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Abstract

This paper studies the revised hours of service regulations for truck drivers in the United States which will enter into force in July 2013. It provides a detailed model of the new regulation and presents and a new simulation-based method to assess the impact of the rule change on operational costs and road safety. Unlike previous methodologies, the new methodology takes into account that carriers can use optimization as a tool to minimize the economic impact of stricter regulations. Simulation experiments are conducted indicating that the monetized safety benefit of reducing the daily driving time limits is on the same order of magnitude compared to the additional operational costs.

1 Introduction

In July 2013, new hours of service regulations for truck drivers in the United States will enter into force (Federal Motor Carrier Safety Administration, 2011). The revised regulations were the outcome of a long dispute concerning the safety impact of previous hours of service regulations. In 2003 the Federal Motor Carrier Safety Administration (FMCSA) increased the previous daily driving time limit of 10 to 11 hours and introduced the commonly called '34-hour restart' provision (Federal Motor Carrier Safety Administration, 2003). These regulations as well as merely identical rules subsequently published were overturned by the U.S. Court of Appeals for the D.C. Circuit. After another lawsuit was filed (Stone et al., 2009) against the once again identical rules published in 2008 (Federal Motor Carrier

Safety Administration, 2008a), the FMCSA signed a settlement agreement and announced that it will reconsider and change the regulation. The now revised regulations restrict the usage of the '34-hour restart' provision and introduce a new provision which requires that drivers must only drive if a period of at least 30 minutes of off-duty time is taken within the last 8 hours. Although the FMCSA considered reducing the daily driving time limit to at most 10 hours and also evaluated a driving time limit of 9 hours, the agency was not able to show that the improved road safety resulting from reducing the maximum daily driving time is justified by the negative impact on productivity. The FMCSA retained the daily driving time limit of 11 hours, but mentioned that it would have favored a lower daily driving time limit. Furthermore, the agency indicated that future research may provide a basis for reconsidering the daily driving limit (Federal Motor Carrier Safety Administration, 2011).

In this paper we review previous regulatory impact assessments and propose a new methodology for assessing the impact of revised regulations on road safety and productivity. The main contributions of this paper are the following. First, we identify several shortcomings of the recent regulatory impact assessments conducted by the FMCSA. To overcome these shortcomings we propose a new simulation-based methodology for assessing the impact of regulations on accident risks and productivity. This methodology is based on a detailed model of the revised regulations and a scheduling procedure capable of automatically generating truck driver schedules complying with the revised regulations. The scheduling procedure presented in this paper can be used by motor carriers to automatically generate and optimize vehicle routes and schedules using computer-based planning approaches. As the method guarantees that drivers are given enough time for regularly taking breaks and rest periods, the method itself can contribute to improved road safety if carriers use planning tools using this method. The regulatory impact assessment based on the proposed methodology indicates that road safety benefits of reducing the daily driving time limit are on the same order of magnitude compared to additional operational costs.

In the next section we will give a description of the revised regulations. After providing an overview over related work and previous regulatory impact assessments in Section 3, the new methodology to assess the impact of hours of service regulations is presented in Section 4. A detailed model of the revised regulations and a method to optimize routes and schedules are described in Section 5. In Section 6, the regulatory impact analysis is given and Section 7 concludes the paper.

2 The revised hours of service regulations

In December 2011, the FMCSA published new hours of service regulations for truck drivers in the United States which will become effective in July 2013. Like the previous regulations, the revised regulations distinguish between *on-duty time* and *off-duty time*. On-duty time refers to all time a driver is working, and includes driving activities as well as other work such as loading and unloading. Off-duty time refers to any time during which a driver is not performing any work.

According to the regulations, a driver must not drive without first taking a period of 10 consecutive hours of off-duty time. In the remainder we refer to such a period as *rest period*. The maximum amount of driving time between two consecutive rest periods is limited to 11 hours. The regulation prohibits a driver from driving after 14 hours have elapsed since the end of the last rest period. While above rules are the same as in the previous regulation, the new regulation furthermore introduces additional break constraints which prohibit a driver from driving after 8 hours have elapsed since the end of the last off-duty period of at least 30 minutes. In the remainder we refer to such a period as *break period*.

If the employing motor carrier operates every day of the week, a driver must not drive after 70 hours of on-duty time are accumulated within a period of 8 days. Otherwise, a driver must not drive after 60 hours of on-duty time are accumulated within a period of 7 days.

If an off-duty period of at least 34 consecutive hours is taken, the driver may restart accumulating on-duty time with respect to the previous provision. According to the revised regulations, this 34 hour off-duty period must include two periods from 1 AM to 5 AM. Furthermore, the calculation of the accumulated on-duty time may only be restarted if 168 or more consecutive hours have passed since the beginning of the last 34 hour off-duty period.

3 Related work

Different methodologies to analyze how a rule change impacts productivity and road safety have been used in the past. If statistical data for periods before and after a regulatory change are available, the impact of the change can be assessed by comparing the respective data sets. The study by McCartt et al. (2008) used survey based data for the periods before and after the rule change of 2003 came into effect. According to the survey, one out of six truck drivers admits to having dozed at wheel in the month prior to the survey. This value has significantly increased since the 2003 rule came into effect. The survey also revealed that less than one out of two truck drivers reported that delivery schedules are always realistic. Truck drivers who reported that they are sometimes or often given unrealistic delivery schedules are approximately three times as likely to violate the work rules as drivers who rarely or never have to deal with unrealistic delivery schedules. Hanowski et al. (2007) conducted a naturalistic driving study based on data collection using sensors and video to analyze the impact of the 2003 rule change on the duration of sleep and involvement in critical incident. They found that prior to a critical incident, drivers received less sleep, and that, compared to the amount of sleep identified in previous research by Mitler et al. (1997), drivers may be getting more sleep after the rule change. In another study Hanowski et al. (2009) analyzed the impact of the 2003 rule change focusing on the increased daily driving time limit. Based on the occurrence of critical incidents as a function of driving hours since the last rest period, Hanowski et al. (2009) could find no evidence that accident risks are increased by changing the daily driving time limit from 10 to 11 hours. Whether the increase in the driving time limit has an impact on accident risks on subsequent days was not assessed.

Obviously, approaches similar to the ones above can only be conducted after a rule change has been implemented. In 2008, the FMCSA conducted a regulatory impact analysis (RIA) using a simulation-based approach (Federal Motor Carrier Safety Administration, 2008b). A truck driver performing full truckload operations is simulated assuming that whenever the driver delivers a load, a new pickup and delivery request is selected from a pool of potential requests. Within the simulation a rule-based approach for scheduling duty and rest periods is used. The scheduling approach is not based on a detailed model of the regulation and assumes that drivers take voluntary breaks although they are not required by the regulation. In the last years significant progress has been made in developing detailed models of hours of service regulations world wide (Archetti and Savelsbergh, 2009; Goel, 2010; Kok et al., 2010; Prescott-Gagnon et al., 2010; Goel and Kok, 2012; Goel and Rousseau, 2012; Goel et al., 2012; Rancourt et al., 2012). These detailed models and the scheduling methods presented in these papers could be used to replace the rule-based approach used in the 2008 RIA. After generating driver schedules, the 2008 RIA analyzes them with respect to operating costs and accident risks. To assess accident risks of work plans the SAFTE/FAST model is used which together with other biomathematical models for human performance and fatigue is surveyed in Mallis et al. (2004). As the SAFTE model does not include the effects of workload, the crash risk after a given number of hours of driving is estimated using a function derived from the analysis by Campbell (2005). The results of both models are then combined to assess the overall impact of the regulations considered on accident risks. In 2006, the Health and Safety Executive in the United Kingdom published a different approach to assess the accident risk associated to work plans of shift workers (Spencer et al., 2006; Health and Safety Executive, 2006). This approach considers the cumulative impact of sleep deprivation, the circadian rhythm as well as the duration of breaks during a work shift. With this integrated tool it is not required to use and combine the results of different models as was done in the regulatory impact assessment of 2008.

For the recently revised regulations the FMCSA conducted a new RIA (Federal Motor Carrier Safety Administration, 2010). In the RIA, typical operating patterns of truck drivers are analyzed and drivers are categorized according to their average weekly work time. Based on this classification of drivers and their share in the industry, estimates are given on how a change in hours of service regulations impacts schedules of truck drivers with respect to productivity, accident risks, and occupational health. All impacts are monetized and the net benefit for different alternative sets of rules are calculated. The RIA evaluates and compares four different regulatory options. The first option is to retain the regulations which came into effect with the 2003 rule change. The other options are to enforce the new regulations which enter into force in July 2013, and two variants of the new regulations in which the daily driving time limit is reduced to 10 hours or 9 hours. As all of the latter options impose stricter limits, the RIA uses the regulations implemented in 2003 as a baseline and tries to estimate how often a driver will not be able to perform the same driving tasks if stricter rules are in place. The RIA calculates how much driving time is lost in any shift and, based on their judgments, the RIA assumes that some of this lost driving time can be transferred to another day. Whether or not the lost time can be transferred to another driver is not assessed and it is assumed that any productivity loss of a driver is a societal costs. Concerning the impact on road safety, the RIA includes similar calculations, however, it assumes that hours not driven on a particular day due to stricter limits will be driven on another day or by another driver. The share of how much time is shifted to another day or another driver is again based on judgment. The impact on road safety is derived using a risk function taking into account the daily and weekly amount of driving. Concerning the impact of regulations on driver health, the FMCSA recognizes that insufficient sleep is associated with obesity, high blood pressure, and diabetes, and that obesity is linked to obstructive sleep apnea, high blood pressure, cardiovascular disease, stroke, diabetes, arthritis, and other diseases. It is, however, argued that it would be difficult to quantify the impact of these health impacts and the analysis focuses on the relationship between the average amount of sleep per night and mortality rates.

The 2010 RIA has several shortcomings. First, the approach does not assess the impact of the newly introduced break provision. Secondly, it is highly dependent on parameter values based on judgment and it is not consistent in assessing cost and safety impacts because the economic assessment does not consider the possibility that lost driving time of one driver is balanced with increased driving time of other drivers. It overestimates societal costs because it does not consider that if work is only transferred from one driver to another we only have a redistribution of income and we cannot claim that stricter rules lead to higher societal costs (compare Saltzman and Belzer, 2002). Thirdly, the same risk functions are used for different regulations. In this paper we will see that stricter regulations may lead to significantly different average risk values and that using the same risk function for different rules overestimates the accident risk for stricter regulations. Lastly, the estimation of health benefits is based on two fundamental relationships used in the RIA. It is assumed that the relationship between the average amount of sleep can be estimated based upon the average amount of daily work by

$$h_{sleep} = 8.128 - 0.183 \cdot h_{work} + 0.0235 \cdot h_{work}^2 - 0.00138 \cdot h_{work}^3,$$

where h_{sleep} denotes the average hours of sleep and h_{work} denotes the average hours of work. This function was estimated using 9781 observations of relevant data from long-haul drivers. Furthermore, it is assumed that the relationship between the average amount of sleep and mortality rates can be estimated by

$$\text{mortality rate} = 11.7603 - 3.1377 \cdot h_{sleep} + 0.2274 \cdot h_{sleep}^2$$

and that each percent of change in mortality rate is linearly linked to the life expectancy. The function for determining the mortality rate is derived from the study by Ferrie et al. (2007) and implies that the amount of sleep is a causal factor for mortality. In Ferrie et al. (2007), it was found that there is a U-shaped relationship between sleep and mortality, i.e. they found that both low and high amounts of sleep can be associated to higher mortality rates. However, it has been noted that in contrast to short sleep-mortality, no potential mechanisms by which long sleep could cause increased mortality have yet been investigated. As no such mechanism is known, it could also be the case that the association between high amounts of sleep and mortality rate results from individuals requiring more sleep pre-mortem. In the RIA, the reported theoretical outcome of reducing the daily driving time limit to 9 hours for drivers who already have sufficient sleep is a negative health benefit of 670 million dollars. In the authors opinion it is very unlikely that the introduction of stricter regulations can lead to deteriorated health and it is highly questionable whether an analysis based on a model with such outcomes can lead to any valid conclusion. In fact, if we use above functions to determine the lowest mortality rate and the associated best amount of sleep, we could conclude that the highest life expectancy would be achieved if drivers work around 12 hours per day. The highest benefit would thus be achieved for a rule which eliminates free days and which ensures that drivers do not work less than 12 hours per day. Considering above mentioned shortcomings, we can conclude that the RIA overestimates societal costs of stricter regulations, underestimates benefits in terms of road safety, and uses a questionable approach in assessing health benefits.

4 Methodology

In this paper we propose a new simulation-based methodology for regulatory impact assessment. The focus of this methodology is the impact of regulations on driving patterns within a planning horizon of one week. In the proposed methodology it is assumed that there is a given demand for the transportation of a set of full truckloads from their origins to their destinations. Whether due to market mechanism or a common decision maker, it is assumed that individual transport requests are assigned to different drivers who must comply with hours of service regulations. The assignment of transportation requests to drivers is the outcome of the endeavor to minimize operating costs while satisfying all operational constraints. Within the proposed methodology this endeavor is simulated using an approach for optimizing vehicle routes with pickups and deliveries and hours of service regulations. This optimization approach is described in more detail in the next section. A crucial component of this approach is the model-based consideration of hours of service regulations. A detailed model for determining whether a sequence of transportation requests which are assigned to a driver can be fulfilled without violating these regulations is also presented in the next section. When all transportation requests are assigned to drivers and the optimization procedure terminates, the distance- and time-related costs for fulfilling the given demand are obtained by accumulating the operating costs of all drivers. For each driver a detailed schedule is generated which is then analyzed using the fatigue and risk index calculator of Health and Safety Executive (2006). With this methodology the tradeoff between economic impact and road safety impact of different regulations can be determined and assessed.

Although, the 2008 RIA is also based on simulation, it differs from the proposed methodology. The 2008 RIA focuses on simulating drivers independently. Throughout the simulation process a driver selects the next transportation task from a pool of tasks based on a myopic utility function. Hours of service regulations are considered using a rule-based approach in which decisions to rests are based on the driver's state. When the simulation run is completed many of the tasks in the pool are not fulfilled. In the proposed methodology of this paper, on the other hand, it is assumed that a set of transportation requests is given and all requests must be served. Routes are generated for several drivers to serve the transport demand. All routes must comply with the regulations and detailed models of the regulatory options are used. Duty and rest periods are scheduled taking into account all alternatives in the decision space of the model. The assignment of transport demand to drivers is based on an objective function which minimizes the operating costs of all drivers. We believe that this approach better resembles the truckload trucking industry, because it explicitly takes into account, that transport companies can optimize routes and schedules to adopt to new regulations. By optimizing plans and schedules, transport companies can avoid additional costs even if stricter regulations are imposed. To the best of our knowledge, the capability of carriers to use optimization as a tool to minimize the economic impact of stricter regulations has not been considered in any regulatory impact assessment published so far.

5 Planning procedure

The methodology to assess the impact of hours of service regulations assumes that a set of transportation requests are fulfilled by truck drivers who must comply with the regulations. The problem of finding an assignment of each transportation request to a driver and a route that can be conducted without violating hours of service regulations is a variant of the well-known vehicle routing problem (see e.g. Toth and Vigo, 2002). Xu et al. (2003) were the first to consider U.S. hours of service regulations within a vehicle routing problem with pickup and deliveries. Similar to the 2008 RIA they used a rule-based approach to generate schedules complying with the regulations. Goel (2009) showed for European Union regulations that significant savings can be achieved compared to rule-based scheduling approaches if more sophisticated methods are used. Archetti and Savelsbergh (2009) and Goel and Kok (2012) present detailed models of the regulations which enteres in force with the 2003 rule change and developed sophisticated approaches for generating truck driver schedules complying with these regulations. Based on the approach by Goel and Kok (2012), Rancourt et al. (2012) present a tabu search metaheuristics for vehicle routing problems considering U.S. hours of service regulations.

As none of the above mentioned approaches can be used when the new rules enter into force in July 2013, a detailed model of the revised regulations and a method to optimize vehicle routes which must comply with the new regulations are presented in this paper. The method to generate vehicle routes is based on the well-known *savings heuristic* of Clarke and Wright (1964). The savings heuristic starts with assigning each transportation request to a different vehicle. The heuristic then determines for each pair of routes whether both routes can be merged so that all of the transportation requests are served by the same vehicle. For each pair of routes which can be merged, the savings with respect to the objective function are determined and the routes with the largest savings are merged. The method terminates when it is impossible to obtain any further savings.

Whenever the saving heuristic checks whether two routes can be merged, it needs to determine whether all transportation requests can be served within the planning horizon by one driver. Furthermore, it must determine the savings that can be obtained. This requires to evaluate the route with respect to distance- and time-related costs. Determining the savings with respect to distance-related costs is straight forward, however, determining the time it takes to serve a sequence of transportation requests requires to find the best schedule complying with the regulations.

We will now present a formal model which allows us to check whether a route can be feasibly served by a driver and which can be used to determine the duration required to do so. Let us assume that a driver must visit a sequence of λ locations denoted by $n_1, \ldots, n_\lambda$, and let us assume that these locations must be visited within time windows denoted by $t_1^{\min}, \ldots, t_\lambda^{\min}$ and $t_1^{\max}, \ldots, t_\lambda^{\max}$. If a location may be visited at any time, we can simply use the entire planning horizon as time window. For each location let $w_1, \ldots, w_\lambda$ denote the durations of loading or unloading which has to be conducted at the location, and let $\delta_{1,2}, \ldots, \delta_{\lambda-1,\lambda}$ denote the driving times which are required to move from one location to the next.

A truck driver schedule can be represented by a sequence of activities to be performed by the driver, where each activity is represented by a tuple $(a^{\text{type}}, a^{\text{length}})$ indicating the type and duration of the activity. Each activity of type `DRIVE` is a period during which the driver is driving, each activity of type `WORK` is a period during which the driver is on-duty but not driving, each activity of type `REST` is a period of at least 10 consecutive hours during which the driver is off-duty, each activity of type BREAK is a period of at least $\frac{1}{2}$ hour during which the driver is off-duty, and each activity of type IDLE is any other off-duty period. Let "." be an operator which concatenates different activities. Then, $a_1.a_2.\ \ldots\ .a_k$ denotes a schedule in which for each $i \in \{1, 2, \ldots, k-1\}$ activity a_{i+1} is performed immediately after activity a_i. For a given schedule $s := a_1.a_2.\ \ldots\ .a_k$ and $1 \leq i \leq k$ let $s_{1,i} := a_1.a_2.\ \ldots\ .a_i$ denote the partial schedule composed of activities a_1 to a_i.

Notation	**Value**	**Description**
t^{drive}	11 hours	The maximum accumulated driving time between two consecutive rest periods
t^{rest}	10 hours	The minimum duration of a rest period
$t^{\text{elapsed}\vert\texttt{R}}$	14 hours	The maximum time after the end of the last rest period until which a driver may drive
t^{break}	$\frac{1}{2}$ hours	The minimum duration of a break period
$t^{\text{elapsed}\vert\texttt{B}}$	8 hours	The maximum time after the end of the last break or rest period until which a driver may drive

Table 1: Parameters imposed by the new regulations

The provisions of the regulations impose constraints on these schedules. To model these constraints we need additional notation describing the regulatory parameters which are relevant for a planning horizon of one week (see Table 1) and the characteristics of the schedules. For each schedule $s := a_1.a_2.\ \ldots\ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$ let l_s^{begin} denote the start time of the first on-duty period of the schedule, let l_s^{end} denote the completion time of the schedule, let l_s^{drive} denote the accumulated driving time since completion of the last rest period, let $l_s^{\text{last\_rest}}$ denote the time of completion of the last rest period, and let $l_s^{\text{last\_break}}$ denote the time of completion of the last break or rest period. The calculation of l_s^{begin} and l_s^{end} is straight forward. The other values can be recursively computed during schedule generation by setting $l_{s_{1,1}}^{\text{drive}} := 0$, $l_{s_{1,1}}^{\text{last\_rest}} := l_{s_{1,1}}^{\text{end}}$, $l_{s_{1,1}}^{\text{last\_break}} := l_{s_{1,1}}^{\text{end}}$, and

$$l_{s.a}^{\text{drive}} := \begin{cases} 0 & \text{if } a^{\text{type}} = \texttt{REST} \\ l_s^{\text{drive}} + a^{\text{length}} & \text{if } a^{\text{type}} = \texttt{DRIVE} \\ l_s^{\text{drive}} & \text{otherwise,} \end{cases}$$

$$l_{s.a}^{\text{last\_rest}} := \begin{cases} l_{s.a}^{\text{end}} & \text{if } a^{\text{type}} = \texttt{REST} \\ l_s^{\text{last\_rest}} & \text{otherwise,} \end{cases}$$

$$l_{s.a}^{\text{last\_break}} := \begin{cases} l_{s.a}^{\text{end}} & \text{if } a^{\text{type}} \in \{\texttt{BREAK}, \texttt{REST}\} \\ l_s^{\text{last\_break}} & \text{otherwise.} \end{cases}$$

For a given sequence of locations $n_1, n_2, \ldots, n_\lambda$ and a schedule $s = a_1.a_2.\ \ldots\ .a_k$, let us denote with $i(\mu)$ the index in s corresponding to the μth stationary work period, i.e. $a_{i(\mu)}$ corresponds to the work performed at location n_μ. With this notation we can now give a formal model of the problem of scheduling duty and rest periods in such a way that the driver complies with the regulations and that the total duration is mininized. The problem is to

$$\text{minimize } l_s^{\text{end}} - l_s^{\text{begin}} \tag{1}$$

subject to

$$\sum_{\substack{i(2)\leq j\leq i(\lambda)\\ a_j^{\text{type}}=\texttt{DRIVE}}} a_j^{\text{length}} = \sum_{\substack{1\leq j\leq k\\ a_j^{\text{type}}=\texttt{DRIVE}}} a_j^{\text{length}} \tag{2}$$

$$a_{i(\mu)}^{\text{length}} = w_\mu \text{ for each } \mu \in \{1,2,\ldots,\lambda\} \tag{3}$$

$$t_\mu^{\min} \leq l_{s_{1,i(\mu)-1}}^{\text{end}} \leq t_\mu^{\max} \text{ for each } \mu \in \{1,2,\ldots,\lambda\} \tag{4}$$

$$\sum_{\substack{i(\mu)\leq j\leq i(\mu+1)\\ a_j^{\text{type}}=\texttt{DRIVE}}} a_j^{\text{length}} = \delta_{\mu,\mu+1} \text{ for each } \mu \in \{1,2,\ldots,\lambda-1\} \tag{5}$$

$$l_{s_{1,i}}^{\text{drive}} \leq t^{\text{drive}} \text{ for each } 1 < i \leq k \tag{6}$$

$$a_i^{\text{length}} \geq t^{\text{rest}} \text{ for each } 1 < i \leq k \text{ with } a_i^{\text{type}} = \texttt{REST} \tag{7}$$

$$l_{s_{1,i}}^{\text{end}} \leq l_{s_{1,i}}^{\text{last\_rest}} + t^{\text{elapsed}|\texttt{R}} \text{ for each } 1 < i \leq k \text{ with } a_i^{\text{type}} = \texttt{DRIVE} \tag{8}$$

$$l_{s_{1,i}}^{\text{end}} \leq l_{s_{1,i}}^{\text{last\_break}} + t^{\text{elapsed}|\texttt{B}} \text{ for each } 1 < i \leq k \text{ with } a_i^{\text{type}} = \texttt{DRIVE} \tag{9}$$

The objective function (1) is to minimize the amount of time required to visit all locations. Condition (2) demands that all driving is conducted between the first and the last work activity. Condition (3) demands that the duration of the μth work activity matches the specified work duration at location n_μ. Condition (4) demands that each work activity begins within the corresponding time window. Condition (5) demands that the accumulated driving time between two work activities matches the driving time required to move from one location to the other. Condition (6) demands that the maximum amount of driving between two rest periods does not exceed the limit given by the regulation. Condition (7) demands that each rest period has the minimum duration required by the regulation. Condition (8) demands that no driving is conducted after 14 hours have elapsed since returning from the last rest period. Condition (9) represents the additional break constraints introduced by the new regulation and demands that no driving is conducted after 8 hours have elapsed since returning from the last break or rest period.

In the following we present a scheduling method that can be used to solve the problem stated above. The main decisions to be made when searching for a solution of the scheduling problem are to determine when and for how long break and rest periods should be scheduled. As we will see, it is possible to solve the problem using an iterative process in which breaks and rest periods are only scheduled when no driving or working is possible. Initially all off-duty periods can be scheduled with a minimal duration and only when off-duty time is unavoidable the duration is extended.

To determine by how much a rest period can be extended we need to identify the maximum amount of time by which break and rest periods can be extended without violating time windows. Furthermore, we need to identify the maximum amount by which we can delay the start of the first on-duty activity in order to find a schedule minimizing the objective function (1). Let us denote these values with $l_s^{\text{extend}|\texttt{B}}$, $l_s^{\text{extend}|\texttt{R}}$, and $l_s^{\text{extend}*}$. If we assume that the first activity in a schedule is a rest period we can recursively compute these values by setting $l_{s_{1,1}}^{\text{extend}|\texttt{B}} := 0$, $l_{s_{1,1}}^{\text{extend}|\texttt{R}} := \infty$, $l_{s_{1,1}}^{\text{extend}*} := \infty$, and

$$l_{s.a}^{\text{extend}|\texttt{B}} := \begin{cases} 0 & \text{if } a^{\text{type}} = \texttt{REST} \\ \infty & \text{if } a^{\text{type}} = \texttt{BREAK} \\ \min\{l_s^{\text{extend}|\texttt{B}}, t_{\mu(s.a)}^{\max} - l_s^{\text{end}}\} & \text{if } a^{\text{type}} = \texttt{WORK} \\ l_s^{\text{extend}|\texttt{B}} & \text{otherwise.} \end{cases}$$

$$l_{s.a}^{\text{extend}|\texttt{R}} := \begin{cases} \infty & \text{if } a^{\text{type}} = \texttt{REST} \\ \min\{l_s^{\text{extend}|\texttt{R}}, t_{\mu(s.a)}^{\max} - l_s^{\text{end}}\} & \text{if } a^{\text{type}} = \texttt{WORK} \\ l_s^{\text{extend}|\texttt{R}} & \text{otherwise} \end{cases}$$

$$l_{s.a}^{\text{extend}*} := \begin{cases} \min\{l_s^{\text{extend}*}, t_{\mu(s.a)}^{\max} - l_s^{\text{end}}\} & \text{if } a^{\text{type}} = \texttt{WORK} \\ l_s^{\text{extend}|\texttt{R}} & \text{otherwise} \end{cases}$$

where $\mu(s)$ denotes the number of work activities in schedule s.

Let us now describe the scheduling method which is illustrated in Figure 1. The method is initialized by setting

$$\mathcal{S}_1 := \big\{(\texttt{REST}, t_1^{\min}).(\texttt{WORK}, w_1)\big\}$$

and

$$\mathcal{S}_\mu := \emptyset \text{ for all } 1 < \mu \leq \lambda.$$

The procedure is then invoked with $\mu = 1$ and starts with initializing the set $\mathcal{S}$ of partial schedules which need to be expanded. In each loop the procedure chooses and removes a schedule s from $\mathcal{S}$ and determines the maximum duration of the next driving activity. Within the scheduling method, δ_s denotes for each partial schedule s the remaining driving time required to reach the next location $n_{\mu+1}$. If the maximum duration of the next driving activity, which is denoted by Δ, is positive, a driving activity of duration Δ is appended to the schedule s.

If $\delta_s > 0$ after scheduling the driving activity, the next location is not yet reached and a break or rest period must be scheduled before another driving activity can be scheduled. The method continues by generating a schedule with an additional rest period of duration t^{rest}. Furthermore, another schedule continuing with an additional break period of duration t^{break} is generated if $l_s^{\text{drive}} < t^{\text{drive}}$ and

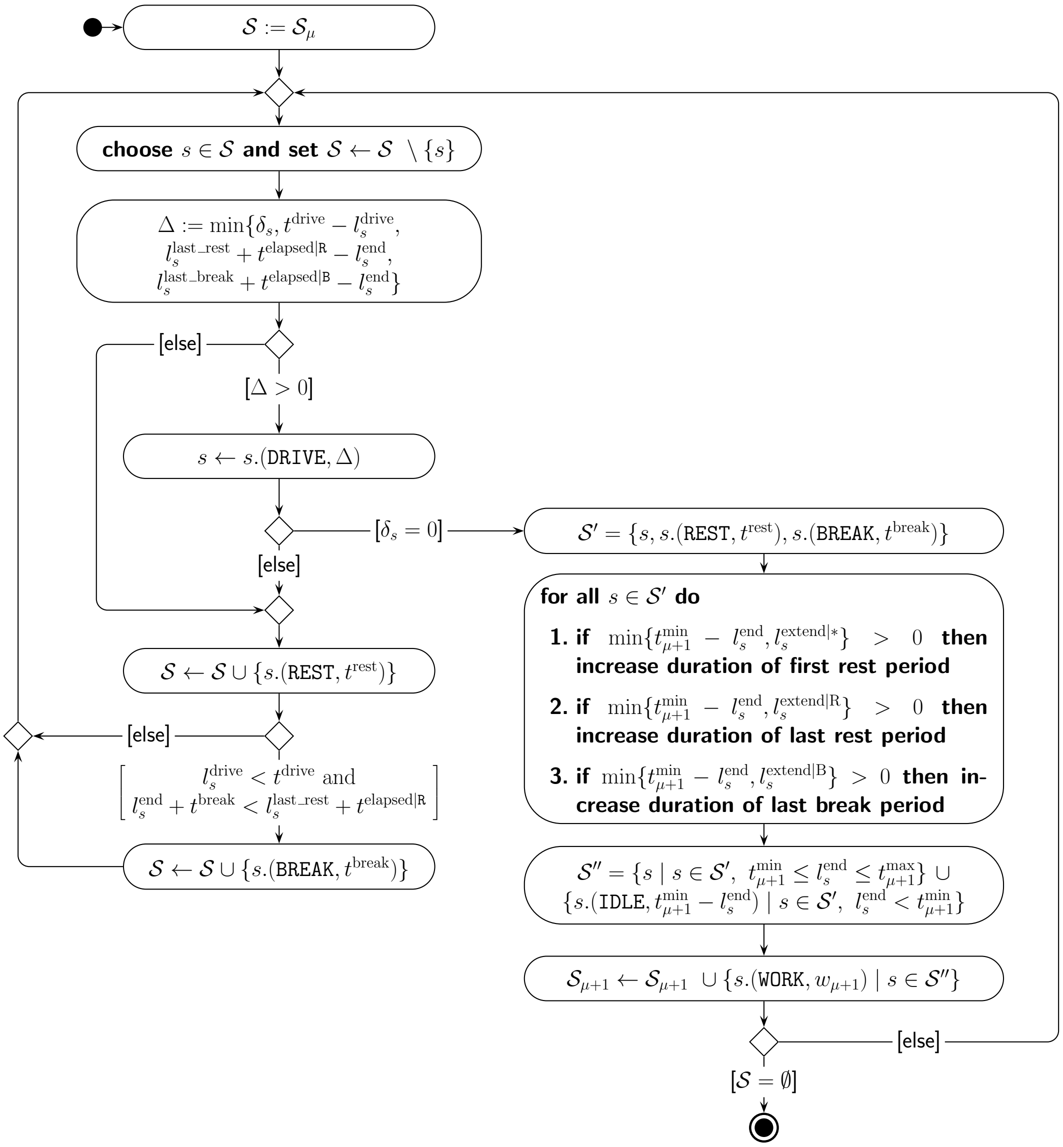

Figure 1: Scheduling method

$l_s^{\text{end}} + t^{\text{break}} < l_s^{\text{last\_rest}} + t^{\text{elapsed}|\texttt{R}}$. That is, a break period is only scheduled if a rest is not required before scheduling the next driving activity. The new schedules are added to $\mathcal{S}$ and the procedure continues with the next loop.

If $\delta_s = 0$ after scheduling a driving activity, the next location is reached and two copies of s are generated: one continuing with an additional rest and one continuing with an additional break. All of these schedules, i.e. the original and the two newly generated schedules, are included to the set $\mathcal{S}'$. For each schedule $s \in \mathcal{S}'$ the following steps are conducted. If the completion time of s is before the opening of the time window and if the start time of the first on-duty activity can be delayed the first rest period in the schedule is extended by $\min\{t_\mu^{\min} - l_s^{\text{end}}, l_s^{\text{extend}*}\}$. If the completion time of s is still before the opening of the time window and if the last rest period in s can be extended, the rest period is extended by $\min\{t_\mu^{\min} - l_s^{\text{end}}, l_s^{\text{extend}|\texttt{R}}\}$. If the completion time of s is still before the opening of the time window and if the last break period in s can be extended, the rest period is extended by $\min\{t_\mu^{\min} - l_s^{\text{end}}, l_s^{\text{extend}|\texttt{B}}\}$.

If these extensions do not suffice to reach the opening of the time window, idle time is added to the schedules. Eventually, the next work activity is appended to each of the partial schedules if the closing time of the time window is not exceeded. The resulting schedules are added to $\mathcal{S}_{\mu+1}$. If the set of partial schedules $\mathcal{S}$ is empty, the procedure terminates and continues with the next loop otherwise. After termination of the procedure, μ is incremented and the procedure is invoked again. The scheduling method terminates prematurely if no solution exists, or it terminates with a set of solutions containing the schedule optimizing (1).

To speed up the scheduling method and to avoid unnecessary calculations we prune *dominated* schedules from $\mathcal{S}_\mu$ in each iteration. A schedule $s' \in \mathcal{S}_\mu$ dominates a schedule $s'' \in \mathcal{S}_\mu$ if

$$\begin{gathered}
l_{s'}^{\text{end}} \leq l_{s''}^{\text{end}} \text{ and } l_{s'}^{\text{drive}} \leq l_{s''}^{\text{drive}} \text{ and} \\
l_{s'}^{\text{end}} - l_{s'}^{\text{last_break}} \leq l_{s''}^{\text{end}} - l_{s''}^{\text{last_break}} \text{ and} \\
l_{s'}^{\text{end}} - l_{s'}^{\text{last_rest}} \leq l_{s''}^{\text{end}} - l_{s''}^{\text{last_rest}} \text{ and} \\
l_{s'}^{\text{last_break}} + l_{s'}^{\text{extend}|\texttt{B}} \geq l_{s''}^{\text{last_break}} + l_{s''}^{\text{extend}|\texttt{B}} \text{ and} \\
l_{s'}^{\text{last_rest}} + l_{s'}^{\text{extend}|\texttt{R}} \geq l_{s''}^{\text{last_rest}} + l_{s''}^{\text{extend}|\texttt{R}} \text{ and} \\
l_{s'}^{\text{begin}} + l_{s'}^{\text{extend}*} \geq l_{s''}^{\text{begin}} + l_{s''}^{\text{extend}*}
\end{gathered}$$

The scheduling method presented above can be used within the savings heuristic to assess whether two routes can be merged feasibly and to determine the operational costs of the routes. Moreover, as the scheduling method can be embedded within any other planning approach used by motor carriers to optimize vehicle routes, the scheduling method itself can contribute to improved compliance with the new regulations and improved road safety.

6 Regulatory impact analysis

In this section the impact of the revised hours of service regulations and variants is analyzed by simulating the operations of a full truckload carrier in the United States. We assume that the carrier seeks to minimize operational costs using the planning procedure described in the previous section. The routes generated by this procedure are analyzed taking into account the respective accident risk calculated using the fatigue and risk index calculator available from Health and Safety Executive (2006). For each driver and each work shift risk indices are calculated considering the amount of sleep loss that is likely to accumulate throughout the work week, the effect of start time and length of the individual daily shifts, and the amount of break time within these shifts. Based on these risk indices, we determine for each vehicle the maximum risk value throughout the planning horizon and the average of these risk values among all vehicles in a solution.

For our analysis we generated several sets of instances assuming that the carrier is given a set of full truckload transportation request and must transport the truckload of each request from its origin to its destination. For simplicity it is furthermore assumed that the route of each vehicle starts at the origin of the first transportation request and ends at the destination of the last request. The six different instance sets generated can be distinguished by the type of problem and the geographical region in which the carrier is operating. Two types of problems are considered: in the first problem type the pickup of each transportation request must be conducted within a given time window, whereas no time window constraints are considered in the second type. The geographical regions considered are the region west and east of the 100th meridian west, and the combination of both.

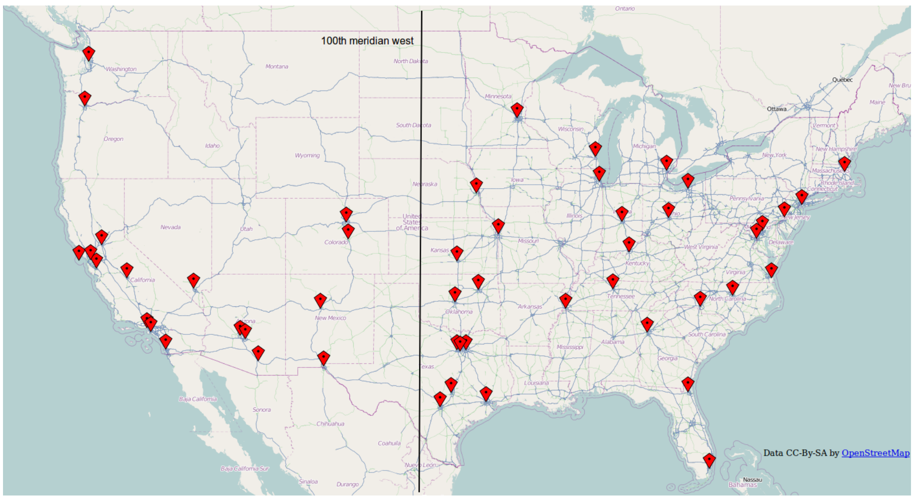

Figure 2: The fifty largest cities in the United States

For each set 200 instances with 25 transportation requests each are generated.

Origin and destination of each transportation request are randomly chosen within the appropriate subset of the fifty largest cities in the United States shown in Figure 2. The probability that one of the cities is chosen as origin or destination is related to the population of the city obtained from Wikipedia (2012). The distance between cities is calculated using spherical approximation (Goel, 2007) based on the geographical coordinates obtained from Wikipedia (2012). The distance d_{AB} between any pair of cities A and B with coordinates $(A_{\texttt{long}}, A_{\texttt{lat}})$ and $(B_{\texttt{long}}, B_{\texttt{lat}})$ is estimated using the approximation function

$$d_{AB} := 1.15 \cdot \frac{6370}{1.609344} \cdot \arccos\Big(\sin A_{\texttt{lat}} \cdot \sin B_{\texttt{lat}} + \cos A_{\texttt{lat}} \cdot \cos B_{\texttt{lat}} \cdot \cos(A_{\texttt{long}} - B_{\texttt{long}}) \Big).$$

Here 1.15 is a multiplier used to take into account that road distances are longer than direct distances. The driving time from A to B is estimated to be $d_{AB}/50 + \frac{1}{2}$, i.e. an average speed of 50 miles per hour is assumed and half an hour is added to account for slower average speed in urban traffic at the start and end of each trip.

The objective function on which the savings are calculated is based on the cost values given in the 2008 RIA. According to the 2008 RIA, the distance-related costs are 1.13 dollars per mile and the time-related costs are 5.40 dollars per hour (of both on- and off-duty time).

For the instances sets with time windows, the pickup must be conducted on a randomly chosen day within the planning horizon of six days. To ensure feasibility, the choice of the pickup time window is restricted in such a way that the destination can be reached within the planning horizon. For each transportation request the duration for loading and unloading is set to one hour.

In our analysis we use the alternative options described in the 2010 RIA. With *US2003* we refer to the option of retaining the rules that came into effect with the 2003 rule change, with *US2013* we refer to the rules which will come into effect in 2013, and with *US2013-10* and *US2013-9* we refer to the options where the daily driving time limit is reduced to 10 and 9 hours. Tables 2 and 3 show the average results for instances with and without time windows. Average costs and risk values over all of the 200 instances as well as the percentage change of these values compared to *US2003* are reported.

The results show that, the introduction of the break provision in 2013 will reduce accident risks by 0.6% to 2.4% without significant impact on costs. The reductions in accident risk resulting from reduced daily driving time limits of 10 hours and 9 hours are significantly larger for all instance sets. The risk reduction is accompanied with a moderate increase in variable costs. The relative increase, however, is of a much smaller magnitude compared to the relative reduction in accident risk. Furthermore, it appears that the impact on variable costs is smaller if time windows must be considered. The reason for this is, that truck drivers sometimes have to wait until a time window opens and schedules typically contain more off-duty time than in the case without time windows. With a lower ratio between on- and off-duty time, the stricter constraints on on-duty periods appear to have less impact on operational costs.

Without	US2003		US2013		US2013-10		US2013-9	
time windows	Costs	Risk	Costs	Risk	Costs	Risk	Costs	Risk
US-All	34151.50	1.06	34227.80	1.04	34369.00	1.00	34353.40	0.96
			0.2%	-1.6%	0.6%	-5.6%	0.6%	-9.4%
US-East	28400.70	1.06	28508.80	1.04	28607.20	1.00	28647.80	0.96
			0.4%	-2.1%	0.7%	-5.8%	0.9%	-9.1%
US-West	21416.90	1.06	21438.80	1.03	21577.00	1.00	21525.00	0.96
			0.1%	-2.4%	0.7%	-4.9%	0.5%	-8.8%
Average	27989.70	1.06	28058.47	1.03	28184.40	1.00	28175.40	0.96
			0.2%	-2.1%	0.7%	-5.4%	0.7%	-9.1%

Table 2: Results for instances with time windows

Without	US2003		US2013		US2013-10		US2013-9	
time windows	Costs	Risk	Costs	Risk	Costs	Risk	Costs	Risk
US-All	33118.70	1.15	33114.90	1.14	33430.60	1.08	33627.30	1.03
			0.0%	-0.6%	0.9%	-5.6%	1.5%	-10.2%
US-East	26920.20	1.16	26941.30	1.15	27172.10	1.10	27371.10	1.04
			0.1%	-0.7%	0.9%	-5.1%	1.7%	-10.5%
US-West	19909.00	1.17	19920.30	1.16	20113.70	1.13	20327.30	1.06
			0.1%	-0.7%	1.0%	-3.3%	2.1%	-9.5%
Average	26649.30	1.16	26658.83	1.15	26905.47	1.10	27108.57	1.04
			0.0%	-0.7%	1.0%	-4.7%	1.7%	-10.1%

Table 3: Results for instances without time windows

According to U.S. Department of Commerce (2012), the annual revenue of long-distance transportation in 2011 was 120,859 millions of dollars. Assuming that the average increase in variable cost is representative for the cost increase of the sector, we could expect an annual increase in transportation costs between 0.0% and 0.4% (US2013), 0.6% and 1.0% (US2013-10), and 0.5%-2.1% (US2013-9). This would results in an increase in transportation cost of between 0 and 483 million dollars (US2013), between 725 million and 1209 million dollars (US2013-10), and between 604 million and 2,538 million dollars (US2013-9).

In their regulatory impact assessment (Federal Motor Carrier Safety Administration, 2010), the FMCSA estimated the crash related costs of long-haul trucks to be around 37,300 million dollars. In a study to determine the causes of crashes involving commercial motor vehicles 967 crashes involving at least one large truck were analyzed (Federal Motor Carrier Safety Administration, 2006). According to this study, the critical reason for the accident can be assigned to the truck or truck driver in around 55% of all crashes and in 87% of those cases the critical reason was assigned to the driver. The 0.6% to 2.4% reduction in relative accident risk can thus be translated in 107 million to 426 million dollars (US2013), the 3.3% to 5.8% reduction in relative accident risk can be translated in 586 million to 1,030 million dollars (US2013-10), the 8.8% to 10.5% reduction in relative accident risk can be translated in 1,563 million to 1,865 million dollars (US2013-9). It must be noted that we included all driver reasons in this calculation including health reasons and wrong decisions taken by the driver. Excluding these reasons from the calculation would underestimate the true safety benefits as tight schedules and cumulative partial sleep deprivations are known to lead to reduced health of drivers (Federal Motor Carrier Safety Administration, 2010) and impaired cognitive performance (Van Dongen et al., 2003). Although, truck related reasons, e.g. brake problems, lights, etc. were excluded from the calculation, it must be noted that with less off-duty time, a driver is less likely to spend the same amount of time and care to check vehicle conditions and identify potentials problems before they lead to an accident. A regulatory change reducing the on- to off-duty time ratio could thus also be expected to reduce these accidents.

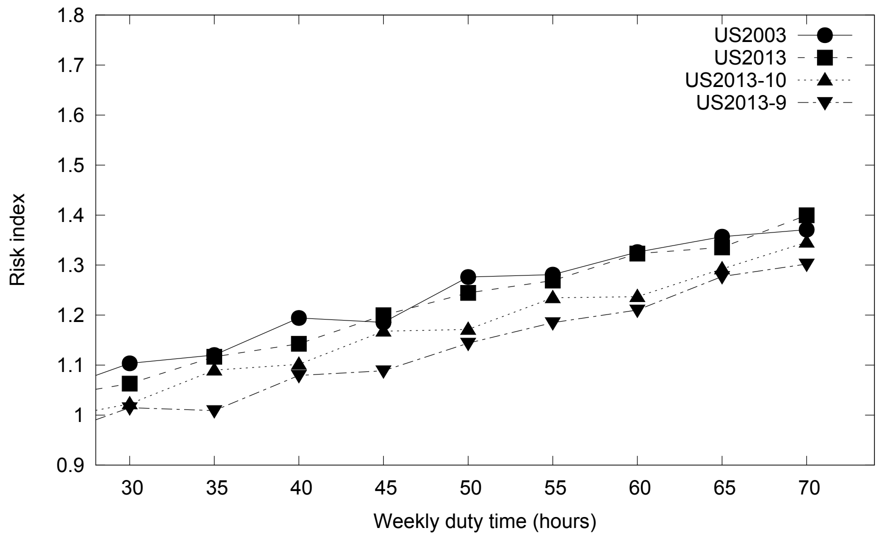

Figure 3: Accident risks for instances with time windows

Let us now have a look at how the different regulations impact the accident risk within a work week. Figures 3 and 4 illustrate the accident risk in relationship to the amount of on-duty time of the driver. Each point in the figures illustrates average risk values after an amount of $(t-5, t]$ hours of on-duty time are accumulated. We can see that accident risks follow an approximately linear relationship with weekly on-duty time for all regulatory options. The figures clearly illustrate the risk impact of cumulative sleep loss for different regulations. The stricter regulations reduce accident risks for drivers independent of whether they are working close to the weekly limits or not. For example, two drivers with the same break pattern during a shift starting after 30 hours of on-duty time, will have a different risk value during this shift if they previously worked according to different regulations. A risk assessment based on a risk function linking on-duty time to accident risk in the same way for all regulatory options, will not be able to take into account these effects of cumulative sleep loss. It can thus be conjectured that

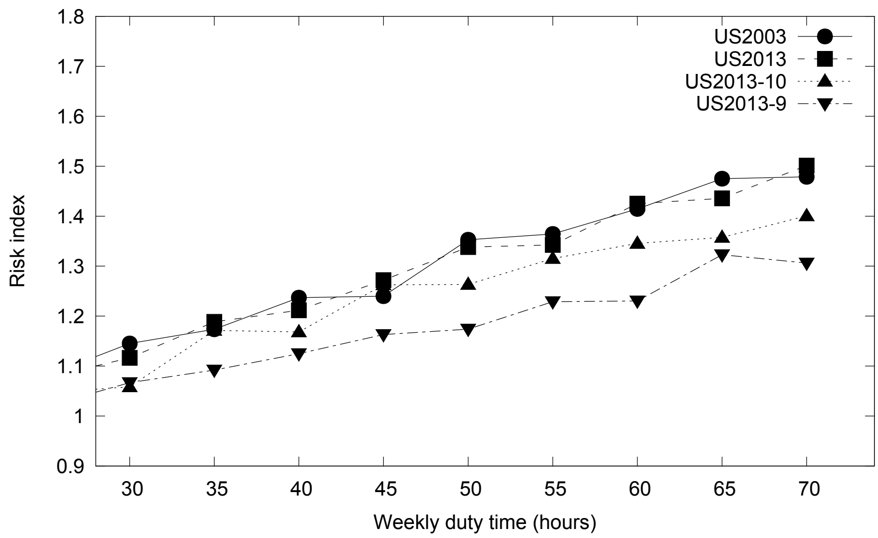

Figure 4: Accident risks for instances without time windows

the 2010 RIA underestimates the safety benefits of reducing the daily driving time limits.

7 Final remarks

This paper studies the revised hours of service regulations in the United States which will enter into force in July 2013. We developed a detailed model of the new regulations and a scheduling method allowing motor carriers to automatically find schedules complying with the new regulations. Planning systems based on the method can be used to optimize vehicle routes and schedules considering the regulation. If this method is deployed by carriers, the method will contribute to reduced accident risks and improved road safety.

In this paper we present a new simulation-based method for assessing the impact of hours of service regulations on operational costs and road safety. Unlike previous approaches, the method presented in this paper considers the fact that transport companies can optimize routes and schedules to avoid additional costs resulting from stricter regulations. Simulation experiments are conducted using the scheduling method to assess different regulatory options which are considered in the regulatory impact assessment conducted for the recent rule change (Federal Motor Carrier Safety Administration, 2010).

Our results indicate that additional costs and monetized road safety benefits are on the same order of magnitude for all regulatory options and, for some sets of instances, the monetized road safety benefits are already above the additional operational costs. Unfortunately, the author is not aware of a sophisticated method for quantifying the health benefits. Depending on the magnitude of health benefits that could be linked to hours of service regulations, a generally positive total net benefit may well be observed if the daily driving time limit is reduced to 10 or 9 hours.

As the FMCSA did not take into account the capability of trucking companies to reduce the economic impact of stricter regulations by optimizing routes and schedules, and as our experiments showed that stricter regulations reduce accident risks for drivers independent of whether they are working close to the weekly limits or not, we must conclude that the regulatory impact assessment of the FMCSA overestimates the economic impact of reducing the daily driving time limits and underestimates the safety benefits. Considering these findings, the FMCSA may come to a different conclusion when reconsidering whether the daily driving time limit should be reduced or not.

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