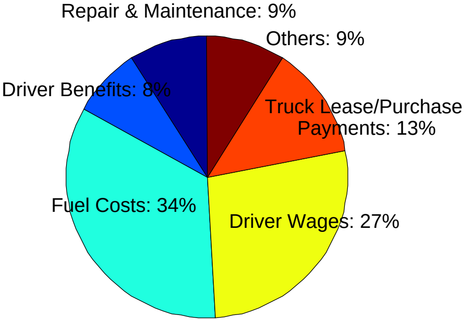
Heavy-Duty Trucks Are Energy Hungry



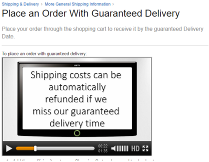
Transportation energy use
(US 2013, source: US DOE)



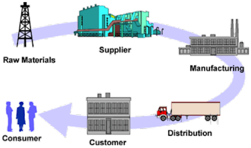
Operational costs of trucking
(US 2014, source: ATRI)

Truck Operation Centers around Timely Delivery

Perishable goods



Amazon SLA



Logistic role in a supply chain

(source: Internet)

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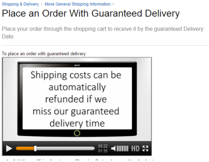

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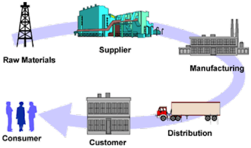

Logistic role in a supply chain

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As estimated by US FHWA, unexpected delay can increase freight cost by 50% to 250%

How to Reduce Fuel Consumption in Timely Transportation?

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- Use more fuel-efficient heavy-duty trucks
  - Designs better engines, drivetrains, aerodynamics and tires, etc.

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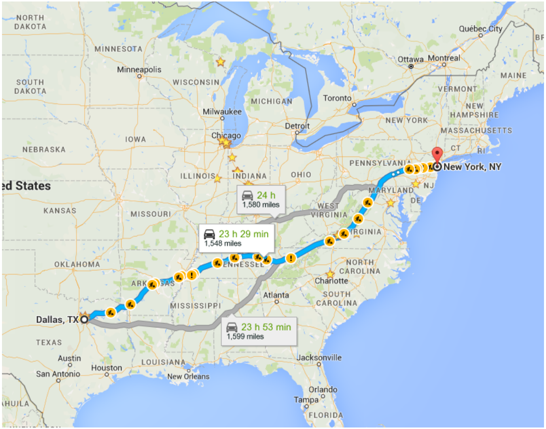
- Use more fuel-efficient heavy-duty trucks
  - Designs better engines, drivetrains, aerodynamics and tires, etc.
- Operate heavy-duty trucks more economically
  - Reduce idling energy consumption
  - Platoon more than one trucks
  - Route planning
  - Speed planning
  - etc.

Route Planning

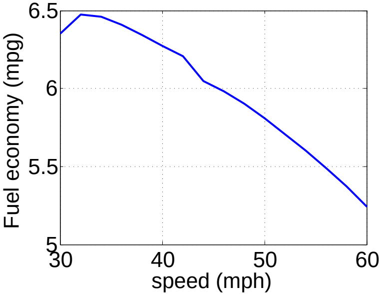


Different routes from Dallas to New York (source: Google Map)

Fuel-related factors:

- mileages
- congestions
- road grades
- surface types
- etc.

Speed Planning



Fuel economy v.s. speed for a 36-ton truck
(source: ADVISOR)

Our Problem and Contributions

Our Problem

- Objective: minimize the energy consumption of a heavy-duty truck
- Constraint: a hard delay constraint
- Design Space: both route planning and speed planning

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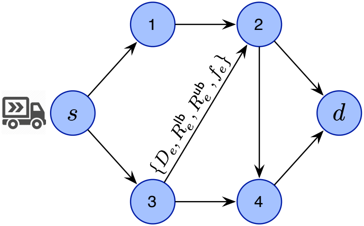
Our Contributions

- Formulate the problem and prove that it is NP-Complete
- Propose an FPTAS with complexity $O(\frac{mn^2}{\epsilon^2})$
- Propose a heuristic algorithm with complexity $O(m + n\log n)$
- Use extensive simulations over real-world US highway networks to show our solutions achieve up to 17% fuel consumption reduction than the fastest/shortest path algorithm

System Model



- Highway Network: $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $n = |\mathcal{V}|, m = |\mathcal{E}|$

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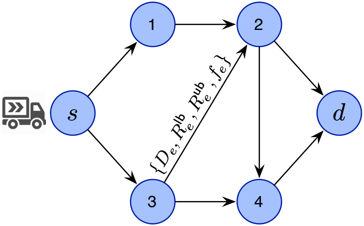

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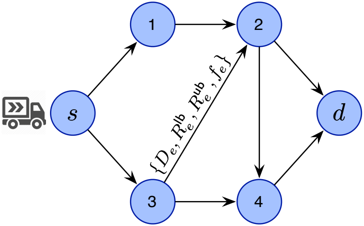

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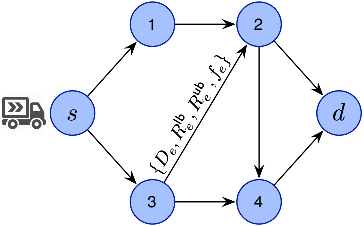

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- Fuel-Rate-Speed Function: f_e
  - $f_e(x)$ is the (instantaneous) fuel consumption rate (gallons per hour, gph) when the truck runs x mph on e
  - Road-dependent
  - Assume $f_e(\cdot)$ is polynomial and strictly convex over $[R_e^{\text{lb}}, R_e^{\text{ub}}]$

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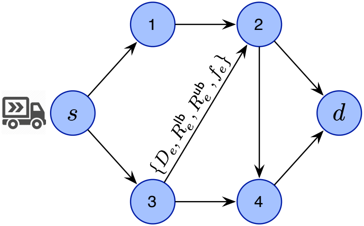

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- (Source, Dest, Hard Delay): (s, d, T)

Problem Formulation

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Path Selection (Route Planning)

$$x_e = \begin{cases} 1, & \text{Edge } e \text{ is on the selected path;} \\ 0, & \text{otherwise.} \end{cases}$$

$$\mathcal{X} \triangleq \{\boldsymbol{x} \in \{0,1\}^m : \text{ One } s - d \text{ path is selected}\}$$

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Speed Optimization (Speed Planning)

$$t_e > 0 : \text{Edge-}e \text{ travel time}$$

$$\mathcal{T} \triangleq \left\{\boldsymbol{t} : t_e^{\mathsf{lb}} \le t_e \le t_e^{\mathsf{ub}}, \forall e\right\} : \text{ speed limits}$$

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Fuel Consumption

Travel Time: t_e

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Fuel Consumption

Travel Time: $t_e \Rightarrow$ Travel Speed: $\frac{D_e}{t_e} \Rightarrow$ Fuel Consumption Rate: $f_e(\frac{D_e}{t_e})$

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Fuel Consumption

Travel Time: $t_e \Rightarrow$ Travel Speed: $\frac{D_e}{t_e} \Rightarrow$ Fuel Consumption Rate: $f_e(\frac{D_e}{t_e})$

$\Rightarrow$ Total Fuel Consumption: $t_e \cdot f_e(\frac{D_e}{t_e}) \triangleq c_e(t_e)$

Problem Formulation

PAth selection and Speed Optimization (PASO)

$$\begin{aligned} \min_{\boldsymbol{x}\in\mathcal{X},\boldsymbol{t}\in\mathcal{T}} \quad & \sum_{e\in\mathcal{E}} x_e \cdot c_e(t_e) \\ \text{s.t.} \quad & \sum_{e\in\mathcal{E}} x_e t_e \le T \end{aligned}$$

Problem Formulation

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Challenges

- Mixed discrete-continuous optimization: $x_e \in \{0,1\}$, $t_e > 0$
- Non-linear non-convex: $\sum_{e\in\mathcal{E}} x_e t_e \le T$

Complexity-Hardness-related Theoretical Results

Theorem

PASO is NP-Complete.

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Definition (Fully Polynomial Time Approximation Scheme (FPTAS))

An algorithm is an FPTAS for PASO if for any given $\epsilon \in (0, 1)$, it can find a $(1 + \epsilon)$-approximate solution in the sense that the solution is feasible and the corresponding fuel consumption is at most $(1 + \epsilon)$OPT, and the time complexity is polynomial in both the problem size and $\frac{1}{\epsilon}$.

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Theorem

PASO has an FPTAS with network-induced time complexity $O(\frac{mn^2}{\epsilon^2})$.

FPTAS still Incurs High Complexity in Practice

- The network-induced complexity of the FPTAS is $O(\frac{mn^2}{\epsilon^2})$
- Still large if we consider practical highway networks with $m, n \sim 10^4$

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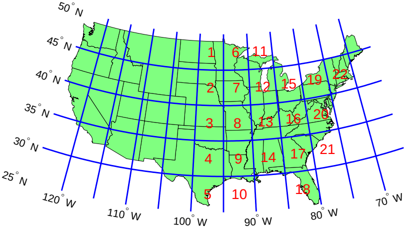

Consider the regions 17&18

n	m	ϵ	Run Time	Memory
3274	7465	0.1	3511s	14.76GB

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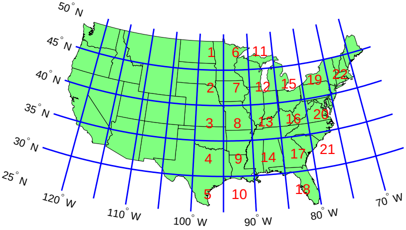

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n	m	ϵ	Run Time	Memory
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- We will introduce a fast dual-based heuristic algorithm with network-induced time complexity $O(m + n \log n)$

Relax the Hard Delay for PASO

PASO

$$
\begin{aligned}
\min_{\boldsymbol{x}\in\mathcal{X},\boldsymbol{t}\in\mathcal{T}} \quad & \sum_{e\in\mathcal{E}} x_e \cdot c_e(t_e) \\
\text{s.t.} \quad & \sum_{e\in\mathcal{E}} x_e t_e \leq T, \qquad [\lambda]
\end{aligned}
$$

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PASO-Relaxed(λ)

$$\min_{\boldsymbol{x}\in\mathcal{X},\boldsymbol{t}\in\mathcal{T}} \sum_{e\in\mathcal{E}} x_e \cdot (c_e(t_e) + \lambda t_e)$$

- λ is the *delay* price
- PASO-Relaxed(λ) can be solved efficiently by a shortest-path like algorithm

Key Observations and Result

PASO-Relaxed(λ)

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- For properly selected λ, solving PASO-Relaxed(λ) gives either an optimal solution or a feasible solution with a small optimality-gap to PASO

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- We propose a heuristic to find the proper λ in $O((m + n\log n))$, much faster than the FPTAS ($O(\frac{mn^2}{\epsilon^2})$)

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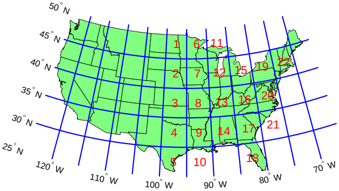
- We propose a heuristic to find the proper λ in $O((m + n\log n))$, much faster than the FPTAS ($O(\frac{mn^2}{\epsilon^2})$)
- We characterize a condition under which an optimal solution to PASO is obtained, and the condition is satisfied in most instances in our case study based on real-world settings

Our Dual-Based Heuristic Runs fast

- The FPTAS has a network-induced complexity of $O(\frac{mn^2}{\epsilon^2})$
- The dual-based heuristic has a network-induced complexity of $O((m + n \log n))$



- Consider the regions 17&18

Alg	n	m	ϵ	Run Time	Memory
FPTAS	3274	7465	0.1	3511s	14.76GB
Heuristic	3274	7465	-	2s	0.29GB

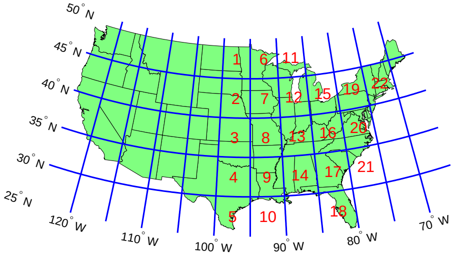
Simulation: Dataset

- Highway Network: US National Highway Systems (CHM Project)
- Elevation: USGS Elevation Point Query Service
- Speed Limits: HERE Map
- Heavy-duty Truck and Fuel Consumption Data: ADVISOR Simulator

Kenworth T800

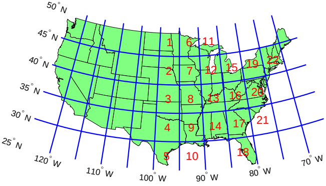
Drag Coefficient c_d	0.7
Frontal area A_f	8.5502 m^2
Glider Mass	2,552kg
Cargo Mass	33,234kg

Simulation: Network Statistics



n	m	avg D_e (mile)	avg R_e^{lb} (mph)	avg R_e^{ub} (mph)	avg $\lvert\theta\rvert$ (%)
38213	82781	3.26	36.43	54.19	0.82

Evaluate/Compare FPTAS and Heuristic



Instance: (s, d, T)

No.	**Network**			**Input**	
	Reg.	n	m	Instance	ϵ
S1	1&2	1185	2568	(1,2,8)	0.1
S2	17&18	3274	7465	(18,17,10)	0.1
S3	1-22	38213	82781	(4,22,40)	0.1
S4	1&2	1185	2568	(1,2,8)	0.05

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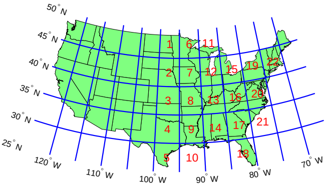

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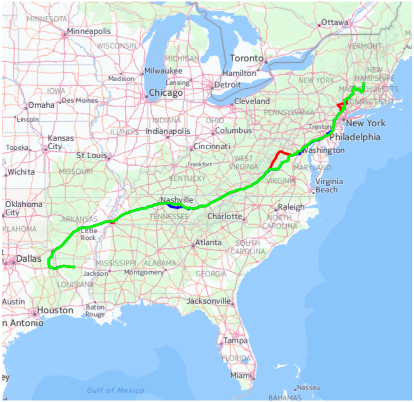
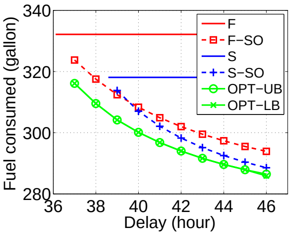
No.	Performance (gallon)		Time (second)		Memory (GB)	
	Heuri. LB/UB	FPTAS	Heuri.	FPTAS	Heuri.	FPTAS
S1	74.811/74.811	74.812	1	50	0.29	2.73
S2	60.2795/60.2795	60.2798	2	3511	0.29	14.76
S3	290.744/290.744	-	365	-	0.29	-
S4	74.811/74.811	74.812	1	126	0.29	6.84

Compare Performance with Baselines (One Instance)



Shortest/Fastest/Optimal paths
of $(s, d, T) = (9, 22, 40)$



Performance of instance
$(s, d) = (9, 22)$

Compare Performance with Baselines (All Instances)

Average performance of all instances (s, d, T)

Sol.	**Avg Time Incre.(%)**	**Avg Dist. Incre.(%)**	**Avg Fuel Incre.(%)**	**Avg Fuel Econ.(mpg)**
Fastest path	-	1.71	20.14	5.05
Shortest path	2.82	-	16.40	5.13
Heuristic	32.89	0.18	0.02	5.96
OPT-LB	32.95	0.17	-	5.96

Conclusion

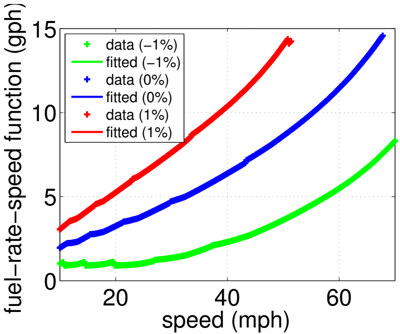
- Propose the problem of energy efficient timely transportation
- Prove that the problem is NP-Complete but has an FPTAS
  - The FPTAS has time complexity $O(\frac{mn^2}{\epsilon^2})$
- Propose a fast dual-based heuristic algorithm
  - It has time complexity $O(m + n \log n)$
  - It has extremely good performance in practice
- Extensive simulation over real-world US highway systems
  - 17% fuel consumption reduction than the fastest path algorithm
  - 14% fuel consumption reduction than the shortest path algorithm

Q&A

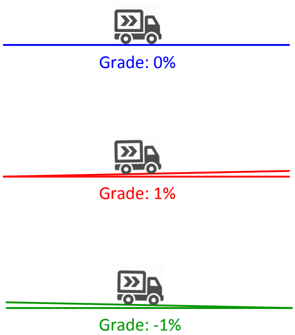
Thank You!

Backup Slides

Fuel-Rate-Speed Function

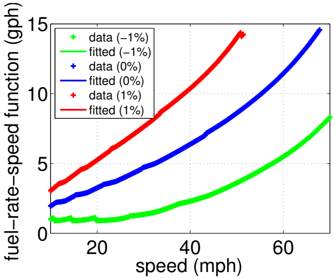


$f_e(\cdot)$ for a 36-ton truck for grades 0%, $\pm 1\%$
Polynomial fit: $f_e(x) = a_e x^3 + b_e x^2 + c_e x + d_e$
(source: ADVISOR)

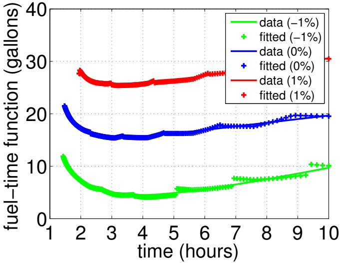


Preprocessing

Define fuel-time function $c_e(t_e) = t_e \cdot f_e\left(\frac{D_e}{t_e}\right)$. Without loss of optimality, we assume that $c_e(\cdot)$ is strictly convex and strictly decreasing over $[t_e^{\text{lb}}, t_e^{\text{ub}}]$.



$f_e(\cdot)$ for a 36-ton truck (source: ADVISOR)



$c_e(\cdot)$ for the truck over a 100-mile road (source: ADVISOR)