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

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Heavy-Duty Trucks Are Energy Hungry

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

- Light vehicles: 58%
- Medium trucks: 5%
- Heavy trucks: 18% (4% vehicle popu.)
- Air: 8%
- Others: 12%

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

- Fuel Costs: 34%
- Driver Wages: 27%
- Repair & Maintenance: 9%
- Driver Benefits: 8%
- Truck Lease/Purchase Payments: 13%
- Others: 9%
Truck Operation Centers around Timely Delivery

Perishable goods

Amazon SLA

(source: Internet)

Logistic role in a supply chain

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

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How to Reduce Fuel Consumption in Timely Transportation?

- Use more fuel-efficient heavy-duty trucks
- Design 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.
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  - etc.
Route Planning

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

Fuel-related factors:
- mileages
- congestions
- road grades
- surface types
- etc.
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

This study generalizes previous works by considering both route planning and speed planning.

Our Contributions

- Formulate the problem and prove that it is NP-Complete
- Propose an FPTAS with complexity $O(mn^2 \epsilon^2)$
- 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
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- 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
Highway Network: $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $n = |\mathcal{V}|, m = |\mathcal{E}|$
System Model

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- Road/Edge Distance: $D_e$ (miles)
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- Road/Edge Distance: \( D_e \) (miles)
- Min/Max Speed: \( R_e^{lb} / R_e^{ub} \) (mph)
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- **Road/Edge Distance**: $D_e$ (miles)
- **Min/Max Speed**: $R_e^{lb} / R_e^{ub}$ (mph)
- **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 $[R_e^{lb}, R_e^{ub}]$
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Highway Network: $G = (\mathcal{V}, \mathcal{E})$ with $n = |\mathcal{V}|, m = |\mathcal{E}|$

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- Assume $f_e(\cdot)$ is polynomial and strictly convex over $[R_{lb}^e, R_{ub}^e]$

(Source, Dest, Hard Delay): $(s, d, T)$
Problem Formulation

Path Selection (Route Planning)

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

\[ X \equiv \{ x \in \{0, 1\}^m : \text{One } s-d \text{ path is selected} \} \]

Speed Optimization (Speed Planning)

\[ t_e > 0 : \text{Edge-} e \text{ travel time } T \equiv \{ t : t_{lb} \leq t_e \leq t_{ub}, \forall e \} : \text{speed limits} \]

Fuel Consumption

Travel Time: \( t_e \Rightarrow \) Travel Speed: \( D \Rightarrow \) Fuel Consumption Rate: \( f_e(D) \Rightarrow \) Total Fuel Consumption: \( t_e \cdot f_e(D) \equiv c_e(t_e) \)
Problem Formulation

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Speed Optimization (Speed Planning)

\( T \triangleq \{ t : t_{lb} \leq t \leq t_{ub}, \forall e \} \): speed limits

Fuel Consumption

Travel Time: \( t \) \Rightarrow \text{Travel Speed: } D \Rightarrow \text{Fuel Consumption Rate: } f_e(D) \Rightarrow \text{Total Fuel Consumption: } t \cdot f_e(D) \triangleq c_e(t) \)
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Fuel Consumption

Travel Time: \( t_e \)
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Fuel Consumption

Travel Time: \( t_e \Rightarrow \text{Travel Speed: } \frac{D_e}{t_e} \)
Path Selection (Route Planning)

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

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

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Fuel Consumption

Travel Time: \( t_e \) ⇒ Travel Speed: \( \frac{D_e}{t_e} \) ⇒ Fuel Consumption Rate: \( f_e(\frac{D_e}{t_e}) \)
Problem Formulation

Path Selection (Route Planning)

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

\[ \mathcal{X} \triangleq \{ \mathbf{x} \in \{0, 1\}^m : \text{One } s \rightarrow d \text{ path is selected} \} \]

Speed Optimization (Speed Planning)

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

\[ \mathcal{T} \triangleq \left\{ t : t_e^{lb} \leq t_e \leq t_{e}^{ub}, \forall e \right\} : \text{speed limits} \]

Fuel Consumption

Travel Time: \( t_e \), Travel Speed: \( \frac{D_e}{t_e} \), Fuel Consumption Rate: \( f_e \left( \frac{D_e}{t_e} \right) \)

\[ \Rightarrow \text{Total Fuel Consumption: } t_e \cdot f_e \left( \frac{D_e}{t_e} \right) \triangleq c_e(t_e) \]
Problem Formulation

Path selection and Speed Optimization (PASO)

\[
\begin{align*}
\min_{x \in \mathcal{X}, t \in \mathcal{T}} & \quad \sum_{e \in \mathcal{E}} x_e \cdot c_e(t_e) \\
\text{s.t.} & \quad \sum_{e \in \mathcal{E}} x_e t_e \leq T
\end{align*}
\]
Problem Formulation

Path selection and Speed Optimization (PASO)

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\text{s.t.} & \quad \sum_{e \in \mathcal{E}} x_et_e \leq T
\end{align*}
\]

Challenges

- Mixed discrete-continuous optimization: \( x_e \in \{0, 1\}, t_e > 0 \)
- Non-linear non-convex: \( \sum_{e \in \mathcal{E}} x_et_e \leq T \)
Theorem

*PASO is NP-Complete.*
Theorem

*PASO is NP-Complete.*

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 $\frac{1}{\epsilon}$. 
Complexity-Hardness-related Theoretical Results

**Theorem**

*PASO is NP-Complete.*

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**Theorem**

*PASO has an FPTAS with network-induced time complexity $O\left(\frac{mn^2}{\epsilon^2}\right)$.*
The network-induced complexity of the FPTAS is $O\left(\frac{mn^2}{\epsilon^2}\right)$

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

Still large if we consider practical highway networks with \( m, n \sim 10^4 \)

Consider the regions 17&18

<table>
<thead>
<tr>
<th>( n )</th>
<th>( m )</th>
<th>( \epsilon )</th>
<th>Run Time</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>3274</td>
<td>7465</td>
<td>0.1</td>
<td>3511s</td>
<td>14.76GB</td>
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</table>

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

\[
\min_{x \in \mathcal{X}, t \in \mathcal{T}} \quad \sum_{e \in \mathcal{E}} x_e \cdot c_e(t_e)
\]

s.t.
\[
\sum_{e \in \mathcal{E}} x_e t_e \leq T, \quad [\lambda]
\]

\(\lambda\) is the delay price.

PASO-Relaxed(\(\lambda\)) can be solved efficiently by a shortest-path like algorithm.
Relax the Hard Delay for PASO

**PASO**

\[
\min_{x \in X, t \in T} \sum_{e \in E} x_e \cdot c_e(t_e)
\]

s.t.

\[
\sum_{e \in E} x_e t_e \leq T, \quad [\lambda]
\]

**PASO-Relaxed(\(\lambda\))**

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

- \(\lambda\) is the *delay* price
- PASO-Relaxed(\(\lambda\)) can be solved efficiently by a shortest-path like algorithm
Key Observations and Result

\[ \text{PASO-Relaxed}(\lambda) \]

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

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

We propose a heuristic to find the proper \( \lambda \) in \( O((m+n \log n)) \), much faster than the FPTAS (\( O((mn^2 \epsilon^2)) \)).

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.

Lei Deng (CUHK)
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For properly selected $\lambda$, solving PASO-Relaxed($\lambda$) gives either an optimal solution or a feasible solution with a small optimality-gap to PASO.
Key Observations and Result

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

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Key Observations and Result

**PASO-Relaxed(λ)**

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

- For properly selected \( \lambda \), solving PASO-Relaxed(\( \lambda \)) gives either an optimal solution or a feasible solution with a small optimality-gap to PASO.
- We propose a heuristic to find the proper \( \lambda \) 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 \( O(\frac{m n^2}{\epsilon^2}) \)
- The dual-based heuristic has a network-induced complexity of \( O((m + n \log n)) \)

Consider the regions 17 & 18

<table>
<thead>
<tr>
<th>Alg</th>
<th>( n )</th>
<th>( m )</th>
<th>( \epsilon )</th>
<th>Run Time</th>
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</tr>
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<tr>
<td>FPTAS</td>
<td>3274</td>
<td>7465</td>
<td>0.1</td>
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</tr>
<tr>
<td>Heuristic</td>
<td>3274</td>
<td>7465</td>
<td>-</td>
<td>2s</td>
<td>0.29GB</td>
</tr>
</tbody>
</table>
Simulation: Dataset

- Elevation: USGS Elevation Point Query Service
- Speed Limits: HERE Map
- Heavy-duty Truck and Fuel Consumption Data: ADVISOR Simulator

Kenworth T800

<table>
<thead>
<tr>
<th>Drag Coefficient $c_d$</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal area $A_f$</td>
<td>8.5502 m$^2$</td>
</tr>
<tr>
<td>Glider Mass</td>
<td>2,552kg</td>
</tr>
<tr>
<td>Cargo Mass</td>
<td>33,234kg</td>
</tr>
</tbody>
</table>
Simulation: Network Statistics

|   |   | avg $D_e$ (mile) | avg $R_e^{lb}$ (mph) | avg $R_e^{ub}$ (mph) | avg $|\theta|$ (%) |
|---|---|------------------|-----------------------|----------------------|------------------|
| 38213 | 82781 | 3.26 | 36.43 | 54.19 | 0.82 |
Evaluate/Compare FPTAS and Heuristic

Instance: \((s, d, T)\)

<table>
<thead>
<tr>
<th>No.</th>
<th>Network</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reg.</td>
<td>(n)</td>
</tr>
<tr>
<td>S1</td>
<td>1&amp;2</td>
<td>1185</td>
</tr>
<tr>
<td>S2</td>
<td>17&amp;18</td>
<td>3274</td>
</tr>
<tr>
<td>S3</td>
<td>1-22</td>
<td>38213</td>
</tr>
<tr>
<td>S4</td>
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7.1 Dataset
Transportation Network: To construct United States National Highway Systems (NHS), we use the graph data. As mentioned in Sec. 7.1, we choose the default vehicle type VEH_KENT800 and Kenworth T800. As mentioned in Sec. 7.1, we choose the default vehicle type VEH_KENT800 and Kenworth T800. For each edge (road segment), we use the average speed limit according to historical flow data. In order to obtain the grade of each road segment, we use the Elevation Point Query Service [7]. In this paper, we only consider the grade/slope (say θ grade points in Tab. 3, where we also put the convex region (22) by using MATLAB's fit function).

The graph data has a reasonable level of accuracy for us to model the NHS network. In order to obtain the grade of each road segment, we use the Elevation Point Query Service [7]. In this paper, we only consider the grade/slope (say θ grade points in Tab. 3, where we also put the convex region (22) by using MATLAB's fit function).


d to query elevations of all 84504 nodes in the NHS graph. Provided U.S. Geological Survey (USGS). We write a script to run a driving cycle test, see ADVISOR [14]. We use the ADVISOR without the GUI by invoking parameters for each road segments. HERE map [6] has put speed detectors over many countries including U.S., and it provides realistic scenarios. For example, when grade is 0 (a flat road), the fuel-rate-speed function is convex if the speed is larger than 16.78mph, which holds generally in reality. This is because that grade is a major factor for fuel-rate-speed function.

7.2 Fuel-Rate-Speed Function Modeling

We will use the following fuel-rate-speed function model, $f(x) = e^x + b e^{x^2} (22)$ from CHM [2], a lot of road segments are very short. To be realistic, we increase their lengths, e.g., we add a width of 100 meters to specify the corridor. We are keeping the convex region (22) from ADVISOR, we can get total fuel consumption of mph and lb (gallons per hour). Although our model (22) can capture of mph and lb (gallons per hour). Although our model (22) can capture

Instance: $(s, d, T)$

![USA map and 22 regions.](image)

<table>
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<td>1&amp;2</td>
<td>1185</td>
</tr>
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</table>

![Performance and Time Comparison](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Performance (gallon)</th>
<th>Time (second)</th>
<th>Memory (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heuri. LB/UB</td>
<td>FPTAS</td>
<td>Heuri.</td>
</tr>
<tr>
<td>S1</td>
<td>74.811/74.811</td>
<td>74.812</td>
<td>1</td>
</tr>
<tr>
<td>S2</td>
<td>60.2795/60.2795</td>
<td>60.2798</td>
<td>2</td>
</tr>
<tr>
<td>S3</td>
<td>290.744/290.744</td>
<td>-</td>
<td>365</td>
</tr>
<tr>
<td>S4</td>
<td>74.811/74.811</td>
<td>74.812</td>
<td>1</td>
</tr>
</tbody>
</table>
Shortest/Fastest/Optimal paths of \((s, d, T) = (9, 22, 40)\)
Average performance of all instances \((s,d,T)\)

<table>
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<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastest path</td>
<td>-</td>
<td>1.71</td>
<td>20.14</td>
<td>5.05</td>
</tr>
<tr>
<td>Shortest path</td>
<td>2.82</td>
<td>-</td>
<td>16.40</td>
<td>5.13</td>
</tr>
<tr>
<td>Heuristic</td>
<td>32.89</td>
<td>0.18</td>
<td>0.02</td>
<td>5.96</td>
</tr>
<tr>
<td>OPT-LB</td>
<td>32.95</td>
<td>0.17</td>
<td>-</td>
<td>5.96</td>
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</table>
Propose the problem of energy efficient timely transportation

Prove that the problem is NP-Complete but has an FPTAS
  - The FPTAS has time complexity $O\left(\frac{mn^2}{\epsilon^2}\right)$

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
Thank You!
Backup Slides
$f_e(\cdot)$ for a 36-ton truck for grades 0%, ±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 $[t_e^{lb}, t_e^{ub}]$.

$f_e(\cdot)$ for a 36-ton truck (source: ADVISOR)  
$c_e(\cdot)$ for the truck over a 100-mile road (source: ADVISOR)