Energy Efficient Timely Transportation: A Comparative Study of Internal Combustion Trucks and Electric Trucks

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ABSTRACT

We carry out a comparative study of energy consumption of the conventional internal combustion truck and the modern electric truck, traveling from origin to destination over the national highway subject to a hard deadline. We focus on understanding energy saving of the latter over the former and key contributing factors. Our study is unique in that (i) it is based on extensive simulations using real-world data over the U.S. highway system, and (ii) we factor in the power system energy-conversion efficiency when calculating the energy consumption of electric trucks for fair comparison. The results show that on average the electric truck save 10% energy as compared to the internal combustion truck, and this saving will improve as power systems incorporate more renewable generation. Furthermore, the energy saving mainly comes from the energy efficiency of electric motors, and other electric-truck features, e.g., regenerative breaking, only have minor contributions.

CCS CONCEPTS

• **Applied computing** → **Transportation**; • **Information systems** → *Spatial-temporal systems.*

KEYWORDS

energy efficient operation, timely transportation, electric truck, comparative study

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1 INTRODUCTION

In the United States, more than 10 billion tons of freight are transported by heavy-duty trucks in 2019, representing 72.5% of total domestic tonnage shipped.More than 43 billion gallons of fuel (1.63 trillion kWh equivalent) are consumed by heavy-duty trucks in 2018 [2], which makes it critical to reduce their fuel consumption. To achieve sustainable truck operations, researchers explore a critical problem by considering both the cost-effectiveness and the timely delivery requirement, which is also known as the *Energy Efficient Timely Transportation* (E2T2) problem. The objective of E2T2 is to minimize the overall energy consumption for a truck travelling from origin to destination over the national highway, with path planning and speed planning, subject to a strict deadline constraint. The E2T2 problem has been widely studied for the conventional internal combustion trucks [3, 5]. These works show that a well-designed operating strategy can significantly reduce energy consumption of heavy-duty trucks, as much as 20%.

Heavy-duty truck electrification is an active developing frontier of the transportation system for its potential to reduce energy consumption and improve air quality. As compared to internal combustion trucks, electric trucks have the following unique characteristics that can be further explored in long-haul E2T2: (i) the electric trucks have regenerative systems to harvest kinetic energy when braking. (ii) the energy efficiency of the electric motor is significantly higher than that of the internal combustion engine. Moreover, its energy efficiency varies less in output power than internal combustion engine.

In this paper, we carry out a comparative study to understand the energy saving of electric trucks over internal combustion trucks. Our study is unique in that (i) it is based on simulations using real-world data over the U.S. highway system, and (ii) we factor in the power system energy-conversion efficiency when calculating the energy consumption of electric trucks for fair comparison. The results show that on average the electric truck save 10% energy as compared to the internal combustion truck, and this saving will improve as power systems incorporate more renewable generation. Furthermore, the energy saving mainly comes from the energy efficiency of electric motors, and other electric-truck features, e.g.,regenerative breaking, only have minor contributions.

2 MODELLING AND APPROACH

Consider a national highway network modelled by a directed graph $G \triangleq (V, E)$. An edge $e \in E$ represents a road segment and a node $v \in V$ represents a connecting point. Each edge e has a length D_e and a minimum (resp. maximum) travelling speed $r_e^l > 0$ (resp. $r_e^u \geq r_e^l$). We define the fuel rate speed function $f_e : [r_e^l, r_e^u] \to \mathbb{R}^+$ (unit: kWh/mile) for a truck to travel through a road segment e. The *Energy Efficient Timely Transportation* (E2T2) problem, that can be readily formulated for both the electric trucks and the internal combustion trucks is described as follows. On a national highway network with the corresponding speed range, grade, and fuel rate function for each road segment, given origin and destination along with a hard time deadline constraint, the E2T2 problem aims to minimize the energy consumption while ensuring on time arrival, by optimizing path planning and speed planning. The solution of an E2T2 problem includes a sequence of edges representing the path profile and the corresponding speed instruction for each

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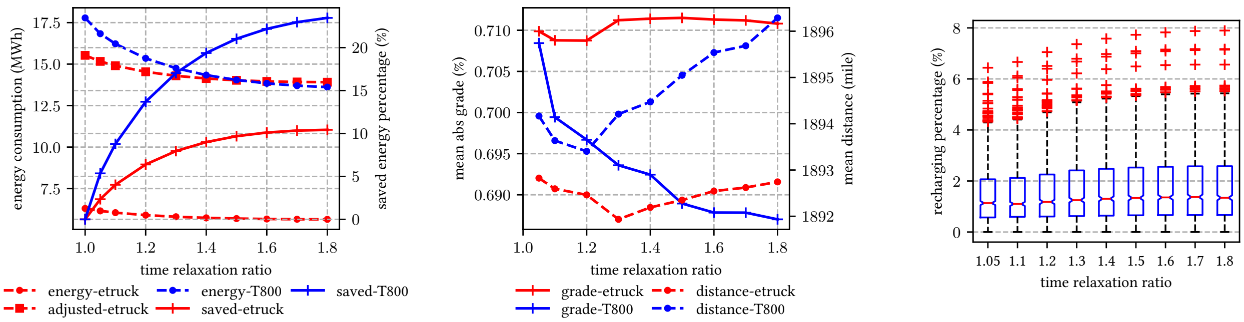

(a) Energy-saving comparison **(b) Driving profile comparison** **(c) recharging percentage**

Figure 1

	T800	etruck
Drag Coefficient	0.7	0.36
Frontal Area (m^2)	8.5502	10
Total Mass (kg)	36,000	36,000
Max Out Power (kW)	380	380

Table 1: Parameters of the internal combustion truck (T800) and the electric truck (etruck).

edge representing the speed profile. In our comparative study, we apply the dual-based algorithm in [3] to solve the formulated E2T2 problems for electric trucks and internal combustion trucks and compare their solutions.

3 SIMULATION

The simulation is conducted on the U.S. national highway system (NHS) consisting of 84, 504 nodes and 178, 238 directed edges. With real-world speed and grade information for each road segment. We select 1, 000 origin-destination pairs with distances longer than 1, 000 miles from the Freight Analysis Framework (FAF). We use *FASTSim* [1] to collect the energy consumption data and fit the data with cubic polynomial functions. The main parameters of the truck models are summarized in Table 1. We use the parameters of Kenworth T800 trailer for the internal combustion truck model and the parameters of Tesla Semi for the electric truck model. We use the *time relaxation ratio* and *energy-saving percentage* compared to the fastest path to study the energy-deadline tradeoff in the E2T2 problem. We also adjust the energy consumption of electric trucks with the power system *energy conversion efficiency* 0.4. This means 1 kWh energy is consumed to generate 0.4 kWh electricity for end use. We calculate the energy conversion efficiency by dividing electricity end uses [4, Table 7.6] by the sum of the the primal consumption of the fossil fuels and nuclear electric power [4, Table 2.6], and the net generation of renewable energy [4, Table 2.7a].

Energy-saving comparison. We compare the (adjusted) energy consumption and energy-saving percentage of both trucks in Figure 1a. Thanks to the high efficiency of the electric motor, the energy consumption for the electric truck is less than half of that for the internal combustion truck. Moreover, the adjusted energy consumption of electric trucks is still smaller than that of internal combustion trucks for small time relaxation ratios. Similar observations can be found from the plots of energy-saving percentage. The energy-saving percentage by optimizing path and speed planning for the electric truck is almost half of that for the internal combustion truck, for any time relaxation ratios in the simulations. Therefore, the energy-saving by optimizing driving profiles for the electric truck is not as significant as that for the internal combustion truck. As electric motors have high energy efficiency across the whole range of vehicle speed, the room for optimizing the energy consumption of electric trucks by speed planning is not as large as internal combustion trucks.

Impact of regenerative systems. For a driving profile, we define the recharging percentage as the ratio of the harvested energy by the regenerative system to the total energy consumption. The impact of regenerative systems is shown in Figure 1c. For most cases, the increase of time relaxation ratio only leads to a slight increase of recharging percentage (cf. blue boxes), and the recharging percentage is small (<3%). Therefore, the impact of regenerative braking on energy consumption reduction is minor compared to that of the high energy efficiency of electric trucks.

Driving profile comparison. We compare the corresponding path profiles of both trucks in Figure 1b. It shows the average absolute values of grades and average distances of two trucks w.r.t. time relaxation ratio. As seen, the E2T2 solutions of the electric truck have steeper road grades and shorter distances as encouraged by the unique characteristics of the electric truck. However, one should note that the relative differences of both the average absolute value of grade (3%) and average distance (0.2%) are minor, and the E2T2 solutions of the electric truck vary less as the time relaxation ratio increases.

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