Truck Driver Scheduling and Australian Heavy Vehicle Driver Fatigue Law

Asvin Goel

Abstract In September 2008 new regulations for managing heavy vehicle driver fatigue entered into force in Australia. According to the new regulations there is a chain of responsibility ranging from drivers to dispatchers and shippers. Thus, carriers must explicitly consider driving and working hour regulations when generating truck driver schedules. This paper presents various heuristics for scheduling driving and working hours of Australian truck drivers.

Keywords Vehicle Scheduling · Working Hour Regulations

1 Introduction

According to a survey of truck drivers in Australia, fatigue is felt as contributing factor in every fifth accident (Williamson et al. [2001]). One out of five drivers reported at least one fatigue related incident on their last trip and one out of three drivers reported breaking road rules on at least half of their trips. Many drivers feel that fatigue is a substantial problem for the industry and feel that their companies should ease unreasonably tight schedules and should allow more time for breaks and rests during their trips. In their efforts to increase road safety the Australian Transport Ministers adopted new regulations for managing heavy vehicle driver fatigue. According to the new regulations there is a chain of responsibility ranging from drivers to dispatchers and shippers. Consequently, road transport companies must ensure that truck driver schedules comply with Australian Heavy Vehicle Driver Fatigue Law. An important key in managing fatigue is to explicitly consider driving and working hour regulations when generating truck driver schedules. Planning problems considering driving and working hours of truck drivers, however, have so far attracted very little interest in

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the vehicle routing and scheduling literature and to the best of the author's knowledge there are currently no planning tools available that allow for truck driver scheduling considering Australian Heavy Vehicle Driver Fatigue Law.

Driver scheduling in road freight transportation differs significantly from airline crew scheduling and driver scheduling in rail transport or mass transit systems which are covered by a comprehensive annotated bibliography by Ernst et al. [2004]. The difference stems from the fact that in road freight transportation it is usually possible to interrupt transportation services in order to take compulsory breaks and rest periods. Furthermore, time constraints in road freight transport are usually not as strict and departure and arrival times can often be scheduled with some degree of freedom.

The first work known to the author explicitly considering government regulations in vehicle routing and scheduling is the work by Xu et al. [2003] who study a rich pickup and delivery problem with multiple time windows and restrictions on drivers' working hours imposed by the U.S. Department of Transport. Xu et al. [2003] conjecture that the problem of finding a feasible schedule complying with U.S. hours of service regulations is NP-hard in the presence of multiple time windows. Archetti and Savelsbergh [2009] show that if weekly rest periods do not need to be considered and all locations shall be visited within single time windows, schedules complying with U.S. hours of service regulations can be determined in polynomial time. U.S. hours of service regulations differ significantly from Australian Heavy Vehicle Driver Fatigue Law because they do not demand short break periods for recuperation. Such short break periods are also included in European legislation which is studied by Goel [2009], Kok et al. [2009], and Goel [2010]. Goel [2009] presents a *Naive* and a *Multi-Label* scheduling method embedded to a Large Neighbourhood Search meta-heuristic for combined vehicle routing and scheduling. Kok et al. [2009] present a truck driver scheduling method extending the Naive method which considers additional provisions of the regulation which are ignored in Goel [2009]. Goel [2010] presents the first approach for scheduling driving and working hours of European truck drivers which is guaranteed to find a feasible truck driver schedule if such a schedule exists. This paper studies the Australian Heavy Vehicle Driver Fatigue Law, which, to the best of the authors knowledge, has yet not been tackled in the scheduling literature.

The remainder of this paper is organised as follows. Section 2 describes the Australian Heavy Vehicle Driver Fatigue Law. Section 3 presents the Australian Truck Driver Scheduling Problem (AUS-TDSP). In Section 4 some structural properties of the AUS-TDSP are given and solution approaches are presented in Section 5. Computation experiments are reported in Section 6.

2 Australian Heavy Vehicle Driver Fatigue Law

In Australia new regulations for managing heavy vehicle driver fatigue entered into force on September 29, 2008. The new regulations comprise three different sets of rules. Operators accredited in the National Heavy Vehicle Accreditation Scheme may operate according to the Basic Fatigue Management Standard (National Transport Commission [2008c]) or the Advanced Fatigue Management Standard (National Transport Commission [2008b]). One condition for being accredited is that operators must plan schedules and rosters to ensure they comply with the respective operating limits. Without accreditation operators must comply with the Standard Hours option

(National Transport Commission [2008a]) which imposes the following constraints on drivers' wschedules:

1. In any period of $5\frac{1}{2}$ hours a driver must not work for more than $5\frac{1}{4}$ hours and must have at least 15 continuous minutes of rest time
2. In any period of 8 hours a driver must not work for more than $7\frac{1}{2}$ hours and must have at least 30 minutes rest time in blocks of not less than 15 continuous minutes
3. In any period of 11 hours a driver must not work for more than 10 hours and must have at least 60 minutes rest time in blocks of not less than 15 continuous minutes
4. In any period of 24 hours a driver must not work for more than 12 hours and must have at least 7 continuous hours of stationary rest time
5. In any period of 168 hours (7 days) a driver must not work for more than 72 hours and must have at least 24 continuous hours of stationary rest time
6. In any period of 336 hours (14 days) a driver must not work for more than 144 hours and must have at least 4 night rest breaks (2 of which must be taken on consecutive days)

In the last provision a "night rest break" means a rest break consisting of (a) 7 continuous hours of stationary rest time taken between 10 PM and 8 AM on the following day; or (b) 24 continuous hours of stationary rest time.

If truck drivers do not work on Saturdays and Sundays, the last two provisions of the regulation are automatically satisfied. For simplicity, we will assume in the remainder that we are only interested in generating schedule for a planning horizon starting on Monday and ending on Friday of the same week.

3 The Truck Driver Scheduling Problem

This section gives describes the Australian Truck Driver Scheduling Problem for a planning horizon starting on Monday and ending on Friday of the same week. Let us consider a sequence of locations denoted by $n_1, n_2, \ldots, n_\lambda$ which shall be visited by a truck driver. At each location n_μ some stationary work of duration w_μ shall be conducted. This work shall begin within a time window denoted by T_μ. We assume that n_1 corresponds to the driver's current location and that the driver completes her or his work week after finishing work at location n_λ. The (positive) driving time required for moving from node n_μ to node $n_{\mu+1}$ shall be denoted by $\delta_{\mu,\mu+1}$. Let us assume that all values representing driving or working times are a multiple of 15 minutes.

In order to give a formal model of the problem, let us denote with `DRIVE` any period during which the driver is driving, with `WORK` any period of working time in which the driver is not driving (e.g. time in which the driver is loading or unloading the vehicle), with `REST` any period in which the driver is neither working nor driving. A truck driver schedule can be specified by a sequence of activities to be performed by the drivers. Let $\mathcal{A} := \{a = (a^{\text{type}}, a^{\text{length}}) \mid a^{\text{type}} \in \{\texttt{DRIVE}, \texttt{WORK}, \texttt{REST}\}, a^{\text{length}} > 0\}$ denote the set of driver activities to be scheduled. Let «.» be an operator that concatenates different activities. Thus, $a_1.a_2. \ \ldots \ .a_k$ 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. During concatenation the operator merges consecutive driving and rest periods. That is, for a given schedule $s := a_1.a_2. \ \ldots \ .a_k$ and an activity a with $a_k^{\text{type}} = a^{\text{type}}$ we have $s.a = a_1. \ \ldots \ .a_{k-1}.(a_k^{\text{type}}, a_k^{\text{length}} + a^{\text{length}})$. 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. Recall that we assumed that the drivers do not work on Saturdays and Sundays and that we are only interested in generating schedules for a planning horizon starting on Monday and ending on Friday of the same week. For simplicity, we will thus only consider schedules which begin with a rest period representing the rest taken on the weekend preceding the planning horizon. That is, we only consider schedules $s := a_1.a_2. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$.

We use the following notation for determining whether a schedule complies with the regulation. For each schedule $s := a_1.a_2. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$ we denote with parameter i_s^{420c} the index of the last rest activity of 420 minutes (7 hours) continuous rest, and with parameters i_s^τ the index of the last rest activity contributing to a total amount of at least τ minutes of rest before the end of the schedule. More formally, the parameters are defined by

$$i_s^{420c} := \max\left\{i \mid a_i^{\text{type}} = \texttt{REST}, a_i^{\text{length}} \geq 420\right\}$$

and

$$i_s^\tau := \max\Big\{i \mid \sum_{\substack{i \leq j \leq k \\ a_j^{\text{type}} = \texttt{REST}}} a_j^{\text{length}} \geq \tau\Big\}.$$

According to provision 1, the total duration of all non rest activities in schedule s which are scheduled after the rest period with index i_s^{15} must not exceed 315 minutes ($5\frac{1}{4}$ hours). According to provision 2, the total duration of all non rest activities in schedule s which are scheduled after the rest period with index i_s^{30} must not exceed 450 minutes ($7\frac{1}{2}$ hours). According to provision 3, the total duration of all non rest activities in schedule s which are scheduled after the rest period with index i_s^{60} must not exceed 600 minutes (10 hours). According to provision 4, the total duration of all non rest activities in schedule s which are scheduled after the rest period with index i_s^{720} must not exceed 720 minutes (12 hours). If the last activity of schedule s is not a rest period, provision 4 furthermore requires that the total duration of all activities which are scheduled after the rest period with index i_s^{420c} must not exceed 1020 minutes (17 hours). If the last activity of schedule s is a rest period, this rest period can still be extended to rest a period if at least 420 minutes (7 hours). In this case, provision 4 requires that the total duration of all activities which are scheduled after the rest period with index i_s^{420c} and before the last rest period must not exceed 1020 minutes (17 hours).

Let us consider a schedule $s = a_1. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$ which complies with the regulation and let a denote some driver activity. Then, schedule $s.a$ complies with the regulation if and only if $a^{\text{type}} = \texttt{REST}$ or

$$a^{\text{length}} \leq 315 - \sum_{\substack{i_s^{15} < j \leq k \\ a_j^{\text{type}} \in \{\texttt{DRIVE},\texttt{WORK}\}}} a_j^{\text{length}} =: \Delta_s^{15}$$

$$a^{\text{length}} \leq 450 - \sum_{\substack{i_s^{30} < j \leq k \\ a_j^{\text{type}} \in \{\texttt{DRIVE},\texttt{WORK}\}}} a_j^{\text{length}} =: \Delta_s^{30}$$

$$a^{\text{length}} \leq 600 - \sum_{\substack{i_s^{60} < j \leq k \\ a_j^{\text{type}} \in \{\texttt{DRIVE},\texttt{WORK}\}}} a_j^{\text{length}} =: \Delta_s^{60}$$

$$a^{\text{length}} \leq 720 - \sum_{\substack{i_s^{720} < j \leq k \\ a_j^{\text{type}} \in \{\texttt{DRIVE},\texttt{WORK}\}}} a_j^{\text{length}} =: \Delta_s^{720}$$

$$a^{\text{length}} \leq 1020 - \sum_{i_s^{420c} < j \leq k} a_j^{\text{length}} =: \Delta_s^{420c}$$

For a given sequence of locations $n_1, n_2, \ldots, n_\lambda$ and a schedule $s = a_1.a_2. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$, let us denote with $i(\mu)$ the index 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. The Australian Truck Driver Scheduling Problem (AUS-TDSP) is the problem of determining whether a schedule $s := a_1.a_2. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$ exists which satisfies

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

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

$$l_{s_{1,i(\mu)-1}}^{\text{end}} \in T_\mu \text{ for each } \mu \in \{1, 2, \ldots, \lambda\} \tag{3}$$

$$\sum_{\substack{i(\mu) \leq j \leq i(\mu+1) \\ a_j^{\text{type}} = \texttt{DRIVE}}} a_j^{\text{length}} = \delta_{\mu,\mu+1} \text{ for each } \mu \in \{1, 2, \ldots, \lambda - 1\} \tag{4}$$

$$\begin{gathered} a_i^{\text{length}} \leq \min\{\Delta_{s_{1,i-1}}^{15}, \Delta_{s_{1,i-1}}^{30}, \Delta_{s_{1,i-1}}^{60}, \Delta_{s_{1,i-1}}^{720}, \Delta_{s_{1,i-1}}^{420c}\} \\ \text{for each } i \in \{1, \ldots, k\} \text{ with } a_i^{\text{type}} \in \{\texttt{DRIVE}, \texttt{WORK}\} \end{gathered} \tag{5}$$

Condition (1) demands that the number of work activities in the schedule is λ and that all driving is conducted between the first and the last work activity. Condition (2) demands that the duration of the μth work activity matches the specified work duration at location n_μ. Condition (3) demands that each work activity begins within the corresponding time window. Condition (4) demands that the accumulated driving time between two work activities matches the driving time required to move from one location to the other. Condition (5) demands that the schedule complies with the regulation. In the remainder of this paper, we will say that a schedule $s := a_1.a_2. \ \ldots \ .a_k$ with $a_1^{\text{type}} = \texttt{REST}$ is *feasible* if and only if it satisfies conditions (1) to (5).

4 Structural Properties

Let us now give some structural properties of the truck driver scheduling problem which help us solving the AUS-TDSP without exploring unnecessarily many partial schedules. The first lemma gives us conditions when we can postpone rest periods in order to schedule a driving or working.

Lemma 1. *Let $s := a_1. \ldots .a_k$ be a feasible schedule with $a_i^{type} = \texttt{REST}$ and $a_{i+1}^{type} \in \{\texttt{DRIVE}, \texttt{WORK}\}$ for some $1 < i < k$. If the partial schedule*

$$a_1. \ \ldots \ .a_{i-1}.a_{i+1}$$

complies with the regulation and all relevant time window constraints, then

$$a_1. \ \ldots \ .a_{i-1}.a_{i+1}.a_i.a_{i+2}. \ \ldots \ .a_k$$

is a feasible schedule.

Proof Let $s' := a_1. \ldots .a_{i-1}.a_i.a_{i+1}$ and $s'' := a_1. \ldots .a_{i-1}.a_{i+1}.a_i$. Obviously s'' complies with the regulation because $a_i^{\text{type}} = \texttt{REST}$. The only difference between schedule s' and s'' is that in s'' one rest period is moved to a later point in time. Thus, we have

$$\Delta^{15}_{s''} \geq \Delta^{15}_{s'}, \Delta^{30}_{s''} \geq \Delta^{30}_{s'}, \Delta^{60}_{s''} \geq \Delta^{60}_{s'}, \Delta^{720}_{s''} \geq \Delta^{720}_{s'}, \text{ and } \Delta^{420c}_{s''} \geq \Delta^{420c}_{s'}.$$

Assume we have two schedules s' and s'' which comply with the regulation and all relevant time window constraints and which satisfy above conditions. Assume we have, furthermore, an activity a for which $s'.a$ complies with the regulation and all relevant time window constraints. Then we have $a^{\text{type}} = \texttt{REST}$ or $a^{\text{type}} \in \{\texttt{DRIVE}, \texttt{WORK}\}$ and $a^{\text{length}} \leq \min\{\Delta^{15}_{s'}, \Delta^{30}_{s'}, \Delta^{60}_{s'}, \Delta^{720}_{s'}, \Delta^{420c}_{s'}\} \leq \min\{\Delta^{15}_{s''}, \Delta^{30}_{s''}, \Delta^{60}_{s''}, \Delta^{720}_{s''}, \Delta^{420c}_{s''}\}$. Thus, $s''.a$ complies with the regulation and all relevant time window constraints. Furthermore, we have

$$\Delta^{15}_{s''.a} \geq \Delta^{15}_{s'.a}, \Delta^{30}_{s''.a} \geq \Delta^{30}_{s'.a}, \Delta^{60}_{s''.a} \geq \Delta^{60}_{s'.a}, \Delta^{720}_{s''.a} \geq \Delta^{720}_{s'.a}, \text{ and } \Delta^{420c}_{s''.a} \geq \Delta^{420c}_{s'.a}.$$

Therefore, $a_1. \ldots .a_{i-1}.a_{i+1}.a_i.a_{i+2}. \ldots .a_k$ is a feasible schedule. □

The next lemma gives us further conditions when we can postpone a rest period in order to schedule some driving time.

Lemma 2. *Let $s := a_1. \ldots .a_k$ be a feasible schedule with and $a_i^{type} = \texttt{REST}$ and $a_{i+1}^{type} = \texttt{DRIVE}$, $a_{i+1}^{length} > 15$ for some $1 < i < k$. If the partial schedule*

$$a_1. \ldots .a_{i-1}.(\texttt{DRIVE}, 15)$$

complies with the regulation, then

$$a_1. \ldots .a_{i-1}.(\texttt{DRIVE}, 15).a_i.(\texttt{DRIVE}, a_{i+1}^{length} - 15).a_{i+2}. \ldots .a_k$$

is a feasible schedule.

Proof Analogue to first lemma.

The next lemma gives us conditions when we can postpone a part of a rest period of less than 420 minutes.

Lemma 3. *Let $s := a_1. \ldots .a_k$ be a feasible schedule with and $a_i^{type} = \texttt{REST}$, $15 < a_i^{length} < 420$, and $a_{i+1}^{type} \in \{\texttt{DRIVE}, \texttt{WORK}\}$ for some $1 < i < k$. If*

$$a_1. \ldots .a_{i-1}.(\texttt{REST}, a_i^{length} - 15).a_{i+1}$$

complies with the regulation and time window constraints, then

$$a_1. \ldots .a_{i-1}.(\texttt{REST}, a_i^{length} - 15).a_{i+1}.(\texttt{REST}, 15).a_{i+2}. \ldots .a_k$$

is a feasible schedule.

Proof Analogue to first lemma.

The next lemma gives us further conditions when we can postpone a part of a rest period of less than 420 minutes in order to schedule a some driving time.

Lemma 4. *Let* $s := a_1. \ \dots \ .a_k$ *be a feasible schedule with and* $a_i^{type} = \texttt{REST}$*,* $15 < a_i^{length} < 420$*, and* $a_{i+1}^{type} = \texttt{DRIVE}$*,* $a_{i+1}^{length} > 15$ *for some* $1 < i < k$*. If*

$$a_1.a_2. \ \dots \ .a_{i-1}.(\texttt{REST}, a_i^{length} - 15).(\texttt{DRIVE}, 15)$$

complies with the regulation, then

$$a_1.a_2.\dots.a_{i-1}.(\texttt{REST}, a_i^{length}-15).(\texttt{DRIVE}, 15).(\texttt{REST}, 15).(\texttt{DRIVE}, a_{i+1}^{length}-15).a_{i+2}.\dots.a_k$$

is a feasible schedule.

Proof Analogue to first lemma.

Because of these lemmata we can now state some conditions that we impose on all schedules to be considered when solving the AUS-TDSP. We say that a feasible schedule $s := a_1. \ \dots \ .a_k$ is *normal form* if and only if

$$\begin{gathered}\text{for all } 1 < i < k \text{ with } a_i^{\text{type}} = \texttt{REST} \text{ and } a_{i+1}^{\text{type}} \in \{\texttt{DRIVE}, \texttt{WORK}\} : \\ a_1. \ \dots \ .a_{i-1}.a_{i+1} \text{ violates the regulation or some time window}\end{gathered} \tag{N1}$$

$$\begin{gathered}\text{for all } 1 < i < k \text{ with } a_i^{\text{type}} = \texttt{REST} \text{ and } a_{i+1}^{\text{type}} = \texttt{DRIVE}, a_{i+1}^{\text{length}} > 15 : \\ a_1. \ \dots \ .a_{i-1}.(\texttt{DRIVE}, 15) \text{ violates the regulation}\end{gathered} \tag{N2}$$

$$\begin{gathered}\text{for all } 1 < i < k \text{ with } a_i^{\text{type}} = \texttt{REST}, 15 < a_i^{\text{length}} < 420 \text{ and } a_{i+1}^{\text{type}} \in \{\texttt{DRIVE}, \texttt{WORK}\} : \\ a_1. \ \dots \ .a_{i-1}.(\texttt{REST}, a_i^{\text{length}} - 15).a_{i+1} \text{ violates the regulation or some time window}\end{gathered} \tag{N3}$$

$$\begin{gathered}\text{for all } 1 < i < k \text{ with } a_i^{\text{type}} = \texttt{REST}, 15 < a_i^{\text{length}} < 420, a_{i+1}^{\text{type}} = \texttt{DRIVE}, a_{i+1}^{\text{length}} > 15 : \\ a_1. \ \dots \ .a_{i-1}.(\texttt{REST}, a_i^{\text{length}} - 15).(\texttt{DRIVE}, 15) \text{ violates the regulation}\end{gathered} \tag{N4}$$

If a feasible schedule for a given tour exists, there also exists a feasible schedule in normal form. Thus, we can ignore all schedules which are not in normal form when searching for a feasible truck driver schedule.

5 Solution Approaches

Assume we knew the start time and end time of each rest period of 7 hours or more. We could try to construct a feasible schedule in normal form by iteratively scheduling driving or working activities as early as possible and rest activities as late as possible. The duration of all driving activities would be set to the largest possible value and the duration of all rest activities scheduled would be set to the smallest possible value. If no feasible schedule in normal form can be constructed by this procedure, no feasible schedule exists.

Unfortunately, determining when a rest period of at least 7 hours should be scheduled and how long this rest period should be is a difficult task. Therefore, we will presents several heuristics for scheduling these rest periods in this paper. These heuristics use the framework given in Figure 1. The heuristic framework begins by choosing a partial schedule s which is feasible for the tour $n_1, \dots, n_\mu$ and sets δ to the driving time required to reach location $n_{\mu+1}$. As long as the next location is not yet reached (i.e. $\delta > 0$), the maximum amount of driving allowed with respect to condition (5) is determined. If condition (5) forbids any driving, a rest period of 15 minutes is appended to the schedule. Otherwise, the longest possible driving period is appended to the schedule and δ is updated. When the next location is reached (i.e. $\delta = 0$), as much rest time as necessary in order to be able to schedule the next working period of duration $w_{\mu+1}$ is appended to the schedule. Then, depending on the specific method, the set $\mathcal{S}(s, \mu+1)$ is determined and included into the set of schedules found for tour $n_1, \dots, n_{\mu+1}$.

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1. choose $s \in \mathcal{S}_\mu$, set $\delta := \delta_{\mu,\mu+1}$
2. while $\delta > 0$ do
   - $\Delta := \min\{\Delta_s^{15}, \Delta_s^{30}, \Delta_s^{60}, \Delta_s^{720}, \Delta_s^{420c}\}$
   - $s := \begin{cases} s.(\texttt{REST}, 15) & \text{if } \Delta = 0 \\ s.(\texttt{DRIVE}, \min\{\delta, \Delta\}) & \text{if } \Delta > 0 \end{cases}$
   - $\delta := \delta - \min\{\delta, \Delta\}$
3. while $w_{\mu+1} > \min\{\Delta_s^{15}, \Delta_s^{30}, \Delta_s^{60}, \Delta_s^{720}\}$ do
   - $s := s.(\texttt{REST}, 15)$
4. $\mathcal{S}_{\mu+1} := \mathcal{S}_{\mu+1} \cup \mathcal{S}(s, \mu+1)$

Fig. 1 Heuristic framework for scheduling activities for the trip from location n_μ to $n_{\mu+1}$

The AUS1 heuristic is a greedy heuristic in which $\mathcal{S}(s, \mu+1)$ contains at most one schedule. If $l_s^{\text{end}} \in T_{\mu+1}$ and $w_{\mu+1} \leq \Delta_s^{420c}$ then $\mathcal{S}(s, \mu+1) := \{s.(\texttt{WORK}, w_{\mu+1})\}$. Otherwise, if for some $\Delta > 0$ a feasible schedule $s.(\texttt{REST}, \Delta).(\texttt{WORK}, w_{\mu+1})$ for tour $n_1, \dots, n_{\mu+1}$ exists, then $\mathcal{S}(s, \mu+1)$ contains the feasible schedule $s.(\texttt{REST}, \Delta).(\texttt{WORK}, w_{\mu+1})$ with the smallest value Δ. If no such schedule exists, then $\mathcal{S}(s, \mu+1) := \emptyset$.

In the AUS2 heuristic $\mathcal{S}(s, \mu+1)$ contains at most two schedules. The first is the schedule which is also determined by the AUS1 heuristic. The second schedule is only included to the set if $l_s^{\text{end}} < \min T_{\mu+1}$ or if the last activity of s is of type REST and has a duration of less than 7 hours. Let a denote the last activity of s and let

$$\Delta' := \begin{cases} a^{\text{length}} & \text{if } a^{\text{type}} = \texttt{REST} \\ 0 & \text{else} \end{cases}$$

If for some $\Delta > 0$ with $\Delta' + \Delta \geq 420$ a feasible schedule $s.(\texttt{REST}, \Delta).(\texttt{WORK}, w_{\mu+1})$ for tour $n_1, \dots, n_{\mu+1}$ exists, then the feasible schedule $s.(\texttt{REST}, \Delta).(\texttt{WORK}, w_{\mu+1})$ with the smallest such value Δ is included to $\mathcal{S}(s, \mu+1)$. If no such schedule exists then $\mathcal{S}(s, \mu+1)$ is the same as for the AUS1 heuristic.

In the AUS3 heuristic $\mathcal{S}(s, \mu+1)$ contains at most three schedules. The first two are the schedules which are also determined by the AUS2 heuristic. The third schedule is only included to the set if $l_s^{\text{end}} < \min T_{\mu+1}$. Let s' denote the schedule which is obtained by extending the last rest period in s, which has a duration of at least 420 minutes, by the largest value which does not exceed $\min T_{\mu+1} - l_s^{\text{end}}$ and for which time window constraints are not violated for any work location visited after the last rest period. If $l_{s'}^{\text{end}} < \min T_{\mu+1}$ and $w_{\mu+1} + \min T_{\mu+1} - l_{s'}^{\text{end}} \leq \Delta_{s'}^{420c}$ then $s'.(\texttt{REST}, \min T_{\mu+1} - l_{s'}^{\text{end}}).(\texttt{WORK}, w_{\mu+1})$ is included to $\mathcal{S}(s, \mu+1)$. If $l_{s'}^{\text{end}} = \min T_{\mu+1}$ and $w_{\mu+1} \leq \Delta_{s'}^{420c}$ then $s'.(\texttt{WORK}, w_{\mu+1})$ is included to $\mathcal{S}(s, \mu+1)$. Otherwise, $\mathcal{S}(s, \mu+1)$ is the same as for the AUS2 heuristic.

The AUS1, AUS2, and AUS3 heuristics begin with

$$\mathcal{S}_1 := \{(\texttt{REST}, \max\{2880, \min T_1\}).(\texttt{WORK}, w_1)\}$$

and $\mu = 1$. Then, the method illustrated in Figure 1 is invoked until each schedule in $\mathcal{S}_\mu$ has been selected. If $\mathcal{S}_{\mu+1} = \emptyset$, the heuristic terminates because no feasible schedule is found for tour $n_1, \dots, n_{\mu+1}$. Otherwise, μ is incremented and the process is repeated until $\mathcal{S}_\lambda \neq \emptyset$.

To reduce the computational effort of the AUS2 and AUS3 heuristic some partial schedules are removed from $\mathcal{S}_\mu$ before invoking the scheduling method. Let us consider two schedules $s', s'' \in \mathcal{S}_\mu$ for some $1 < \mu < \lambda$. If $l^{\text{end}}_{s'} + 720 \leq l^{\text{end}}_{s''}$, then s'' is removed from $\mathcal{S}_\mu$. In the case that s'' is not removed and s' ends with a rest period followed by a work period let a denote this rest period and let

$$\Delta := \begin{cases} \max\{420, 720 - a^{\text{length}}\} & \text{if } a^{\text{length}} < 420 \\ \max\{0, 720 - a^{\text{length}}\} & \text{if } a^{\text{length}} \geq 420. \end{cases}$$

If $l^{\text{end}}_{s'} + \Delta \leq l^{\text{end}}_{s''}$, then s'' is removed from $\mathcal{S}_\mu$.

6 Computational Experiments

Scheduling of driving and working hours is of particular importances for long distance haulage where drivers do not return home every day. In order to evaluate the scheduling method presented in this paper we generate benchmark instances for a planning horizon starting on Monday morning and ending on Friday evening. In the benchmark set each handling activity requires one hour of working time (i.e. $w_\mu = 1$ for all $1 \leq \mu \leq \lambda$) and the driving time between two subsequent locations is 4, 8, 12, or 16 hours (i.e. $\delta_{\mu,\mu+1} \in \{4, 8, 12, 16\}$ for all $1 \leq \mu < \lambda$). Assuming an average speed of 75 km/h, this implies that the distance between two subsequent locations ranges from 300 km to 1200 km. Each location must be visited on a specific day between 6.00h and 13.59h or between 14.00h and 21.59h.

Algorithm	Instances	Computation time
AUS1	64,785	123'43"
AUS2	67,556	275'57"
AUS3	67,556	360'29"

Table 1 Number of instances for which a feasible schedule is found by the method and total computation time required

In total, around 15.6 million instances where generated in which time window constraints could be satisfied if driving and working times were unrestricted. Only 3,166,146 of these instances do not exceed the accumulated weekly working time of 72 hours. All other instances are discarded by the heuristics before starting to construct schedules. Table 1 gives an overview of the number of instances for which the AUS1, AUS2 and AUS3 heuristic find a feasible schedule and the total computation time required. The AUS2 heuristic can find a feasible schedule for 2,771 instances more than the AUS1 heuristic. However, it requires almost double the computation time. Although it is easy to find examples in which the AUS3 heuristics is superior to the

AUS2 heuristic, the AUS3 heuristic cannot find a feasible schedule for more instances considered in this experiment. The AUS1 heuristic has by far the smallest running time and is capable of finding a feasible schedule for approximately 96 per cent of the instances for which the more sophisticated approaches can find a feasible schedule. Thus, it appears that, for similarly structured practical problem instances, the AUS1 heuristic has the best trade-off between exactness and computational effort.

7 Summary

This paper studies the Australian Heavy Vehicle Driver Fatigue Law and formulates the Australian Truck Driver Scheduling Problem. Structural properties of the problem are analysed and used to develop heuristics for solving the problem.

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