The Truck Driver Scheduling Problem with Idling Options

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Abstract

This paper studies the Truck Driver Scheduling Problem with Idling Options (TDSP-IO), an extension of the long-haul truck driver scheduling problem with a more comprehensive objective function that accounts for driving cost, fuel and CO_2 emissions cost, and idling cost. The best-known idling option is the widespread practice of keeping the vehicle engine running while the vehicle is not moving, which primarily stems from the drivers' desire to keep their vehicle at an adequate comfort level during breaks. Here, we explore two additional cleaner idling options: resting at an Electrified Parking Space (EPS) or using an Auxiliary Power Unit (APU) while idling. We also account for the initial investments associated with the equipment required for the use of these technologies. We formulate a mathematical model for the TDSP-IO under these three idling options, and we perform extensive computational experiments on 12 realistic instances. The paper sheds light on the trade-offs between various performance indicators and offers several managerial insights. Our analyses quantify the advantages of using EPSs and APUs, and show that they yield both economical and environmental benefits.

Keywords. Truck driver scheduling problem; Idling; Long-haul transportation; Fuel consumption; CO_2 emissions; Hours of service regulations.

1 Introduction

In long-haul transportation, where travel distances can be considerable, drivers often have to be on the road for several consecutive days. As a natural consequence, truck driver fatigue emerges as a significant cause of serious accidents (see McCartt et al., 2008). The United States (US) Hours of Service (HOS) regulations restricts the duration of driving and imposes rest periods on commercial vehicles making long-haul trips (FMCSA, 2014). Similar rules exist in the European Union (EU), Canada, Australia and other countries (Goel and Vidal, 2014).

During rest periods at truck stops or while loading and unloading at customer locations, drivers tend to keep the engine of their vehicle running in order to maintain their comfort level, resulting from the use of air conditioners, heaters, televisions, refrigerators and lights (Argonne, 2015; Brodrick et al., 2002b). This practice is called *engine idling*. In the US, an idling heavy-duty vehicle consumes an average of three liters of fuel per hour, and a truck idles an average of six hours per day or 1,800 hours per year (Argonne, 2016). Engine idling is a major problem in long-haul transportation since it increases fuel consumption as well as emissions of NOx, PM, CO_2, CO, and hydrocarbons.

On average, if an engine idles for more than 10 seconds, it consumes more fuel than does a restart (Brodrick et al., 2002a). An idling engine cannot function at an efficient operating temperature and results in incomplete fuel combustion, which leaves fuel residues in the exhaust (Rahman et al., 2013). Furthermore, engine idling accelerates wear and tear, and decreases the time interval between oil changes which not only increases fuel consumption, but also maintenance and repair costs. Over a year, engine idling is equivalent to 322,000 extra km of engine wear and adds operational costs of between $4,000 and $7,000 per truck (Argonne, 2015). The impact of engine idling on CO_2 emissions is also well documented (see Brodrick et al., 2002a; Frey and Kuo, 2009; Khan et al., 2009). Thus each year in the US, truck idling consumes up to 3.78 billion liters of fuel, corresponding to 8.78 billion kg of CO_2 emissions, at a cost of around $3 billion. However, engine idling can be avoided since diesel engines stay warm for several hours after shutdown, which is more than enough to avoid restart problems (Argonne, 2016). Some jurisdictions impose strict engine idling limits through fines. For example, in the US the states of California and New York, engine idling is limited to five minutes and the fines for violations range from $300 to $10,000, and from $375 to $22,500, respectively (ATRI, 2015).

We consider two alternative idling options that could save money and reduce pollution: Electrified Parking Spaces (EPSs) and Auxiliary Power Units (APUs). An EPS enables the vehicle to be plugged into an electric power outlet and thus vehicles will not consume fuel while idling. An APU provides sufficient power for functions required during idling and consumes significantly less fuel than engine idling. Depending on how much a truck idles and on fuel prices, these two idling options can pay for themselves in as little as six months according to Rahman et al. (2013) and Windover et al. (2015).

The HOS regulations, engine idling and truck driver scheduling all bear on emissions in long-haul transportation. While the routing and scheduling aspects of long-haul trucking are already well studied (Kok et al., 2010; Rancourt et al., 2013), the interplay between vehicle scheduling and idling options, and the influence of these options on costs and emissions has not yet been investigated. Our purpose is to analyze these interrelated components of long-haul transportation within a unified framework. Before we proceed with our study, we briefly review the relevant literature on long-haul truck scheduling.

1.1 Literature review on the Truck Driver Scheduling Problem

Several studies have focused on the Truck Driver Scheduling Problem (TDSP) under the HOS regulations. Archetti and Savelsbergh (2009) studied the problem of sequencing full truckload requests, each with a dispatch window at the origin. These authors proposed an algorithm that produces a feasible schedule in polynomial time if one exists. Goel (2012a) later developed a mixed integer linear programming formulation and a dynamic programming algorithm for a variant of the TDSP in which customers have multiple time windows, with the aim of minimizing total duration under the US and EU regulations. A similar problem was studied by Goel and Kok (2012) in which each customer location must be visited within one of several time windows. Provided the gaps between windows are at least 10 hours, the complexity of their proposed algorithm is similar to that of the single window case. Goel (2014) later considered the US HOS regulations introduced in 2013 and presented a simulation-based algorithm to assess their impact on operational costs and road safety. Goel and Rousseau (2012) developed two heuristics and an exact algorithm for the TDSP under Canadian regulations, while Goel (2012b) proposed a mixed integer linear programming formulation and an iterative dynamic programming algorithm for the minimum route duration problem. Goel (2012c) presented a mixed integer programming formulation and valid inequalities for the problem arising from the Australian regulations, and Goel et al. (2012) later developed four heuristics and an exact method with dominance criteria for the same problem.

Several researchers have also studied the combined vehicle routing and TDSP, which simultaneously determines routing and scheduling decisions under the HOS regulations. The first such study is due to Xu et al. (2003). Ceselli et al. (2009) later solved a rich problem containing several operational difficulties arising in real-world applications. Goel (2009) focused on several EU regulations. Kok et al. (2010) integrated a basic break scheduling method within a dynamic programming framework under the EU regulations. Prescott-Gagnon et al. (2010) developed a large neighborhood search algorithm based on a column generation heuristic under the EU regulations, while Kok et al. (2011) proposed a sequential insertion heuristic for the vehicle routing and time-dependent travel times in the same context. Rancourt et al. (2013) later solved a long-haul truck routing and scheduling problem under the US regulations with a heterogeneous fleet of vehicles, by embedding several scheduling algorithms within a tabu search heuristic. Finally, Goel and Vidal (2014) developed a unified genetic algorithm for the EU, US, Canadian and Australian HOS regulations.

1.2 Scientific contributions and structure of the paper

Fuel consumption and CO_2 emissions have been extensively studied by researchers within the context of vehicle routing (see Bektaş and Laporte, 2011; Franceschetti et al., 2013; Koç et al., 2014, 2016). These studies focused on the routing aspect of the problem and on the use of speed optimization as a means of reducing CO_2 emissions. Here we assume that vehicle routes have already been designed and are given as inputs. We concentrate instead on the combined scheduling and idling components of the problem. In particular we investigate how to optimally combine scheduling decisions with the choice of idling options in order to minimize operational and emissions costs. To our knowledge, we are the first authors to optimize and quantify idling costs within the context of long-haul truck scheduling. We note that in the TDSP papers surveyed, the trucks can idle at rest areas or at customer locations, and sometimes anywhere along their route. Here we take a more restrictive yet natural approach by disallowing the latter possibility, since it is reasonable to assume that drivers will prefer rest areas given the facilities that they provide.

In this paper, we make two main scientific contributions. We first introduce the Truck Driver Scheduling Problem with Idling Options (TDSP-IO) as a variant of the TDSP using a comprehensive objective function that minimizes the cost of fuel consumption and CO_2 emissions along with the costs of drivers and idling options. We then develop a mixed integer linear programming model, and we perform extensive analyses under the US HOS regulations in order to shed light on the trade-offs between the problem components, such as route duration, CO_2 emissions, idling options and fuel prices.

The remainder of this paper is structured as follows. Section 2 introduces a general framework for our analysis, provides a formal description of the problem and a mathematical formulation, and presents an illustrative example. Extensive computational experiments are presented in Section 3, followed by conclusions and managerial insights in Section 4.

2 Problem setting and description

We first describe the idling options in Section 2.1, followed by the US HOS regulations and their parameters in Section 2.2. We then present the formal problem definition and mathematical formulation in Section 2.3. We finally provide an illustrative example in Section 2.4.

2.1 Idling options

We consider three idling options: engine idling, EPS idling and APU idling.

Engine idling: Drivers often make driving breaks at interstate rest areas (IRAs) and at truck stops. For the purpose of this study, we only consider IRAs. In the US, IRAs generally provide parking space and restrooms to truck drivers. Some also contain information kiosks, vending machines, and picnic areas. IRAs are funded and maintained by the Departments of Transportation of the state governments. The current IRA locations in the US are depicted in Figure 1 (US Rest Areas., 2016). To maintain an adequate comfort level, drivers who do not possess an APU typically keep their engine running when stopping at an IRA or at a customer location.

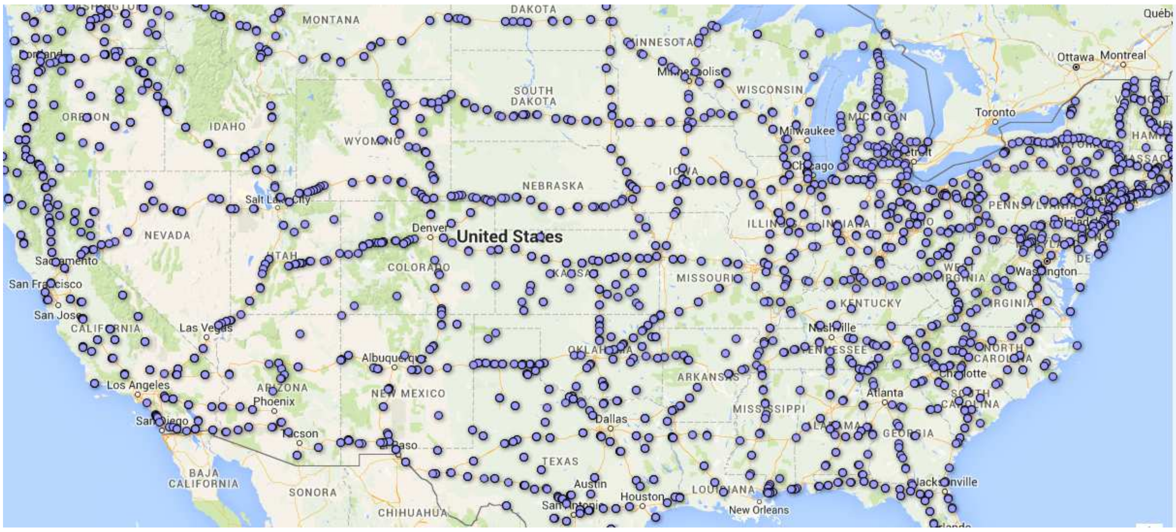

Figure 1: Current Interstate Rest Areas in the United States (US Rest Areas., 2016)

(a) Electrified Parking Space **(b)** Auxiliary Power Unit

Figure 2: Electrified Parking Space (Shorepower, 2016) and Auxiliary Power Unit (Carrier, 2016)

Electrified parking space (EPS) idling: EPSs (see Figure 2.a), also known as truck stop electrification or shore power, allow truck drivers to switch off their engines and provide power for heating, ventilation, air conditioning and other amenities without idling the engine (Argonne, 2015). Like IRAs, EPSs also provide several amenities. In the US, EPS data are collected by the National Renewable Energy Laboratory (NREL) (NREL, 2016) from current EPS owner companies (CMI, 2016; EnviroDock, 2016; IdleAir, 2016; Shorepower, 2016). The information about EPSs, such as station name, address, phone number, hours of operation and directions, are verified by the NREL by calling the facilities directly approximately once every six months. Furthermore, the NREL periodically checks sources to identify new EPSs and adds them to the list. The NREL geocodes and maps the EPS addresses. With this publicly open access tool, the US Department of Energy aims to inform heavy-duty truck companies and truck drivers about the EPS locations, during rest and break periods (DOE, 2016a). The locations of current EPSs are shown in Figure 3 (DOE, 2016a). Each truck requires an on-board equipment so that it can plug into an off-board outlet at the EPS. This equipment, which has an average initial cost of $2,500, includes an inverter to convert 120-volt power, electrical equipment, and hardware to plug into the EPS. The trucking company or the truck driver owns and maintains this on-board equipment. The cost of using an EPS is $1.00 per hour (Argonne, 2015).

Auxiliary power unit (APU) idling: APUs (see Figure 2.b) provide truck drivers with on-board power for climate control and electrical devices. Drivers can use an APU wherever needed and can keep their comfort level for as long as desired. However, APUs have a relatively high purchase and installation cost, which ranges between $8,000 and $12,000 (DOE, 2016b). APUs are powered by diesel and burn about 0.95 liter of fuel per hour.

Table 1 presents the parameters related to fuel consumption, CO_2 emissions and the costs of engine idling, EPS idling and APU idling for a heavy-duty vehicle (DOE, 2016b; Windover et al., 2015). We assume that fuel cost is $0.52/L ($1.98/gallon) (EIA, 2016). Fuel consumption cost is $0.1 per km (Koç et al., 2014). The amount of CO_2 emissions (in kg) is based on the assumption that one liter of fuel generates 2.32 kg of CO_2 (Coe, 2005). The social cost of CO_2 is evaluated at $0.22/kg, which reflects the economic damage to the environment, crops, human health and productivity (Moore et al., 2015). Based on the fuel consumption rates, we conclude that the operating cost f^{ENG} of engine idling for a heavy-duty truck is $3.09/h. The cost of using an EPS is $1.00/h and is denoted by f^{EPS}. The cost of using an APU is $0.98/h and is denoted by f^{APU}. The

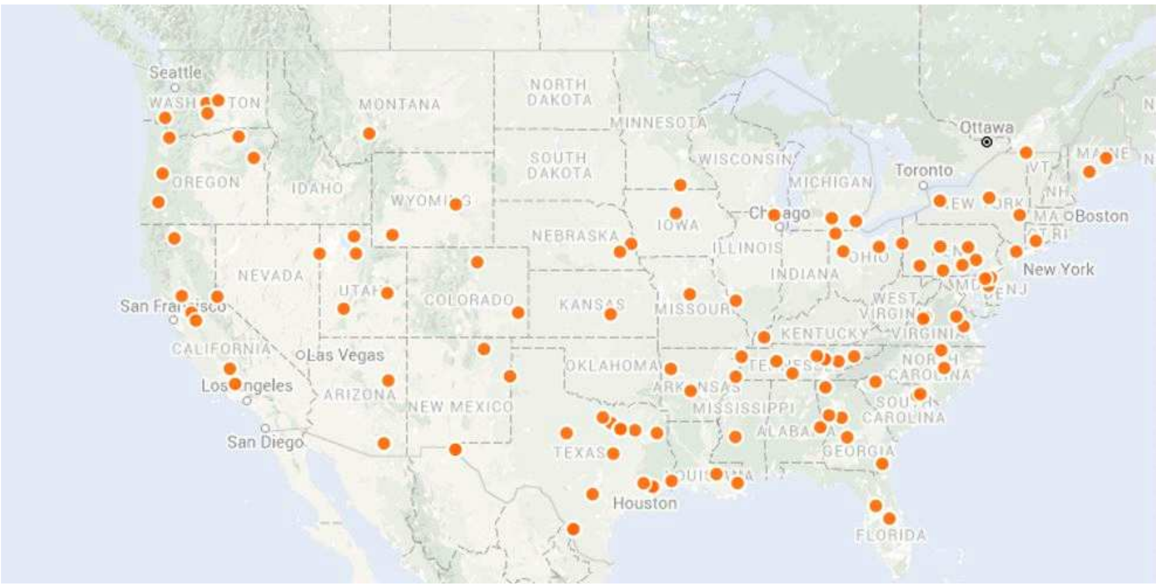

Figure 3: Current Electrified Parking Spaces in the United States (DOE, 2016a)

hourly wage of truck drivers is \$17.34/h and is denoted by f^{DRI} (Pay Scale, 2016). Since the owner of an EPS is responsible for CO_2 emissions which is the result of electricity consumption, we do not include the CO_2 emissions cost into f^{EPS}. The fixed costs of EPS equipment and APU are \$2,500 and \$10,000, respectively (Argonne, 2015). We assume that the economic lives of EPS equipment and APU are 10 years, but we will conduct sensitivity analyses on this estimate in Section 3.4. We approximate the EPS and APU fixed costs by their weekly values as f_s^{EPS} =\$4.81 and f_s^{APU} =\$19.23, respectively.

Table 1: Parameters related to engine, EPS and APU idling.

Option	Fuel consumption (L/h)	CO_2 emissions (kg/h)	Hourly costs			
			Fuel cost (\$/h)	CO_2 emissions cost (\$/h)	Charge (\$/h)	Total cost (\$/h)
Engine idling	3.00	6.96	1.56	1.53	–	3.09
EPS idling	–	–	–	–	1.00	1.00
APU idling	0.95	2.20	0.49	0.48	–	0.98

2.2 The United States Hours of Service regulations

In the US, truck drivers are subject to various rules. *Driving time* refers to the total time spent at the driving controls of a vehicle in operation. *On-duty time* refers to the time a truck driver is working.

It includes driving time as well as the time needed for other activities such as waiting for service, supervising, loading and unloading, and handling paperwork for shipments. *Off-duty time* refers to any time during which truck drivers have no obligation to perform any work.

Drivers may take break periods or rest periods. According to the US HOS regulations, a break lasts a minimum of 30 minutes whereas a rest has a minimal duration of 10 hours. A truck driver may not drive after a cumulative 60/70 hours of on-duty work in seven/eight consecutive days and can restart a seven consecutive day period after 34 or more consecutive hours off-duty. A truck driver can drive a maximum of 11 hours after 10 or more consecutive hours off-duty, and cannot be on-duty beyond 14 consecutive hours following 10 or more consecutive hours off-duty. In addition to these rules, the US Federal Motor Carrier Safety Agency released an additional rule in July 2013, by which a truck driver cannot drive if eight hours or more have elapsed since the end of the last off-duty period of at least 30 minutes (FMCSA, 2014). Table 2 summarizes the parameters of the US HOS used in this paper.

Table 2: Parameters imposed by the US HOS regulations.

Notation	Value (h)	Description
t^w	60/70	The maximal cumulative on-duty hours during seven/eight consecutive days.
t^d	11	The maximal cumulative driving hours between two rest periods.
t^{rp}	14	The maximal cumulative on-duty hours since the end of the last rest period.
t^{bp}	8	The maximal cumulative on-duty hours since the end of the last break period.
t^r	10	The minimal duration of a rest period to regain driving time.
t^b	0.5	The minimal duration of a break period to regain driving time.

2.3 Formal problem definition and mathematical formulation

The TDSP-IO is defined on a given route $\mathcal{R} = (0, i, \ldots, n, n{+}1)$ made up of a sequence of locations. The locations 0 and $n{+}1$ represent depots which correspond to the beginning and end of the route. The set of locations is denoted by $\mathcal{N} = \mathcal{N}_0 \cup \mathcal{N}_c \cup \mathcal{N}_e \cup \mathcal{N}_a$, where $\mathcal{N}_0$, $\mathcal{N}_c$, $\mathcal{N}_e$ and $\mathcal{N}_a$ represent depots, customers, EPSs and IRAs, respectively. Each location $i \in \mathcal{N}$ must be visited once by a vehicle. The driving time from location $i \in \mathcal{N}$ to location $i+1$ is denoted by $d_{i,i+1}$. The service time at customer location $i \in \mathcal{N}_c$ is equal to s_i. An ordered set T_i of time windows is associated with each location $i \in \mathcal{N}$. The service must begin within one of its time windows, and must be completed without interruption. The τ^{th} time window $(\tau \in T_i)$ at location $i \in \mathcal{N}$ is denoted by the interval $[t_{i,\tau}^{min}, t_{i,\tau}^{max}]$. If a vehicle arrives before the opening of the first available time window, it has to wait. It must also arrive before the closing of the selected time window because otherwise the driver will have to wait until the opening of the next available time window. The time horizon is denoted by $t^{horizon}$. We assume that the depots, the EPSs and the IRAs have very wide time windows $[t_{i,1}^{min} = 0, t_{i,1}^{max} = 168]$.

Like other authors (see Rancourt et al., 2013), we assume that the truck driver has been off-duty and off-the-road for at least 34 consecutive hours before departure from the starting depot, and each trip has a maximum duration of seven days, i.e., $t^w = 60$ hours. The use of EPSs or IRAs implies that the truck driver can take rest or break periods at EPS or at IRA locations, but not at customer locations. The EPSs and IRAs are located on the route and do not require deviations. We assume that drivers without an APU keep their engines running while waiting at IRAs or at customer locations. However, instead of idling the engine, a driver operating a truck equipped with an APU will use it during rest and break times at an IRA, and during waiting and service time at a customer. As in Rancourt et al. (2013), we also assume that a driver is paid for on-duty time only.

For a given truck route, the TDSP-IO consists of deciding when the truck driver will drive, serve a customer, rest or break at an IRA or at an EPS, and use an APU or not. The solution must comply with the US HOS regulations and ensure that all locations on a given route are visited within one of their time windows.

To formulate the TDSP-IO, we define the following decision variables:

- $u_i^{r,EPS}$: the duration of a rest period at EPS location $i \in \mathcal{N}_e$;
- $u_i^{b,EPS}$: the duration of a break period at EPS location $i \in \mathcal{N}_e$;
- $u_i^{r,IRA}$: the duration of a rest period at IRA location $i \in \mathcal{N}_a$;
- $u_i^{b,IRA}$: the duration of a break period at IRA location $i \in \mathcal{N}_a$;
- $x_i^{arrival}$: arrival time at location $i \in \mathcal{N}$;
- x_i^{start}: start time of the service, rest or break at location $i \in \mathcal{N}$;

- x_i^{end}: end time of the service, rest or break at location $i \in \mathcal{N}$;
- q^{ENG}: the total duration of total engine idling;
- q^{APU}: the total duration of total APU idling;
- $y_i = (y_{i,\tau})_{\tau \in T_i}$: $y_{i,\tau}$ is equal to 1 if the τ^{th} time window of location $i \in \mathcal{N}$ is used and to 0 otherwise;
- $z_i^{r,EPS} = \begin{cases} 1 & \text{if a rest is taken at EPS location } i \in \mathcal{N}_e \\ 0 & \text{otherwise;} \end{cases}$
- $z_i^{b,EPS} = \begin{cases} 1 & \text{if a break is taken at EPS location } i \in \mathcal{N}_e \\ 0 & \text{otherwise;} \end{cases}$
- $z_i^{r,IRA} = \begin{cases} 1 & \text{if a rest is taken at IRA location } i \in \mathcal{N}_a \\ 0 & \text{otherwise;} \end{cases}$
- $z_i^{b,IRA} = \begin{cases} 1 & \text{if a break is taken at IRA location } i \in \mathcal{N}_a \\ 0 & \text{otherwise;} \end{cases}$
- $w^{EPS} = \begin{cases} 1 & \text{if EPS equipment is installed and used} \\ 0 & \text{otherwise;} \end{cases}$
- $w^{APU} = \begin{cases} 1 & \text{if APU is installed and used} \\ 0 & \text{otherwise.} \end{cases}$

The mixed integer linear programming formulation of the TDSP-IO is then:

$$\text{Minimize} \quad f^{DRI}\Bigg(x_{n+1}^{end} - x_0^{start} - \sum_{i \in \mathcal{N}_e}\left(u_i^{r,EPS} + u_i^{b,EPS}\right) - \sum_{i \in \mathcal{N}_a}\left(u_i^{r,IRA} + u_i^{b,IRA}\right)\Bigg) \tag{1}$$

$$+ f^{ENG} q^{ENG} \tag{2}$$

$$+ f^{EPS} \sum_{i \in \mathcal{N}_e}\left(u_i^{r,EPS} + u_i^{b,EPS}\right) \tag{3}$$

$$+ f^{APU} q^{APU} \tag{4}$$

$$+ f_s^{EPS} w^{EPS} \tag{5}$$

$$+ f_s^{APU} w^{APU} \tag{6}$$

subject to

$$x_i^{arrival} = x_i^{start} = x_i^{end} \qquad i \in \mathcal{N}_0 \tag{7}$$

$$x_i^{arrival} \le x_i^{start} \qquad i \in \mathcal{N}_c \tag{8}$$

$$x_i^{start} + s_i = x_i^{end} \qquad i \in \mathcal{N}_c \tag{9}$$

$$x_i^{arrival} = x_i^{start} \qquad i \in \mathcal{N}_e \cup \mathcal{N}_a \tag{10}$$

$$x_i^{start} + u_i^{r,EPS} + u_i^{b,EPS} = x_i^{end} \qquad i \in \mathcal{N}_e \tag{11}$$

$$x_i^{start} + u_i^{r,IRA} + u_i^{b,IRA} = x_i^{end} \qquad i \in \mathcal{N}_a \tag{12}$$

$$x_i^{end} + d_{i,i+1} = x_{i+1}^{arrival} \qquad i \in \mathcal{N} \tag{13}$$

$$\sum_{\tau \in T_i} y_{i,\tau} = 1 \qquad i \in \mathcal{N} \tag{14}$$

$$\sum_{\tau \in T_i} y_{i,\tau} t_{i,\tau}^{min} \le x_i^{start} \qquad i \in \mathcal{N} \tag{15}$$

$$x_i^{start} \le \sum_{\tau \in T_i} y_{i,\tau} t_{i,\tau}^{max} \qquad i \in \mathcal{N} \tag{16}$$

$$x_k^{arrival} - x_i^{end} \le t^{rp} + M\Bigg(\sum_{j=i, j \in \mathcal{N}_e}^{k} z_j^{r,EPS} + \sum_{j=i, j \in \mathcal{N}_a}^{k} z_j^{r,IRA}\Bigg) \qquad i, k \in \mathcal{N}, i < k \tag{17}$$

$$x_k^{arrival} - x_i^{end} \leq t^{bp} + M\Bigg(\sum_{j=i, j \in \mathcal{N}_e}^{k} \left(z_j^{r,EPS} + z_j^{b,EPS} \right) + \sum_{j=i, j \in \mathcal{N}_a}^{k} \left(z_j^{r,IRA} + z_j^{b,IRA} \right) \Bigg) \qquad i, k \in \mathcal{N}, i < k \tag{18}$$

$$x_{jn+1}^{end} - \sum_{i \in \mathcal{N}_e} \left(u_i^{r,EPS} + u_i^{b,EPS} \right) - \sum_{i \in \mathcal{N}_a} \left(u_i^{r,IRA} + u_i^{b,IRA} \right) \leq t^w \tag{19}$$

$$\sum_{j=i}^{k-1} d_{j,j+1} \leq t^d + M\Bigg(\sum_{j=i+1, j \in \mathcal{N}_s}^{k-1} z_j^{r,EPS} + \sum_{j=i+1, j \in \mathcal{N}_a}^{k-1} z_j^{r,IRA} \Bigg) \qquad i, k \in \mathcal{N}, i < k \tag{20}$$

$$z_i^{r,EPS} + z_i^{b,EPS} \leq 1 \qquad i \in \mathcal{N}_e \tag{21}$$

$$z_i^{r,IRA} + z_i^{b,IRA} \leq 1 \qquad i \in \mathcal{N}_a \tag{22}$$

$$u_i^{r,EPS} \leq M z_i^{r,EPS} \qquad i \in \mathcal{N}_e \tag{23}$$

$$u_i^{r,IRA} \leq M z_i^{r,IRA} \qquad i \in \mathcal{N}_a \tag{24}$$

$$u_i^{b,EPS} \leq M z_i^{b,EPS} \qquad i \in \mathcal{N}_e \tag{25}$$

$$u_i^{b,IRA} \leq M z_i^{b,IRA} \qquad i \in \mathcal{N}_a \tag{26}$$

$$t^r z_i^{r,EPS} \leq u_i^{r,EPS} \qquad i \in \mathcal{N}_e \tag{27}$$

$$t^r z_i^{r,IRA} \leq u_i^{r,IRA} \qquad i \in \mathcal{N}_a \tag{28}$$

$$t^b z_i^{b,EPS} \leq u_i^{b,EPS} \qquad i \in \mathcal{N}_e \tag{29}$$

$$t^b z_i^{b,IRA} \leq u_i^{b,IRA} \qquad i \in \mathcal{N}_a \tag{30}$$

$$\sum_{i \in \mathcal{N}_e} \left(u_i^{r,EPS} + u_i^{b,EPS} \right) \leq M w^{EPS} \tag{31}$$

$$q^{ENG} + q^{APU} = \sum_{i \in \mathcal{N}_c} \left(x_i^{end} - x_i^{arrival} \right) + \sum_{i \in \mathcal{N}_a} \left(u_i^{r,IRA} + u_i^{b,IRA} \right) \tag{32}$$

$$q^{APU} \leq M w^{APU} \qquad i \in \mathcal{N}_c \tag{33}$$

$$x_i^{arrival} \in [0, t^{horizon}], x_i^{start} \in [0, t^{horizon}], x_i^{end} \in [0, t^{horizon}] \qquad i \in \mathcal{N} \tag{34}$$

$$y_i \in \{0, 1\} \qquad i \in \mathcal{N} \tag{35}$$

$$q^{ENG} \geq 0, q^{APU} \geq 0 \tag{36}$$

$$w^{EPS} \in \{0, 1\}, w^{APU} \in \{0, 1\} \tag{37}$$

$$z_i^{r,EPS} \in \{0, 1\}, z_i^{b,EPS} \in \{0, 1\} \qquad i \in \mathcal{N}_e \tag{38}$$

$$z_i^{r,IRA} \in \{0, 1\}, z_i^{b,IRA} \in \{0, 1\} \qquad i \in \mathcal{N}_a \tag{39}$$

$$u_i^{r,EPS} \geq 0, u_i^{b,EPS} \geq 0 \qquad i \in \mathcal{N}_e \tag{40}$$

$$u_i^{r,IRA} \geq 0, u_i^{b,IRA} \geq 0 \qquad i \in \mathcal{N}_a. \tag{41}$$

The first term (1) of the objective function represents the driver cost during on-duty time. Terms (2), (3) and (4) compute the engine idling, EPS idling and APU idling cost, respectively. Terms (5) and (6) compute the fixed cost of EPS and APU equipment, respectively. Since the route is known, the cost of fuel and CO_2 emissions while driving is fixed. Therefore, this cost is not included in the optimization, yet we consider it in the computational experiments when calculating the total cost.

Constraints (7) ensure that the departure time at a depot is equal to the start time and to the arrival time. Constraints (8) guarantee that the service start time at customer locations is at least equal to the arrival time. Constraints (9) state that the departure time at customer locations is equal to the sum of the start and service times. Constraints (10) ensure that the start time at an EPS or at an IRA location is equal to the arrival time. Constraints (11) and (12) imply that the departure time at an EPS or at an IRA location is equal to the sum of start, rest and break times. Constraints (13) state that the arrival time at a location is equal the end time of the previous location, plus the driving time. Constraints (14) ensure that exactly one of the time windows is used at each location. Constraints (15) and (16) enforce the time windows restrictions. Constraints (17) and (18) guarantee that the time elapsed since the end of the last rest and break period must lie within the regulation parameters. Constraints (19) state that the accumulated amount of on-duty hours cannot exceed the weekly on-duty limit. Note that we consider a seven-day horizon. Constraints (20) ensure that the total driving hours between two rest periods does not exceed the daily driving limit t^d. Constraints (21) impose that at each EPS location at most one rest or break period is scheduled scheduled. Constraints (22) ensure that at each IRA location at most one rest or break period is scheduled. Constraints (23)–(26) are linking constraints. Constraints (27)–(30) guarantee that rest or break periods satisfy the HOS regulations. Constraints (31)–(33) are engine, EPS and APU idling time linking constraints. Finally, constraints (34) and (41) define the domains of the decision variables, where M is a large number calculated as

$$M = t^{horizon} - \sum_{i \in \mathcal{N}} d_{i,i+1} - \sum_{i \in \mathcal{N}_c} s_i. \quad (42)$$

2.4 An illustrative example

Figure 4 depicts a feasible TDSP-IO solution with six locations, three customers, two IRAs and one EPS. Each horizontal line represents a time line either for the depot, an EPS, an IRA, or a customer. The square brackets and associated values on a time line represent time windows. The numbers in the middle of the double arrows on the right-hand side show the driving times between locations. A vehicle trip is represented by a path that reads from the top left corner to the bottom right corner. A path between the depot line and the last location line represents a driver schedule. The inclined black and grey segments mean that the driver is driving, resting or taking a break, respectively. A horizontal segment represents waiting time (grey dotted line). A customer is served by a driver when a dark dotted line appears in a time window. The characteristics of the locations are as follows:

- $i = 0, (i \in \mathcal{N}_0), (t_{0,1}^{min} = 0, t_{0,1}^{max} = 168)$;
- $i = 1, (i \in \mathcal{N}_a), (t_{1,1}^{min} = 0, t_{1,1}^{max} = 168)$;
- $i = 2, (i \in \mathcal{N}_c), (w_2 = 60)$ min, $(T_2 = \{[150, 270], [670, 750], [1550, 1880]\}, \tau \in T_2)$;
- $i = 3, (i \in \mathcal{N}_a), (t_{3,1}^{min} = 0, t_{3,1}^{max} = 168)$;
- $i = 4, (i \in \mathcal{N}_c), w_4 = 60$ min, $(T_4 = \{[140, 260], [720, 940], [1500, 1800]\}, \tau \in T_4)$;
- $i = 5, (i \in \mathcal{N}_e), (t_{5,1}^{min} = 0, t_{5,1}^{max} = 168)$;
- $i = 6, (i \in \mathcal{N}_0), (t_{6,1}^{min} = 0, t_{6,1}^{max} = 168)$.

The vehicle starts at time zero and passes the first IRA without taking any rest or break. It then arrives at the first customer at time 240 which lies within a time window. After 60 minutes of customer service, the vehicle continues to drive, takes a 60 minutes break at the second IRA, and

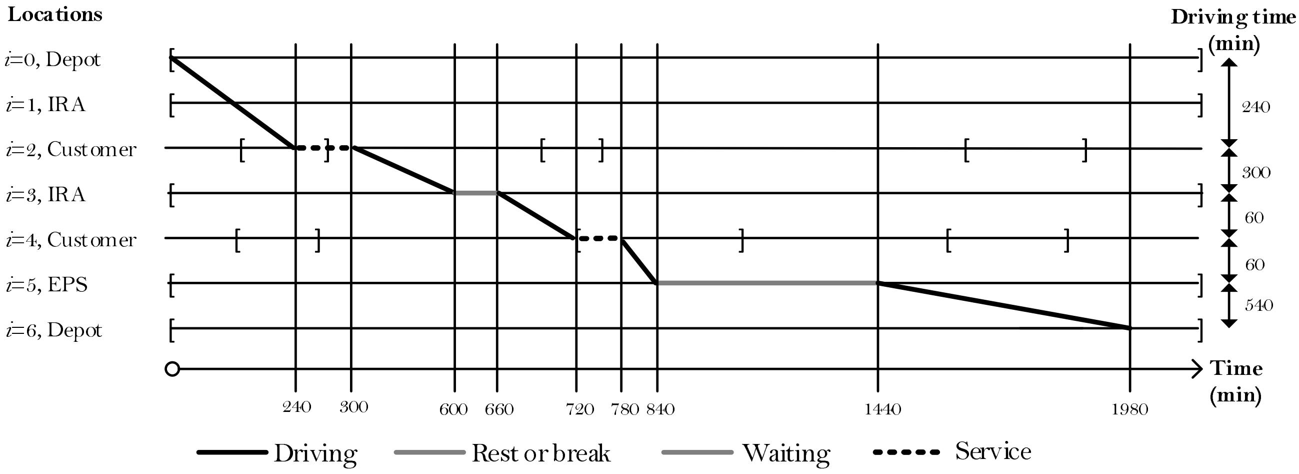

Figure 4: An illustrative example of the TDSP-IO.

then reaches the second customer at time 720. The vehicle leaves the customer at time 780 and reaches the EPS at time 840. The driver takes 10-hour rest until time 1,440. The vehicle finally reaches the depot at time 1,980, which includes the total driving time (1,200 minutes), the total rest time at EPSs (600 minutes), the total break time at IRAs (60 minutes), and the total service time at customers (120 minutes).

3 Computational experiments and analyses

This section presents the results of our computational experiments. All computations were performed on an Intel 3.6 GHz processor. We used CPLEX 12.6 with its default settings as the optimizer to solve the mixed integer linear programming formulation.

3.1 Benchmark instances

We generated 12 *base case* instances, corresponding to routes in the US, which are shown in Figures 5–8. Locations represented by square, triangular and circular shapes denote the depots, EPSs and customers, respectively. The distances between the locations are directly taken from the real-life road network of Google Maps (2016). To generate the locations of IRAs which are widely available on the highways, we assumed that an IRA is located every 100 km on every route. We used the EPS locations provided by the NREL (2016). Table 3 summarizes the characteristics of the benchmark instances. The costs of the idling options have already been provided in Section 2.1.

We fixed the vehicle speed at 100 km/h and the service time at one hour for each customer. We considered a seven-day horizon ($t^{horizon} = 168$ h), and we randomly generated the multiple time windows, stated in hours, for each customer within the intervals [0,24], [25,48], [49,72], [73,96], [97,120], [121,144] and [145,168] for day 1, 2, 3, 4, 5, 6 and 7, respectively.

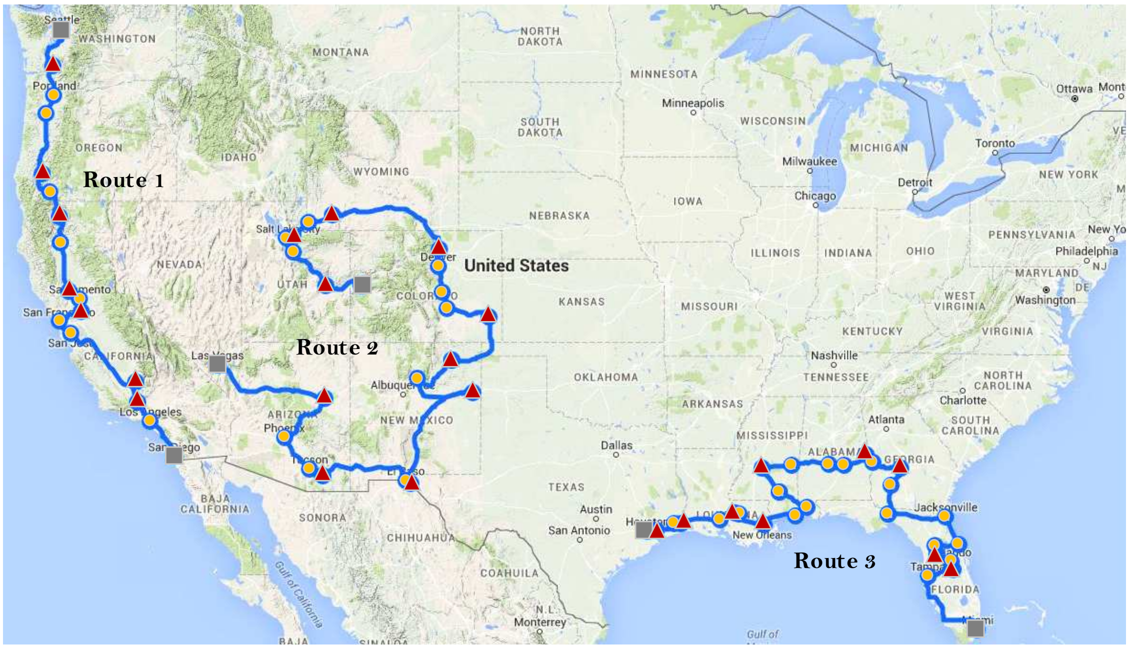

Figure 5: Routes 1, 2 and 3

Figure 6: Routes 4, 5 and 6

Figure 7: Routes 7, 8 and 9

Figure 8: Routes 10, 11 and 12

Table 3: Characteristics of benchmark instances.

Instance	# of customers	# of EPSs	# of IRAs	Total distance	Total service time
US-Route-1	8	8	28	2343	8
US-Route-2	11	10	48	4826	11
US-Route-3	18	10	35	3565	18
US-Route-4	13	6	31	3166	13
US-Route-5	10	6	30	3058	10
US-Route-6	19	13	40	4019	19
US-Route-7	16	14	41	4156	16
US-Route-8	8	11	48	4879	8
US-Route-9	8	9	31	3103	8
US-Route-10	9	7	49	4997	9
US-Route-11	10	7	46	4662	10
US-Route-12	11	8	45	4579	11

3.2 Results for the base case on the 12 benchmark instances of the TDSP-IO

This section presents the detailed results for the base case on the 12 benchmark instances of the TDSP-IO. In Table 4, the columns display the driver cost ($), the route cost ($) which is the fuel and CO_2 emissions cost associated with the traveled distance, the engine idling cost ($), the EPS idling cost ($), the APU idling cost ($), the EPS fixed cost ($), the APU fixed cost ($), the total cost ($), and the computation time in seconds. In Table 5, the columns display the number of rests, the rest time (h), the number of breaks and the break time (h) at EPSs and IRAs. The last three columns show the waiting time at customers (h), the total route duration (h) and the CO_2 emissions in kg which reflects the emissions resulting only from idling.

According to Table 4, the total cost ranges from $832.26 to $1,628.31, with an average of $1,375.43. With one exception, all instances use an APU. Instance US-Route-6 uses EPS and APU idling. Instance US-Route-8 is the only one that uses engine idling; it also uses EPSs, but no APU. In all instances, at least one break is scheduled at an IRA. It is clear that the total cost is dominated by the driver cost. Table 5 shows that the total route duration ranges from 71.38 h to 141.65 h, with an average of 117.55 h. CO_2 emissions resulting from idling activities range from 59.16 kg to 220.51 kg, with an average of 162.74 kg. It is worth mentioning that the waiting time at customer locations is zero for all instances. Instead of spending on-duty time while waiting at customer locations, it is preferable to take longer rests or breaks at EPSs or IRAs. These results clearly indicate that the APU idling option is economically preferable to the EPS and engine idling options.

3.3 Comparison of the three idling options

This section presents the comparison of the three idling options. In particular, we compare five idling scenarios (Scenarios 2–6) with the base case (Scenario 1), which are defined in Table 6. Note that the scenario that uses only the EPS idling option is infeasible since without it engine idling is necessary at customer locations. Tables 7 presents the average results over all 12 instances for each of the six feasible scenarios, while Table 8 presents average deviations from the base case. For detailed results, the reader is referred to Tables A.1–A.2 in the Appendix. The columns show the average percentage deviation of driver cost (Dev_{DR}), engine idling cost (Dev_{ENGi}), EPS idling

Table 4: Computational results for the base case of the TDSP-IO.

Instance	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	Time (s)
			Engine	EPS	APU	EPS	APU		
US-Route-1	530.95	234.30	0.00	0.00	47.78	0.00	19.23	832.26	0.50
US-Route-2	1014.91	482.60	0.00	0.00	90.03	0.00	19.23	1606.77	2.06
US-Route-3	930.29	356.50	0.00	0.00	98.23	0.00	19.23	1404.25	1.16
US-Route-4	826.94	316.60	0.00	0.00	81.63	0.00	19.23	1244.40	0.78
US-Route-5	703.66	305.80	0.00	0.00	59.60	0.00	19.23	1088.29	0.64
US-Route-6	1026.35	401.90	0.00	10.00	89.63	4.81	19.23	1551.92	1.12
US-Route-7	998.09	415.60	0.00	0.00	96.01	0.00	19.23	1528.93	1.49
US-Route-8	961.16	487.90	26.26	62.65	0.00	4.81	0.00	1542.78	2.38
US-Route-9	624.76	310.30	0.00	0.00	38.33	0.00	19.23	992.62	0.66
US-Route-10	1022.54	499.70	0.00	0.00	86.84	0.00	19.23	1628.31	1.64
US-Route-11	981.79	466.20	0.00	0.00	85.61	0.00	19.23	1552.83	1.51
US-Route-12	984.74	457.90	0.00	0.00	69.89	0.00	19.23	1531.76	1.61
Average	883.85	394.61	2.19	6.05	70.30	0.80	17.63	1375.43	1.30

Table 5: Additional results for the base case of the TDSP-IO.

Instance	EPS				IRA				Waiting time (h)	Total duration (h)	CO_2 idling (kg)
	# of rests	Rest time (h)	# of breaks	Break time (h)	# of rests	Rest time (h)	# of breaks	Break time (h)			
US-Route-1	0	0.00	0	0.00	2	38.20	2	1.00	0.00	71.38	107.27
US-Route-2	0	0.00	0	0.00	6	79.87	2	1.00	0.00	139.40	202.11
US-Route-3	0	0.00	0	0.00	5	74.83	2	1.05	0.00	135.88	220.51
US-Route-4	0	0.00	0	0.00	5	66.27	2	1.00	0.00	114.96	183.26
US-Route-5	0	0.00	0	0.00	3	46.15	3	4.35	0.00	91.40	133.80
US-Route-6	1	10.00	0	0.00	5	64.16	8	7.49	0.00	141.65	201.21
US-Route-7	0	0.00	0	0.00	5	76.92	5	2.61	0.00	139.53	215.53
US-Route-8	5	61.15	3	1.50	0	0.00	1	0.50	0.00	118.58	59.16
US-Route-9	0	0.00	0	0.00	2	25.36	9	5.43	0.00	68.14	86.04
US-Route-10	0	0.00	0	0.00	5	77.08	3	1.50	0.00	138.58	194.94
US-Route-11	0	0.00	0	0.00	6	75.86	3	1.50	0.00	133.98	192.19
US-Route-12	0	0.00	0	0.00	4	54.61	5	2.50	0.00	117.11	156.90
Average	0.50	5.93	0.25	0.13	4.00	56.61	3.75	2.49	0.00	117.55	162.74

cost (Dev$_{EPSi}$), APU idling cost (Dev$_{APUi}$), EPS fixed cost (Dev$_{EPSs}$), APU fixed cost (Dev$_{APUs}$), total cost (Dev$_{TC}$), and CO_2 emissions (Dev$_{CO_2}$) from the base case, i.e., Scenario 1.

The base case yields the lowest cost, as expected. However, Scenario 4, which considers only EPS and APU idling, is very similar since engine idling is rarely used in the base case. The worst-case corresponds to Scenario 6 which only considers engine idling; it yields a cost increase of 14.29% over the base case. Scenarios 3 and 5 yield the same total cost, which is 3.34% higher than that of the base case. In terms of CO_2 emissions resulting from idling activities, the percent deviations go in the same direction as the costs, but are even more dramatic. Thus, Scenario 6 which exclusively uses engine idling generates CO_2 emissions that exceed those of the base case by an astonishing 244.28%.

Table 6: Definitions of seven scenarios for idling options.

Scenario	Engine idling	EPS idling	APU idling
1 (base case)	✓	✓	✓
2	✓	✓	
3	✓		✓
4		✓	✓
5			✓
6	✓		
7 (infeasible)		✓	

Table 7: Average results of comparison of the six scenarios.

Scenario	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
			Engine	EPS	APU	EPS	APU		
1 (base case)	883.85	394.61	2.19	6.05	70.30	0.80	17.63	1375.43	162.74
2	925.87	394.61	86.78	50.45	0.00	4.81	0.00	1462.52	195.47
3	928.63	394.61	0.00	0.00	78.89	0.00	19.23	1421.36	177.10
4	883.85	394.61	0.00	1.67	75.29	0.80	19.23	1375.45	169.02
5	928.63	394.61	0.00	0.00	78.89	0.00	19.23	1421.36	177.10
6	928.63	394.61	248.75	0.00	0.00	0.00	0.00	1571.99	560.30

We have also compared the total cost and CO_2 emissions resulting from idling activities of all scenarios that use APU or EPS idling to Scenario 6 which only uses engine idling. These results are presented in Table 9. They indicate cost savings in the range of 6.96% and 12.50%, and CO_2 reductions in between 65.11% and 70.95%. This clearly demonstrates the benefits of using the EPS or APU technology.

Table 8: Average percentage deviations from the base case scenario.

Scenario	Dev_{DR} (%)	Dev_{ENGi} (%)	Dev_{EPSi} (%)	Dev_{APUi} (%)	Dev_{EPSs} (%)	Dev_{APUs} (%)	Dev_{TC} (%)	Dev_{CO_2} (%)
1 (base case)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	4.75	3865.54	733.38	−100.00	500.00	−100.00	6.33	20.11
3	5.07	−100.00	−100.00	12.22	−100.00	9.09	3.34	8.82
4	0.00	−100.00	−72.47	7.10	0.00	9.09	0.00	3.86
5	5.07	−100.00	−100.00	12.22	−100.00	9.09	3.34	8.82
6	5.07	11267.21	−100.00	−100.00	−100.00	−100.00	14.29	244.28

Table 9: Average percentage deviations from the Scenario 6.

Scenario	Dev_{TC} (%)	Dev_{CO_2} (%)
1 (base case)	−12.50	−70.95
2	−6.96	−65.11
3	−9.58	−68.39
4	−12.50	−69.83
5	−9.58	−68.39
6	0.00	0.00

3.4 Amortization period and the effect of the length of economic life of APU and EPS equipment

Table 10 presents the amortization periods for the EPS and APU investments. The average saving column is obtained by the difference between the variable costs of the results without equipment and with equipment. The computation of the last column is based on a 90% truck utilization over a year (7874 hours). Our results show that the amortization cost of an APU can be recouped in slightly less than a year, but this value is higher than that reported by Rahman et al. (2013) and Windover et al. (2015), partly because fuel prices were higher when these studies made (see Section 3.5 on this topic). Nevertheless, the amortization periods are small in all cases, and it makes sense to buy both the APU and the EPS equipment since the amortization period for both systems is about the same as for the APU only and there is added benefit in having both, in terms of cost and CO_2 reductions, as the first line of Table 9 indicates.

In the base case, we consider the length of economic life of APU and EPS equipment to be 10 years, but in practice this value can vary depending on the quality of the products. We now analyze the variations in the length of the economic life of APU and EPS equipment. To this end,

Table 10: Amortization period for APU and EPS equipment.

Equipment	Acquisition cost ($)	Scenario 6 average variable cost without equipment ($)	Average variable cost with equipment ($)	Average saving per route ($)	Average route duration (h)	Average hourly saving ($)	Amortization period (years)
EPS and APU	12500.00	1571.99	1357.00	214.99	117.55	1.83	0.87
EPS	2500.00	1571.99	1457.71	114.28	117.59	0.97	0.33
APU	10000.00	1571.99	1402.13	169.86	119.56	1.42	0.89

we considered the following variations: five, 15 and 20 years. Tables 11 and 12 show the average results and average percentage deviations with respect to the base case. For detailed results, the reader is referred to Table A.3 in the Appendix.

Table 12 indicates that the total cost increases by 1.34% when the length of economic life of these equipment is five years, and decreases by 0.48% and 0.73% when it is 15 and 20 years, respectively. The costs of engine, EPS and APU idling do not change when their life is five years. On the other hand, if the length of economic life is 15 or 20 years, engine idling is never a selected option, and EPS idling is less often used. These results indicate that APU idling becomes more beneficial if useful life of the equipment is longer. A shorter economic life does not effect the CO_2 emissions resulting from idling activities, but when it increases to 15 and 20 years, CO_2 emissions increase by 3.86%, which is the result of APU idling.

Table 11: Average results of variations in the length of economic life of APU and EPS equipment.

Length of economic life (years)	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
			Engine	EPS	APU	EPS	APU		
5	883.85	394.61	2.19	6.05	70.30	1.60	35.26	1393.86	162.74
10	883.85	394.61	2.19	6.05	70.30	0.80	17.63	1375.43	162.74
15	883.85	394.61	0.00	1.67	75.29	0.53	12.82	1368.77	169.02
20	883.85	394.61	0.00	1.67	75.29	0.40	9.62	1365.44	169.02

Table 12: Average percentage deviations of variations in the length of economic life of APU and EPS equipment.

Length of economic life (years)	Dev_{DR} (%)	Dev_{ENGi} (%)	Dev_{EPSi} (%)	Dev_{APUi} (%)	Dev_{EPSs} (%)	Dev_{APUs} (%)	Dev_{TC} (%)	Dev_{CO_2} (%)
5	0.00	0.00	0.00	0.00	100.00	100.00	1.34	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	−100.00	−72.47	7.10	−33.47	−27.27	−0.48	3.86
20	0.00	−100.00	−72.47	7.10	−50.10	−45.43	−0.73	3.86

3.5 The impact of variations in the fuel prices

Fuel prices are subject to high variations but have mostly decreased in recent years (EIA, 2016). In this section, we investigate the impact of variations in fuel prices. To this end, we have decreased the fuel price by 25%, 50% and 75%, and we have increased it by 25%, 50% and 75%. Table 13 shows the average results of these experiments for all instances. For detailed results, the reader is referred to Tables A.4–A.5 in the Appendix. Table 14 presents average deviations from the base case of each fuel price variant.

Our results indicate that the total cost decreases by 13.54%, 7.13% and 3.54% when the fuel price decreases by 75%, 50% and 25%, respectively. Likewise, the total cost increases by 6.29%, 9.52% and 12.64% when the fuel price increases by 25%, 50% and 75%, respectively. Irrespective of fuel prices, it is advantageous to equip the trucks with an APU. However, the use of EPSs is relatively more important when the fuel price goes up. In terms of environmental impacts, CO_2 emissions resulting from idling activities increase by 3.86% when the fuel price decreases by 25%, 50% or 75%. On the other hand, CO_2 emissions radically decrease by 44.77%, 58.68% and 60.91%, when the fuel price increases by 25%, 50% and 75%, respectively. This is only made possible by the optimized joint usage of the these two idling options.

Table 13: Average results of variations in fuel prices.

Change in fuel price	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
			Engine	EPS	APU	EPS	APU		
−75%	883.85	236.77	0.00	1.67	46.87	0.80	19.23	1189.18	169.02
−50%	883.85	315.69	0.00	1.67	56.09	0.80	19.23	1277.32	169.02
−25%	883.85	355.15	0.00	1.67	66.07	0.80	19.23	1326.77	169.02
0	883.85	394.61	2.19	6.05	70.30	0.80	17.63	1375.43	162.74
25%	883.85	473.53	0.00	37.64	44.95	2.81	19.23	1462.00	89.89
50%	883.85	512.99	0.00	47.93	37.90	4.41	19.23	1506.31	67.25
75%	883.85	552.45	0.00	49.58	39.33	4.81	19.23	1549.25	63.62

Finally, we have computed in Table 15 the amortization period for EPS equipment and APU for various fuel prices. As expected, the amortization period becomes shorter when fuel prices increase.

Table 14: Average percentage deviations of variations in fuel prices.

Change in fuel price (%)	Dev_{DR} (%)	Dev_{ENGi} (%)	Dev_{EPSi} (%)	Dev_{APUi} (%)	Dev_{EPSs} (%)	Dev_{APUs} (%)	Dev_{TC} (%)	Dev_{CO_2} (%)
−75%	0.00	−100.00	−72.47	−33.33	0.00	9.09	−13.54	3.86
−50%	0.00	−100.00	−72.47	−20.22	0.00	9.09	−7.13	3.86
−25%	0.00	−100.00	−72.47	−6.01	0.00	9.09	−3.54	3.86
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25%	0.00	−100.00	521.67	−36.06	250.00	9.09	6.29	−44.77
50%	0.00	−100.00	691.69	−46.08	450.00	9.09	9.52	−58.68
75%	0.00	−100.00	718.93	−44.06	500.00	9.09	12.64	−60.91

Table 15: Results for the amortization period for EPS equipment and APU for various fuel prices.

Change in fuel price (%)	Fuel price ($/L)	Amortization period (years)		
		EPS and APU	EPS	APU
−75%	0.13	1.24	0.40	1.29
−50%	0.26	1.07	0.32	1.08
−25%	0.39	0.95	0.27	0.94
0 (base case)	0.52	0.87	0.33	0.89
25%	0.65	0.77	0.21	0.74
50%	0.78	0.69	0.19	0.67
75%	0.91	0.62	0.17	0.61

4 Conclusions and Managerial Insights

We have studied the joint impact of the truck driver scheduling and idling under the US HOS regulations within a long-haul transportation context. To this end, we have considered three idling options: engine idling, EPS idling, and APU idling. We have introduced, modeled and solved the Truck Driver Scheduling Problem with Idling Options (TDSP-IO), a variant of the TDSP that uses a comprehensive objective function. We have performed extensive analyses to shed light on the trade-offs between different problem components, such as route duration, CO_2 emissions, idling options and fuel prices.

Our analysis reveals that it makes economic and ecological sense to acquire EPS and APU equipments. From a cost perspective, we have shown that EPSs and APUs can be jointly amortized within a year and yield cost savings ranging between 6.96% and 12.50%. These figures most likely underestimate the actual savings since they do not account for the extra maintenance costs due to engine idling. The amortization period decreases when fuel prices go up, which is a likely outcome in the coming years. Regarding the environmental benefits, our results indicate the CO_2

reductions resulting from idling activities between 65.11% and 70.95% over the scenario that only allows engine idling can be achieved with the use of these more ecological equipments. We have also shown that APU acquisition is beneficial over all fuel price ranges whereas EPSs become relatively more interesting in higher fuel price ranges.

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Appendix

Tables A.1–A.5 present the detailed computational results.

Table A.1: Results of Scenarios 2, 3 and 4.

Instance	Scenario	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
				Engine	EPS	APU	EPS	APU		
US-Route-1	2	530.95	234.30	63.53	28.20	0.00	4.81	0.00	861.79	143.10
US-Route-2	2	1014.91	482.60	64.89	70.87	0.00	4.81	0.00	1638.08	146.16
US-Route-3	2	1434.54	356.50	55.62	82.73	0.00	4.81	0.00	1934.20	125.28
US-Route-4	2	826.94	316.60	138.96	38.33	0.00	4.81	0.00	1325.64	312.99
US-Route-5	2	703.66	305.80	124.71	20.46	0.00	4.81	0.00	1159.44	280.91
US-Route-6	2	1026.35	401.90	58.71	82.46	0.00	4.81	0.00	1574.23	132.24
US-Route-7	2	998.09	415.60	111.24	61.97	0.00	4.81	0.00	1591.71	250.56
US-Route-8	2	961.16	487.90	26.26	62.65	0.00	4.81	0.00	1542.78	59.16
US-Route-9	2	624.76	310.30	59.70	19.79	0.00	4.81	0.00	1019.36	134.47
US-Route-10	2	1022.54	499.70	122.05	49.11	0.00	4.81	0.00	1698.21	274.92
US-Route-11	2	981.79	466.20	108.18	52.35	0.00	4.81	0.00	1613.33	243.67
US-Route-12	2	984.74	457.90	107.50	36.53	0.00	4.81	0.00	1591.48	242.14
US-Route-1	3	530.95	234.30	0.00	0.00	47.78	0.00	19.23	832.26	107.27
US-Route-2	3	1014.91	482.60	0.00	0.00	90.03	0.00	19.23	1606.77	202.11
US-Route-3	3	930.29	356.50	0.00	0.00	98.23	0.00	19.23	1404.25	220.51
US-Route-4	3	826.94	316.60	0.00	0.00	81.63	0.00	19.23	1244.40	183.26
US-Route-5	3	703.66	305.80	0.00	0.00	59.60	0.00	19.23	1088.29	133.80
US-Route-6	3	1429.86	401.90	0.00	0.00	112.79	0.00	19.23	1963.78	253.20
US-Route-7	3	998.09	415.60	0.00	0.00	96.01	0.00	19.23	1528.93	215.53
US-Route-8	3	1095.02	487.90	0.00	0.00	79.96	0.00	19.23	1682.11	179.50
US-Route-9	3	624.76	310.30	0.00	0.00	38.33	0.00	19.23	992.62	86.04
US-Route-10	3	1022.54	499.70	0.00	0.00	86.84	0.00	19.23	1628.31	194.94
US-Route-11	3	981.79	466.20	0.00	0.00	85.61	0.00	19.23	1552.83	192.19
US-Route-12	3	984.74	457.90	0.00	0.00	69.89	0.00	19.23	1531.76	156.90
US-Route-1	4	530.95	234.30	0.00	0.00	47.78	0.00	19.23	832.26	107.27
US-Route-2	4	1014.91	482.60	0.00	0.00	90.03	0.00	19.23	1606.77	202.11
US-Route-3	4	930.29	356.50	0.00	0.00	98.23	0.00	19.23	1404.25	220.51
US-Route-4	4	826.94	316.60	0.00	0.00	81.63	0.00	19.23	1244.40	183.26
US-Route-5	4	703.66	305.80	0.00	0.00	59.60	0.00	19.23	1088.29	133.80
US-Route-6	4	1026.35	401.90	0.00	10.00	89.63	4.81	19.23	1551.92	201.21
US-Route-7	4	998.09	415.60	0.00	0.00	96.01	0.00	19.23	1528.93	215.53
US-Route-8	4	961.16	487.90	0.00	10.00	59.93	4.81	19.23	1543.03	134.53
US-Route-9	4	624.76	310.30	0.00	0.00	38.33	0.00	19.23	992.62	86.04
US-Route-10	4	1022.54	499.70	0.00	0.00	86.84	0.00	19.23	1628.31	194.94
US-Route-11	4	981.79	466.20	0.00	0.00	85.61	0.00	19.23	1552.83	192.19
US-Route-12	4	984.74	457.90	0.00	0.00	69.89	0.00	19.23	1531.76	156.90

Table A.2: Results of Scenarios 5 and 6.

Instance	Scenario	Driver cost ($)	Route cost ($)	Idling costs ($) Engine	Idling costs ($) EPS	Idling costs ($) APU	Fixed costs ($) EPS	Fixed costs ($) APU	Total cost ($)	CO_2 idling (kg)
US-Route-1	5	530.95	234.30	0.00	0.00	47.78	0.00	19.23	832.26	107.27
US-Route-2	5	1014.91	482.60	0.00	0.00	90.03	0.00	19.23	1606.77	202.11
US-Route-3	5	930.29	356.50	0.00	0.00	98.23	0.00	19.23	1404.25	220.51
US-Route-4	5	826.94	316.60	0.00	0.00	81.63	0.00	19.23	1244.40	183.26
US-Route-5	5	703.66	305.80	0.00	0.00	59.60	0.00	19.23	1088.29	133.80
US-Route-6	5	1429.86	401.90	0.00	0.00	112.79	0.00	19.23	1963.78	253.20
US-Route-7	5	998.09	415.60	0.00	0.00	96.01	0.00	19.23	1528.93	215.53
US-Route-8	5	1095.02	487.90	0.00	0.00	79.96	0.00	19.23	1682.11	179.50
US-Route-9	5	624.76	310.30	0.00	0.00	38.33	0.00	19.23	992.62	86.04
US-Route-10	5	1022.54	499.70	0.00	0.00	86.84	0.00	19.23	1628.31	194.94
US-Route-11	5	981.79	466.20	0.00	0.00	85.61	0.00	19.23	1552.83	192.19
US-Route-12	5	984.74	457.90	0.00	0.00	69.89	0.00	19.23	1531.76	156.90
US-Route-1	6	530.95	234.30	150.67	0.00	0.00	0.00	0.00	915.92	339.37
US-Route-2	6	1014.91	482.60	283.88	0.00	0.00	0.00	0.00	1781.39	639.42
US-Route-3	6	930.29	356.50	309.71	0.00	0.00	0.00	0.00	1596.50	697.60
US-Route-4	6	826.94	316.60	257.40	0.00	0.00	0.00	0.00	1400.94	579.77
US-Route-5	6	703.66	305.80	187.93	0.00	0.00	0.00	0.00	1197.39	423.31
US-Route-6	6	1429.86	401.90	355.63	0.00	0.00	0.00	0.00	2187.39	801.03
US-Route-7	6	998.09	415.60	302.73	0.00	0.00	0.00	0.00	1716.42	681.87
US-Route-8	6	1095.02	487.90	252.11	0.00	0.00	0.00	0.00	1835.03	567.87
US-Route-9	6	624.76	310.30	120.85	0.00	0.00	0.00	0.00	1055.91	272.21
US-Route-10	6	1022.54	499.70	273.80	0.00	0.00	0.00	0.00	1796.04	616.73
US-Route-11	6	981.79	466.20	269.94	0.00	0.00	0.00	0.00	1717.93	608.03
US-Route-12	6	984.74	457.90	220.38	0.00	0.00	0.00	0.00	1663.02	496.39

Table A.3: Results of variations in the length of economic life of APU and EPS equipment.

Instance	Length of economic life (years)	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
				Engine	EPS	APU	EPS	APU		
US-Route-1	5	530.95	234.30	0.00	0.00	47.78	0.00	38.46	851.49	107.27
US-Route-2	5	1014.91	482.60	0.00	0.00	90.03	0.00	38.46	1626.00	202.11
US-Route-3	5	930.29	356.50	0.00	0.00	98.23	0.00	38.46	1423.48	220.51
US-Route-4	5	826.94	316.60	0.00	0.00	81.63	0.00	38.46	1263.63	183.26
US-Route-5	5	703.66	305.80	0.00	0.00	59.60	0.00	38.46	1107.52	133.80
US-Route-6	5	1026.35	401.90	0.00	10.00	89.63	9.62	38.46	1575.96	201.21
US-Route-7	5	998.09	415.60	0.00	0.00	96.01	0.00	38.46	1548.16	215.53
US-Route-8	5	961.16	487.90	26.26	62.65	0.00	9.62	0.00	1547.59	59.16
US-Route-9	5	624.76	310.30	0.00	0.00	38.33	0.00	38.46	1011.85	86.04
US-Route-10	5	1022.54	499.70	0.00	0.00	86.84	0.00	38.46	1647.54	194.94
US-Route-11	5	981.79	466.20	0.00	0.00	85.61	0.00	38.46	1572.06	192.19
US-Route-12	5	984.74	457.90	0.00	0.00	69.89	0.00	38.46	1550.99	156.90
US-Route-1	15	530.95	234.30	0.00	0.00	47.78	0.00	12.82	825.85	107.27
US-Route-2	15	1014.91	482.60	0.00	0.00	90.03	0.00	12.82	1600.36	202.11
US-Route-3	15	930.29	356.50	0.00	0.00	98.23	0.00	12.82	1397.84	220.51
US-Route-4	15	826.94	316.60	0.00	0.00	81.63	0.00	12.82	1237.99	183.26
US-Route-5	15	703.66	305.80	0.00	0.00	59.60	0.00	12.82	1081.88	133.80
US-Route-6	15	1026.35	401.90	0.00	10.00	89.63	3.20	12.82	1543.90	201.21
US-Route-7	15	998.09	415.60	0.00	0.00	96.01	0.00	12.82	1522.52	215.53
US-Route-8	15	961.16	487.90	0.00	10.00	59.93	3.20	12.82	1535.01	134.53
US-Route-9	15	624.76	310.30	0.00	0.00	38.33	0.00	12.82	986.21	86.04
US-Route-10	15	1022.54	499.70	0.00	0.00	86.84	0.00	12.82	1621.90	194.94
US-Route-11	15	981.79	466.20	0.00	0.00	85.61	0.00	12.82	1546.42	192.19
US-Route-12	15	984.74	457.90	0.00	0.00	69.89	0.00	12.82	1525.35	156.90
US-Route-1	20	530.95	234.30	0.00	0.00	47.78	0.00	9.62	822.65	107.27
US-Route-2	20	1014.91	482.60	0.00	0.00	90.03	0.00	9.62	1597.16	202.11
US-Route-3	20	930.29	356.50	0.00	0.00	98.23	0.00	9.62	1394.64	220.51
US-Route-4	20	826.94	316.60	0.00	0.00	81.63	0.00	9.62	1234.79	183.26
US-Route-5	20	703.66	305.80	0.00	0.00	59.60	0.00	9.62	1078.68	133.80
US-Route-6	20	1026.35	401.90	0.00	10.00	89.63	2.40	9.62	1539.90	201.21
US-Route-7	20	998.09	415.60	0.00	0.00	96.01	0.00	9.62	1519.32	215.53
US-Route-8	20	961.16	487.90	0.00	10.00	59.93	2.40	9.62	1531.01	134.53
US-Route-9	20	624.76	310.30	0.00	0.00	38.33	0.00	9.62	983.01	86.04
US-Route-10	20	1022.54	499.70	0.00	0.00	86.84	0.00	9.62	1618.70	194.94
US-Route-11	20	981.79	466.20	0.00	0.00	85.61	0.00	9.62	1543.22	192.19
US-Route-12	20	984.74	457.90	0.00	0.00	69.89	0.00	9.62	1522.15	156.90

Table A.4: Results of decreasing fuel prices.

Instance	Change in fuel price (%)	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
				Engine	EPS	APU	EPS	APU		
US-Route-1	−25	530.95	210.87	0.00	0.00	41.93	0.00	19.23	802.98	107.27
US-Route-2	−25	1014.91	434.34	0.00	0.00	79.01	0.00	19.23	1547.49	202.11
US-Route-3	−25	930.29	320.85	0.00	0.00	86.20	0.00	19.23	1356.57	220.51
US-Route-4	−25	826.94	284.94	0.00	0.00	71.64	0.00	19.23	1202.75	183.26
US-Route-5	−25	703.66	275.22	0.00	0.00	52.31	0.00	19.23	1050.42	133.80
US-Route-6	−25	1026.35	361.71	0.00	10.00	78.66	4.81	19.23	1500.76	201.21
US-Route-7	−25	998.09	374.04	0.00	0.00	84.25	0.00	19.23	1475.61	215.53
US-Route-8	−25	961.16	439.11	0.00	10.00	52.59	4.81	19.23	1486.90	134.53
US-Route-9	−25	624.76	279.27	0.00	0.00	33.63	0.00	19.23	956.89	86.04
US-Route-10	−25	1022.54	449.73	0.00	0.00	76.20	0.00	19.23	1567.70	194.94
US-Route-11	−25	981.79	419.58	0.00	0.00	75.13	0.00	19.23	1495.73	192.19
US-Route-12	−25	984.74	412.11	0.00	0.00	61.34	0.00	19.23	1477.42	156.90
US-Route-1	−50	530.95	187.44	0.00	0.00	35.59	0.00	19.23	773.21	107.27
US-Route-2	−50	1014.91	386.08	0.00	0.00	67.07	0.00	19.23	1487.29	202.11
US-Route-3	−50	930.29	285.20	0.00	0.00	73.17	0.00	19.23	1307.89	220.51
US-Route-4	−50	826.94	253.28	0.00	0.00	60.81	0.00	19.23	1160.26	183.26
US-Route-5	−50	703.66	244.64	0.00	0.00	44.40	0.00	19.23	1011.93	133.80
US-Route-6	−50	1026.35	321.52	0.00	10.00	66.77	4.81	19.23	1448.68	201.21
US-Route-7	−50	998.09	332.48	0.00	0.00	71.52	0.00	19.23	1421.32	215.53
US-Route-8	−50	961.16	390.32	0.00	10.00	44.64	4.81	19.23	1430.16	134.53
US-Route-9	−50	624.76	248.24	0.00	0.00	28.55	0.00	19.23	920.78	86.04
US-Route-10	−50	1022.54	399.76	0.00	0.00	64.69	0.00	19.23	1506.22	194.94
US-Route-11	−50	981.79	372.96	0.00	0.00	63.77	0.00	19.23	1437.75	192.19
US-Route-12	−50	984.74	366.32	0.00	0.00	52.06	0.00	19.23	1422.35	156.90
US-Route-1	−75	530.95	140.58	0.00	0.00	29.74	0.00	19.23	720.50	107.27
US-Route-2	−75	1014.91	289.56	0.00	0.00	56.04	0.00	19.23	1379.74	202.11
US-Route-3	−75	930.29	213.90	0.00	0.00	61.14	0.00	19.23	1224.56	220.51
US-Route-4	−75	826.94	189.96	0.00	0.00	50.81	0.00	19.23	1086.94	183.26
US-Route-5	−75	703.66	183.48	0.00	0.00	37.10	0.00	19.23	943.47	133.80
US-Route-6	−75	1026.35	241.14	0.00	10.00	55.79	4.81	19.23	1357.32	201.21
US-Route-7	−75	998.09	249.36	0.00	0.00	59.76	0.00	19.23	1326.44	215.53
US-Route-8	−75	961.16	292.74	0.00	10.00	37.30	4.81	19.23	1325.24	134.53
US-Route-9	−75	624.76	186.18	0.00	0.00	23.86	0.00	19.23	854.03	86.04
US-Route-10	−75	1022.54	299.82	0.00	0.00	54.05	0.00	19.23	1395.64	194.94
US-Route-11	−75	981.79	279.72	0.00	0.00	53.29	0.00	19.23	1334.03	192.19
US-Route-12	−75	984.74	274.74	0.00	0.00	43.51	0.00	19.23	1322.22	156.90

Table A.5: Results of increasing fuel prices.

Instance	Change in fuel price (%)	Driver cost ($)	Route cost ($)	Idling costs ($)			Fixed costs ($)		Total cost ($)	CO_2 idling (kg)
				Engine	EPS	APU	EPS	APU		
US-Route-1	25	530.95	281.16	0.00	0.00	53.64	0.00	19.23	884.98	107.27
US-Route-2	25	1014.91	579.12	0.00	70.87	23.10	4.81	19.23	1712.04	46.20
US-Route-3	25	930.29	427.80	0.00	72.23	30.80	4.81	19.23	1485.16	61.60
US-Route-4	25	826.94	379.92	0.00	0.00	91.63	0.00	19.23	1317.72	183.26
US-Route-5	25	703.66	366.96	0.00	0.00	66.90	0.00	19.23	1156.75	133.80
US-Route-6	25	1026.35	482.28	0.00	82.46	20.90	4.81	19.23	1636.03	41.80
US-Route-7	25	998.09	498.72	0.00	61.97	39.60	4.81	19.23	1622.42	79.20
US-Route-8	25	961.16	585.48	0.00	62.65	9.35	4.81	19.23	1642.68	18.70
US-Route-9	25	624.76	372.36	0.00	0.00	43.02	0.00	19.23	1059.37	86.04
US-Route-10	25	1022.54	599.64	0.00	49.11	43.45	4.81	19.23	1738.78	86.90
US-Route-11	25	981.79	559.44	0.00	52.35	38.51	4.81	19.23	1656.13	77.02
US-Route-12	25	984.74	549.48	0.00	0.00	78.45	0.00	19.23	1631.90	156.90
US-Route-1	50	530.95	304.59	0.00	28.20	25.49	4.81	19.23	913.27	45.23
US-Route-2	50	1014.91	627.38	0.00	70.87	26.04	4.81	19.23	1763.24	46.20
US-Route-3	50	930.29	463.45	0.00	72.23	34.72	4.81	19.23	1524.73	61.60
US-Route-4	50	826.94	411.58	0.00	38.33	55.76	4.81	19.23	1356.65	98.93
US-Route-5	50	703.66	397.54	0.00	20.46	50.05	4.81	19.23	1195.75	88.79
US-Route-6	50	1026.35	522.47	0.00	82.46	23.56	4.81	19.23	1678.88	41.80
US-Route-7	50	998.09	540.28	0.00	61.97	44.64	4.81	19.23	1669.02	79.20
US-Route-8	50	961.16	634.27	0.00	62.65	10.54	4.81	19.23	1692.66	18.70
US-Route-9	50	624.76	403.39	0.00	0.00	48.50	0.00	19.23	1095.88	86.04
US-Route-10	50	1022.54	649.61	0.00	49.11	48.98	4.81	19.23	1794.28	86.90
US-Route-11	50	981.79	606.06	0.00	52.35	43.41	4.81	19.23	1707.65	77.02
US-Route-12	50	984.74	595.27	0.00	36.53	43.14	4.81	19.23	1683.72	76.54
US-Route-1	75	530.95	328.02	0.00	28.20	27.96	4.81	19.23	939.17	45.23
US-Route-2	75	1014.91	675.64	0.00	70.87	28.56	4.81	19.23	1814.02	46.20
US-Route-3	75	930.29	499.10	0.00	72.23	38.08	4.81	19.23	1563.74	61.60
US-Route-4	75	826.94	443.24	0.00	38.33	61.16	4.81	19.23	1393.71	98.93
US-Route-5	75	703.66	428.12	0.00	20.46	54.89	4.81	19.23	1231.17	88.79
US-Route-6	75	1026.35	562.66	0.00	82.46	25.84	4.81	19.23	1721.35	41.80
US-Route-7	75	998.09	581.84	0.00	61.97	48.96	4.81	19.23	1714.90	79.20
US-Route-8	75	961.16	683.06	0.00	62.65	11.56	4.81	19.23	1742.47	18.70
US-Route-9	75	624.76	434.42	0.00	19.79	26.28	4.81	19.23	1129.29	42.50
US-Route-10	75	1022.54	699.58	0.00	49.11	53.72	4.81	19.23	1848.99	86.90
US-Route-11	75	981.79	652.68	0.00	52.35	47.61	4.81	19.23	1758.47	77.02
US-Route-12	75	984.74	641.06	0.00	36.53	47.31	4.81	19.23	1733.68	76.54

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