Hours of service regulations in road freight transport: an optimization-based international assessment

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Driver fatigue is internationally recognized as a significant factor in approximately 15 to 20% of commercial road transport crashes. In their efforts to increase road safety and improve working conditions of truck drivers, governments world wide are enforcing stricter limits on the amount of working and driving time without rest. This paper describes an effective optimization algorithm for minimizing transportation costs for a fleet of vehicles considering business hours of customers and complex hours of service regulations. The algorithm combines the exploration capacities of population-based metaheuristics, the quick improvement abilities of local search, with efficient tree search procedures for checking compliance with hours of service regulations. The proposed approach can be used to assess the impact of different hours of service regulations from a carrier-centric point of view. Extensive computational experiments conducted for various sets of regulations in the United States, Canada, the European Union, and Australia are conducted to provide an international assessment of the impact of different rules on transportation costs and accident risks. Our experiments demonstrate that European Union rules lead to the highest safety, while Canadian regulations are the most competitive in terms of economic efficiency. Australian regulations appear to have unnecessarily high risk rates with respect to operating costs. The recent rule change in the United States reduces accident risk rates with a moderate increase in operating costs.

Key words: Hours of Service Regulations; Fatigue; Road Safety; Truck Driver Scheduling; Vehicle Routing and Scheduling

1. Introduction

Driver fatigue is a significant factor in approximately fifteen to twenty percent of commercial road transport crashes (Williamson et al. 2001, European Transport Safety Council 2001, Federal Motor Carrier Safety Administration 2008). In Europe it is estimated that one out of two long haul drivers has fallen asleep while driving (European Transport Safety Council 2001). One out of five long distance road transport drivers in Australia 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

(Williamson et al. 2001). A survey among truck drivers in the United States revealed that one out of six truck drivers has dozed at wheel in the month prior to the survey, and less than one out of two truck drivers reported that delivery schedules are always realistic (McCartt et al. 2008). Undoubtedly, fatigue is a threat to road safety and companies must give drivers enough time for breaks and rest periods during their trips.

In their efforts to increase road safety and improve working conditions, governments world wide are adopting stricter regulations concerning driving and working hours of truck drivers. These regulations impose maximum limits on the amount of driving and working within certain time periods and minimum requirements on the number and duration of break and rest periods which must be taken by drivers. Compulsory break and rest periods have a significant impact on total travel durations, which are typically more than twice as long as the pure driving time required in long distance haulage. Consequently, motor carriers must take applicable hours of service regulations into account when generating routes and truck driver schedules. Not doing so would inevitably result in unrealistic schedules, large delays, violations of regulations, and reduced road safety.

In this paper, a hybrid genetic algorithm is introduced for the problem of determining a set of routes for a fleet of vehicles, such that each customer is visited within given time windows, that each driver can comply with applicable hours of service regulations, and that transportation costs are minimized. The proposed optimization method is specifically designed to efficiently handle explicit schedule generation during route evaluations and can be applied for various hours of service regulations world wide. Extensive computational experiments on benchmark instances developed for vehicle routing and truck driver scheduling in the European Union demonstrate the remarkable performance of the method in comparison to previous approaches. In particular, 103/112 best known solutions for these instances were either obtained or improved, and 72/112 were strictly improved. This shows that our approach can provide a valuable tool for transport operators to minimize costs and likewise give drivers enough time for recuperation.

Furthermore, policy makers, unions, and transport companies can use our approach to assess the impact of regulations or agreements to find the best trade-off between road safety, working conditions of truck drivers as well as speed and costs of transportation. In this paper we assess and compare of hours of service regulations in the United States, Canada, the European Union, and Australia with regards to operating costs and accident risks. Specific subsets of rules such as split breaks and rests or extended driving times and reduced rests in the European Union as well as the impact of the recent rule change in the United States are analyzed.

2. Hours of service regulations

This section presents the hours of service regulations in the United States, Canada, the European Union, and Australia. For the sake of conciseness only the most important rules for a planning horizon of six days (i.e. Monday to Saturday) are described. For more details about these regulations the reader is referred to Federal Motor Carrier Safety Administration (2011), Transport Canada (2005), European Union (2006, 2002) and National Transport Commission (2008a,b,c).

2.1. United States

In December 2011, the Federal Motor Carrier Safety Agency published new hours of service regulations in the United States. These 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.

The regulations limit the maximum amount of accumulated driving time between two rest periods to 11 hours. After accumulating 11 hours of driving, the driver must be off duty for 10 consecutive hours before driving again. The regulations prohibit a driver from driving after 14 hours have elapsed since the end of the last rest period. However, a driver may conduct other work after 14 hours have elapsed since the end of the last rest period. Furthermore, a driver must not drive after accumulating 60 hours of on-duty time within a period of 7 days. Alternatively, a driver must not drive after accumulating 70 hours of on-duty time within a period of 8 days. For the sake of conciseness, however, this second option is not considered in the remainder of this paper.

Above rules are the same as in the previous regulations. The new regulations, furthermore, include new rules which will become effective in July 2013. According to these new rules a truck driver must not drive if 8 hours or more have elapsed since the end of the last off-duty period of at least 30 minutes.

2.2. Canada

Canadian hours of service regulations are described in Transport Canada (2005) and interpreted in Canadian Council of Motor Transport Administrators (2007). Two sets of regulations exist, one of which applies to driving conducted south of latitude 60° N and one to driving north of latitude 60° N. In this paper we focus on the subset of regulations applicable for driving south of latitude 60° N, because this is the area of major economic concern. On- and off-duty times are defined as described above for U.S. hours of service regulations. The regulations demand that a driver must not drive after accumulating 13 hours of driving time, after accumulating 14 hours of on-duty time, or after 16 hours of time have elapsed since the end of the last period of at least 8 consecutive hours of off-duty time. In any of these cases the driver may only commence driving again after taking another period of at least 8 consecutive hours of off-duty time.

Furthermore, the regulations impose restrictions on the maximum amount of on-duty time and the minimum amount of off-duty time during a *day*. According to the regulations a *day* means a

24-hour period that begins at some time designated by the motor carrier. For simplicity and w.l.o.g. let us assume in the remainder that this time is midnight. The regulations demand that a driver does not drive for more than 13 hours in a day and that a driver accumulates at least 10 hours of off-duty time in a day. At least 2 of these hours must not be part of a period of 8 consecutive hours of off-duty time as required by the provisions described in the previous paragraph. However, if a period of more than 8 consecutive hours of off-duty time is scheduled, the amount exceeding the 8th hour may contribute to these 2 hours. Off-duty periods of less than 30 minutes do not count toward the minimum off-duty time requirements. Eventually, the regulations demand that a driver does not drive after accumulating 70 hours of on-duty time within a period of 7 days.

2.3. European Union

In the European Union, truck drivers must comply with regulation (EC) No 561/2006 and the national implementations of Directive 2002/15/EC.

Regulation (EC) No 561/2006 distinguishes between four driver activities: rest periods, breaks, driving time, and other work. Rest periods are periods during which a driver may freely dispose of her or his time and have the purpose of giving drivers enough time to sleep. Breaks are short periods exclusively used for recuperation during which a driver must not carry out any work. Driving time refers to the time during which a driver is operating a vehicle and includes any time during which the vehicle is temporarily stationary due to reasons related to driving, e.g. traffic jams. Other work refers to any work except for driving and includes time spent for loading or unloading, cleaning and technical maintenance, customs, and so on.

Regulation (EC) No 561/2006 demands that a driver takes a break of at least 45 minutes after accumulating $4\frac{1}{2}$ hours of driving. A daily rest period of at least 11 hours must be completed within 24 hours after the end of the previous rest period, and the accumulated driving time between two rest periods shall not exceed 9 hours. Furthermore, the driving time in a week must not exceed 56 hours, and the accumulated driving and working time in a week must not exceed 60 hours.

The basic set of rules described above are sufficient to comply with regulation (EC) No 561/2006. The regulation, furthermore, allows a driver to take break and rest periods in two parts. A break period may be taken in two parts if the first part is a period of at least 15 minutes and the second part is a period of at least 30 minutes. A rest period may be taken in two parts if the first part is a period of at least 3 hours and the second part is a period of at least 9 hours. If a rest period is taken in two parts, the second part must be completed within 24 hours after the end of the previous rest period. Within a planning horizon of one week a driver is allowed to reduce the duration of at most three rest periods to 9 hours. Furthermore, the amount of driving between two rest periods may be extended twice a week to at most 10 hours.

According to Directive 2002/15/EC, a truck driver must not work for more than 6 hours without taking at least 30 minutes of break time. If a truck driver works for more than 9 hours at least 45 minutes of break time must be taken. The break time may be taken in several periods of at least 15 minutes each. The directive, furthermore, applies additional rules for night work. However, these rules not are not considered in the scope of this paper because they differ throughout the member states of the European Union.

2.4. Australia

In Australia, motor carriers accredited in the National Heavy Vehicle Accreditation Scheme may operate according to the Basic Fatigue Management Standard (National Transport Commission 2008b). Motor carriers without accreditation must comply with the *standard hours* option of the Australian Heavy Vehicle Driver Fatigue described in National Transport Commission (2008c).

Standard Hours

Australian motor carriers without accreditation must comply with the following constraints on driver schedules:

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 7 days a driver must not work for more than 72 hours and must have at least 24 continuous hours of stationary rest time.

When evaluating whether a truck driver schedule complies with these provisions, the duration of each work period is rounded up to the nearest multiple of 15 minutes and the duration of each rest period is rounded down to the nearest multiple of 15 minutes.

Basic Fatigue Management

Australian motor carriers accredited in the National Heavy Vehicle Accreditation Scheme (NHVAS) may operate according to the Basic Fatigue Management (BFM) option which imposes the following constraints:

1. In any period of $6\frac{1}{4}$ hours a driver must not work for more than 6 hours and must have at least 15 continuous minutes of rest time.

2. In any period of 9 hours a driver must not work for more than $8\frac{1}{2}$ hours and must have at least 30 minutes rest time in blocks of not less than 15 continuous minutes.
3. In any period of 12 hours a driver must not work for more than 11 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 14 hours and must have at least 7 continuous hours of stationary rest time.
5. In any period of 7 days a driver must not accumulate more than 36 hours of long/night work time; the term *long/night work time* refers to any work time in excess of 12 hours in a 24 hour period plus any work time between midnight and 6.00 AM.

The BFM option limits the amount of driving and working to at most 144 hours of work within 14 days. As the accumulated amount of driving and working within a period of 7 days is not explicitly constrained, we will assume a limit of 72 hours in the remainder. The duration of work and rest periods is rounded in the same way as in the standard hours options.

2.5. Discussion

It is interesting to see that all regulations have some specific characteristics which make it difficult to analytically compare their impact on road freight transport. Table 1 illustrates some of the main characteristics of the different regulations.

	US	**CAN**	**EU (Basic)**	**EU (All)**	**AUS (Std.)**	**AUS (BFM)**
Duration of a long rest period	10	8	11	9	7	7
Driving time between two long rest periods	11	13	9	10	12	14
On-duty time between two long rest periods	14^+	14^+	$12\frac{1}{4}$	$14\frac{1}{4}$	12	14
Time elapsed between two long rest periods	14^+	16^+	13	15	17	17
Driving time within six days	60	70	56	56	72	72
On-duty time within six days	60^+	70^+	60	60	72	72

Table 1 Comparison of the regulations

All regulations require long rest periods to be regularly taken. Requirements on when to take these rest periods as well as their minimum duration differ between the regulations. With 11 hours, the longest continuous rest period is required by the basic regulations in the European Union in which rest periods may neither be split nor reduced and driving time may not be extended. When exploiting all of the rules of the regulations this minimum duration can be reduced to 9 hours. The accumulated amount of driving between two long rest periods differs significantly and ranges from 9 or 10 hours in the European Union to 13 hours in Canada and 14 hours in Australia if the BFM option is used. It is worth noting that, according to the current rules in the United States and in Canada, a driver may drive for the full amount of driving that is allowed between two long rest periods without taking a break. According to the new rules in the United States, as well as in the European Union and Australia, drivers must take short breaks after accumulating a certain amount of driving and/or work time.

Australian regulations do not differentiate between on-duty periods in which the driver is driving or working. Hours of service regulations in the United States and in Canada, on the other hand, do not explicitly limit the amount of on-duty time between rest periods and allow drivers to keep on working when the respective driving time limits are reached. In the table these limits are indicated with a "+". The maximum amounts of driving and working within a period of six days differ significantly between the regulations and, again, European Union regulations have the most restrictive limits.

3. Problem statement and related work

As hours of service regulation have a significant impact on travel times, transport companies must consider respective regulations when generating vehicle routes. The resulting decision problem is a variant of vehicle routing problem with time windows (VRPTW). The *vehicle routing and truck driver scheduling problem (VRTDSP)* aims to find a set of routes for a fleet of vehicles, such that each customer requesting service is visited within given time windows, that the accumulated load to be delivered to (or collected from) the customers of a route does not exceed the capacity of the vehicle, that each truck driver can comply with applicable hours of service regulations, and that transportation costs, considered proportional to the travel distance, are minimized.

The VRPTW has attracted a lot of attention in the operations research literature. The most efficient exact methods (Kallehauge et al. 2006, Jepsen et al. 2008, Baldacci et al. 2011) can solve most instances with up to 100 customers, and a few instances with up to 1000 customers. However, their performance heavily depends upon the specificities of instances and the width of time windows. Hence, metaheuristics are currently the method of choice to address practical settings. In the VRPTW literature, almost every prominent metaheuristic paradigm has been applied, including tabu search (Gendreau et al. 1994, Cordeau et al. 2001a), adaptive large neighborhood search (Pisinger and Ropke 2007), iterated local search (Ibaraki et al. 2005, 2008), genetic algorithms and evolution strategies (Mester and Bräysy 2005, Labadi et al. 2008, Repoussis et al. 2009, Nagata et al. 2010, Vidal et al. 2011a), path relinking (Hashimoto et al. 2008), other metaheuristic hybrids (Prescott-Gagnon et al. 2009), and cooperative and parallel methods (Le Bouthillier and Crainic 2005, Le Bouthillier et al. 2005). A comprehensive review of recent VRPTW heuristics is conducted in Gendreau and Tarantilis (2010). Overall, hybrid methods combining genetic algorithms with local search are well represented in the current state-of-the-art methods (Nagata et al. 2010, Vidal et al. 2011a).

The problem of determining whether time window constraints of all customers in a route can be complied with has been studied for long (Savelsbergh 1985, 1992). When using efficient data structures this problem can be solved in $O(1)$ operations for each route determined within the course of a local search approach. A comprehensive overview of vehicle routing variants with time features, including multiple time windows, time-dependent costs and travel times, flexible travel times, etc. is given by Vidal et al. (2011b). It is worth noting that for most of these variants the problem of determining adequate service date to customers for a fixed sequence of visits can be modeled as a linear or convex mathematical program on continuous variables. As this is not the case when hours of service regulations must be complied with, determining whether all locations in a route can be visited within given time windows can become a particularly difficult task.

Regulations concerning working hours of mobile staff in the transportation sector have been studied since the 1960s. An early survey on airline crew scheduling is presented by Arabeyre et al. (1969). Kohl and Karisch (2004) describe typical rules and regulations arising in airline crew rostering. Various approaches have been developed for combined aircraft routing and crew scheduling (Cordeau et al. 2001b, Mercier et al. 2005, Sandhu and Klabjan 2007), for simultaneous vehicle and driver scheduling for mass transit systems (Haase et al. 2001, Valouxis and Housos 2002, Freling et al. 2003, Huisman et al. 2005) and for limousine rental (Laurent and Hao 2007). Ernst et al. (2004) provide a comprehensive annotated bibliography on personnel scheduling which covers crew and driver scheduling problems for airlines, railways, and mass transit systems.

Until very recently, hours of service regulations in road freight transport have received little attention in the literature. Scheduling in road freight transportation differs significantly from scheduling in airlines, railways, and mass transit systems which typically operate on time tables. In road freight transport arrival times are usually given by time windows. As travel times between customer locations depend on previous driving and rest patterns and as many different driving and rest patterns are possible, efficient solution procedures are required to determine whether all customer locations in a route can be visited within given time windows. Comprehensive models of different hours of service regulations world wide are provided by Archetti and Savelsbergh (2009), Goel and Kok (2011), Goel (2010), Goel and Rousseau (2011), Goel et al. (2012), and Goel (2012b). These works present exact methods for the problem of determining whether a truck driver schedule complying with specific hours of service regulations exists for a fixed sequence of visits to customers with respective time windows. For current U.S. hours of service regulations, this problem is known to be solvable in polynomial time (Archetti and Savelsbergh 2009, Goel and Kok 2011). For the other regulations and the new rules in the United States, the existence of a polynomial algorithm for this scheduling problem is still an open research question.

Heuristic approaches for the VRTDSP have been introduced by Goel (2009), Kok et al. (2010), and Prescott-Gagnon et al. (2010) for EU regulations, and by Rancourt et al. (2010) for U.S. regulations. Other specific variants have also been addressed by Xu et al. (2003) and Zäpfel and

Bögl (2008). So far, no approach for the VRTDSP in Canada, Australia, or the new rules in the United States has been presented, no approach can handle more than one set of rules, and no international comparison on the impact of different hours of service regulations on motor carrier profitability has been made.

4. An optimization method for combined vehicle routing and truck driver scheduling

We introduce a new metaheuristic for the VRTDSP for different hours of service regulations around the world. This approach relies on two main building blocks, namely the hybrid genetic search with advanced diversity control (HGSADC) for route optimization (Vidal et al. 2012), and the truck driver scheduling procedures of Goel and Kok (2011), Goel and Rousseau (2011), Goel (2010), Goel et al. (2012) and Goel (2012b).

The general behavior of the proposed HGSADC for the VRTDSP is represented in Figure 1. As a member of the family of genetic algorithms (GA), the HGSADC evolves a population of individuals representing different solutions, by means of elitist selection, mutation and recombination operations. Furthermore, unlike classical GA, the proposed approach relies on an incomplete solution representation *without trip delimiters* with dedicated *Split* and *Removal* procedures to pass from individual representations to full solutions (see Section 4.1). Both feasible and individual solutions are produced and evaluated relatively to their cost, feasibility, and contribution to diversity (see Section 4.2). To generate new individuals, a crossover operator is used as well as local search-based *Education* and *Repair* procedures (see Section 4.3). The feasible and infeasible individuals produced by the previous operations are managed in two separate *sub-populations* (see Section 4.4).

Any route created in the course of the search, especially during *Education*, *Repair* and *Split*, must be evaluated with respect to capacity and time window constraints. In order to evaluate compliance with time windows, truck driver schedules complying with applicable hours of service regulations must be generated (see Section 4.5). The computational challenges that must be tackled to achieve an efficient method are discussed in Section 4.6.

4.1. Solution representation

Each individual in HGSADC is represented as a *giant tour* without *trip delimiters* (Prins 2004). This representation allows the use of simple permutation-based crossover operators, and has been used successfully for many vehicle routing variants. A *Split* procedure fulfills the role of partitioning a given giant tour into several vehicle routes to obtain the associated VRTDSP solution, thus providing the means to evaluate individuals and apply local search-based improvement procedures. In reverse, generating a giant tour from a solution is done by ordering the routes by increasing

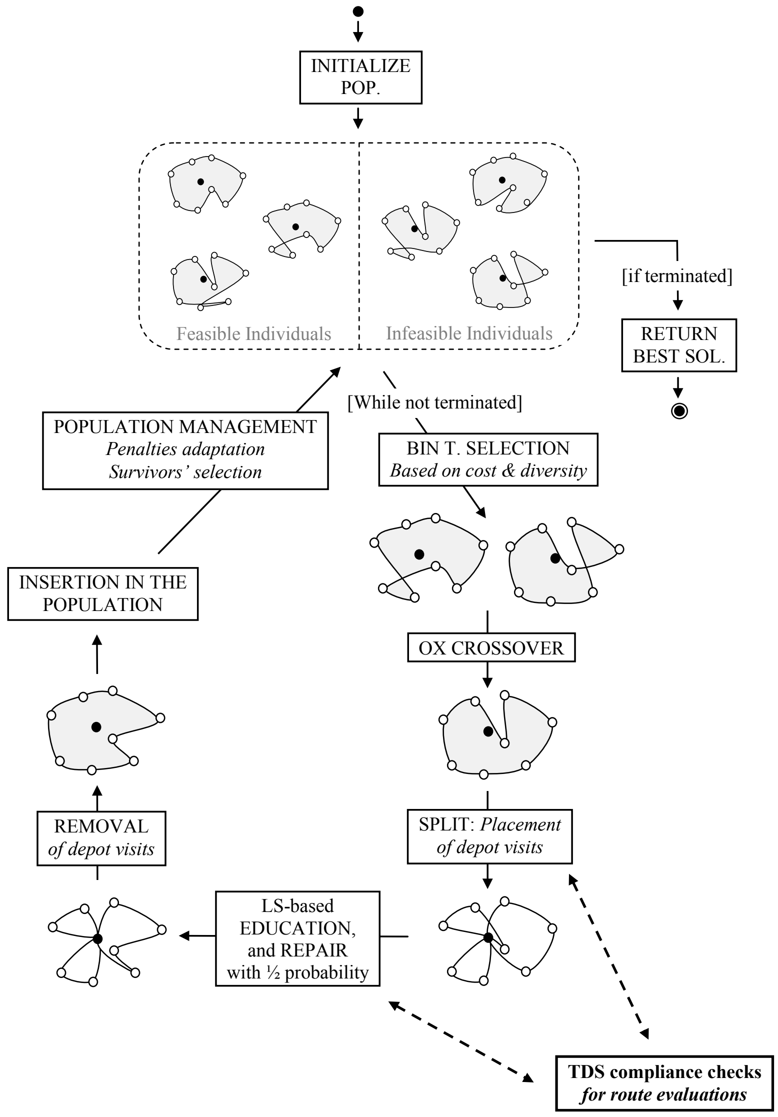


Figure 1 General behavior of the hybrid genetic algorithm with adaptive diversity control for the VRTDSP

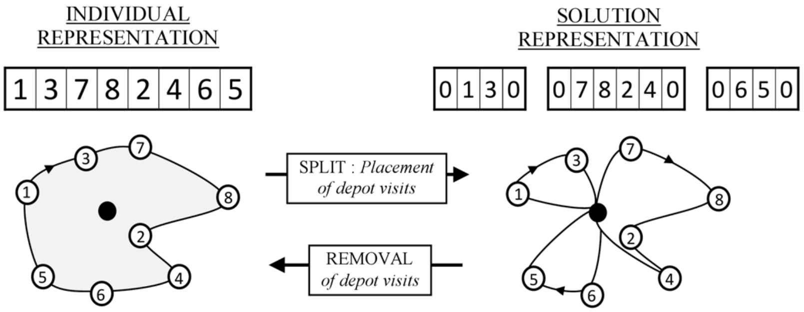


Figure 2 From individual to solution representation

barycenter's polar angle around the depot, and then removing depot occurrences. Figure 2 illustrates the relationship between giant tour and solution representation.

The problem of optimally segmenting a giant tour by inserting visits to the depot is modeled as a shortest path problem on a directed acyclic auxiliary graph (Beasley 1983). In this graph, each arc is associated to a potential route servicing a subsequence of consecutive visits from the giant tour, which must be evaluated with respect to cost and route constraints (including hours of service regulations). There are $\mathcal{O}(nb)$ such arcs to evaluate, where n denotes the number of customers and $b \leq n$ represents a bound on the number of customers per route. Once arc costs in this graph are determined, the splitting problem is solved in $\mathcal{O}(nb)$ using the Bellman algorithm. If the fleet is limited to m vehicles, a path with less than m edges can be found in $\mathcal{O}(mnb)$.

4.2. Evaluation of individuals

The VRTDSP can be qualified as a "tightly constrained" problem in the sense that only a relatively small proportion of all possible sequences of customer locations represent feasible solutions. To better transition between structurally different solutions in the course of the search, penalized infeasibility with respect to capacity and time window constraints is allowed, and the evaluation of individuals is based on both *penalized costs* and *contribution to diversity* metrics.

The *penalized cost* $\phi^{\text{COST}}_{\mathcal{P}}(p)$ of an individual p is defined as the sum of the penalized costs its routes, determined relatively to load, distance, and lateness measures. Computation of distance and load on a route is straightforward, whereas evaluating lateness in presence of hours of service regulations requires to explicitly build truck driver schedules. This difficult and computationally intensive task is discussed in Section 4.5. For a route r with distance $\varphi^{\text{D}}(r)$, load $\varphi^{\text{Q}}(r)$, and lateness $\varphi^{\text{L}}(r)$, the penalized cost $\phi(r)$ is then given by

$$\phi(r) = \varphi^{\text{D}}(r) + \omega^{\text{Q}} \max\{0, \varphi^{\text{Q}}(r) - Q\} + \omega^{\text{L}} \varphi^{\text{L}}(r), \tag{1}$$

where ω^{Q} and ω^{L} are penalty coefficients for capacity violation and lateness. Like in Vidal et al. (2012), these coefficients are adapted during the search relatively to the proportion of feasible individuals.

The *diversity contribution* $\phi^{\text{DIV}}_{\mathcal{P}}(p)$ of an individual p to its sub-population $\mathcal{P}$ is defined as the average proportion of arcs in common with each of the μ^{CLOSE} most similar individuals in the sub-population (Vidal et al. 2011a).

The *biased fitness* $f_{\mathcal{P}}(p)$ of an individual p is defined in Equation (2) as the weighted sum of the rank $f^{\text{COST}}_{\mathcal{P}}(p)$ of p in its sub-population $\mathcal{P}$ in terms of penalized cost and of its rank $f^{\text{DIV}}_{\mathcal{P}}(p)$ in $\mathcal{P}$ in terms of diversity contribution. The parameter μ^{ELITE} balances the role of both components.

$$f_{\mathcal{P}}(p) = f^{\text{COST}}_{\mathcal{P}}(p) + \left(1 - \frac{\mu^{\text{ELITE}}}{|\mathcal{P}|}\right) f^{\text{DIV}}_{\mathcal{P}}(p) \tag{2}$$

The biased fitness thus reflects the amount of innovation, the cost, and the feasibility of solutions.

4.3. Generation of new individuals

Sub-populations are initially filled with randomly generated individuals, which are *Educated*, and *Repaired* as described in the next paragraphs. The method proceeds by iteratively selecting two "parents" in the combined population of feasible and infeasible individuals by a *binary tournament* (Goldberg and Deb 1991) based on the biased fitness measure. These parents serve as input of the *ordered crossover* (OX) (see Prins 2004) to produce a new individual called *offspring*. This offspring is converted into a full solution by means of the *Split* procedure, before being *Educated*, and *Repaired* with probability $\pi^{\text{REP}} = 0.5$ if infeasible.

Education is a local search procedure based on well-known VRP neighborhoods such as 2-opt, 2-opt*, and CROSS-exchanges. As in Vidal et al. (2011a), neighboring solutions are explored in a random order and any improving move is directly applied. To reduce the computational effort, only moves between related customers with regards to distance and time characteristics are attempted.

The *Repair* operator temporarily increases the penalty coefficients by a factor of 10 and calls *Education* to redirect the search towards feasible solutions.

4.4. Population management

All individuals produced by means of the previous operations are included in the appropriate sub-population. Each individual can start to "reproduce" immediately after being created. Sub-populations are independently managed to contain between μ^{MIN} and $\mu^{\text{MIN}} + \mu^{\text{GEN}}$ individuals. Whenever a sub-population reaches a maximum size $\mu^{\text{MIN}} + \mu^{\text{GEN}}$, a *survivor selection* phase is triggered. This phase involves to remove μ^{GEN} times the worst individual with regards to the biased fitness function $f_{\mathcal{P}}$ previously defined, privileging the removal of individuals that appear identically several times in the sub-population. The previous cycle of operations is repeated until a maximum number of individual creations without improvement λ^{IT} is reached. The best found solution is finally returned.

4.5. Truck driver scheduling for route evaluations

The routes produced in the course of the search must be evaluated with respect to time window constraints. For this, a schedule complying with hours of service regulations must be generated which minimizes lateness in customer service times. In this process, any voluntary increase in service lateness to a customer with an eye to reduced lateness at subsequent customers is forbidden.

For a route $r = (r_1, r_2, \ldots, r_{n_r})$ with n_r locations, a forward labeling algorithm is used which iteratively generates a set of schedules S_i for each partial route $(r_1, r_2, \ldots, r_i)$, $i \in \{1, \ldots, n_r\}$. The algorithm begins with a set of truck driver schedules $\mathcal{S}_1$ for the partial route consisting solely of node r_1. In each subsequent iteration, for $2 \leq i \leq n_r$, each schedule from $\mathcal{S}_{i-1}$ is extended into new schedules for the partial route $(r_1, r_2, \ldots, r_i)$ by subsequently appending driving, working and off-duty periods to the end of the schedule and by extending the duration of off-duty periods already scheduled. Different types of off-duty periods must be scheduled depending on the regulations. As any voluntary increase in service lateness is forbidden, only schedules with a minimal lateness value are included in the set $\mathcal{S}_i$. A *dominance* relationship is then used to prune schedules from $\mathcal{S}_i$.

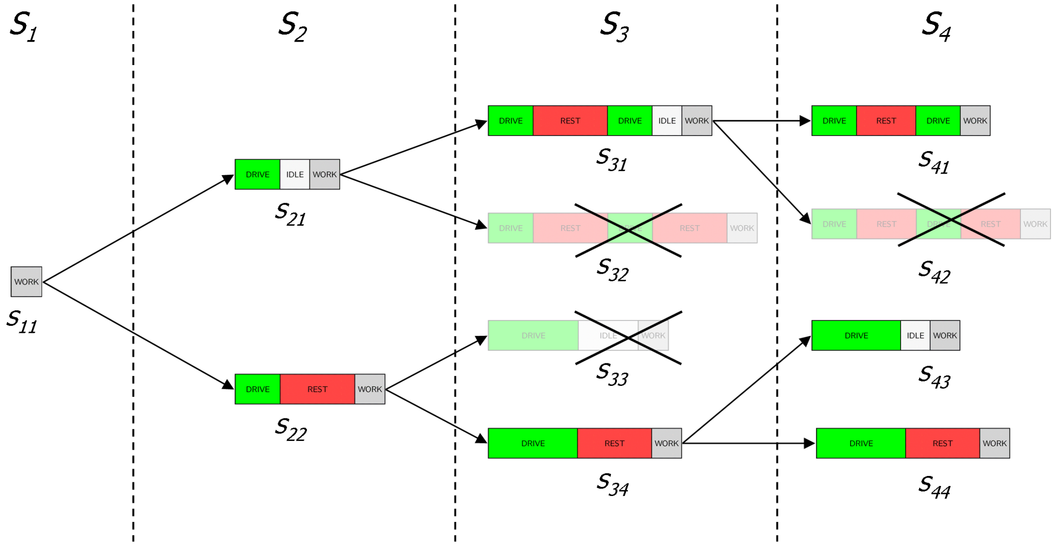


Figure 3 **Truck driver scheduling procedure for a route with four locations**

Figure 3 illustrates the search tree of the truck driver scheduling procedure for a route $r = (r_1, r_2, r_3, r_4)$ and current U.S. hours of service regulations. The scheduling method for current U.S. hours of service regulations extends each non-dominated schedule into two child schedules, one of them comprising an additional rest period immediately before service. Schedules s_{32}, s_{33}, and s_{42} are pruned using a dominance relationship based on the completion time, the accumulated driving time since the last rest period, and the time elapsed since the last rest period.

The details on how schedules are extended, how many alternative schedules need to be generated, and the dominance relationship depend on the specific rules of the regulations. Different forward labeling algorithm for hours of service regulations in the United States, Canada, the European Union, and Australia can be found in Goel and Kok (2011), Goel (2012b), Goel and Rousseau (2011), Goel (2010), and Goel et al. (2012). In this paper, we use adaptations of these algorithms that allow penalized lateness with respect to time window constraints, and also account for multiple time windows as done in Goel and Kok (2011). For European Union regulations, we extended the approach of Goel (2010) in order to consider the possibility of reducing the duration of rest periods to 9 hours and extending the amount of driving between two rest periods to 10 hours. The method was thus modified in such a way that additional schedules exploiting these possibilities are generated whenever this could be beneficial. Further modifications were also made to include the same set of rules from Directive 2002/EC/15 as in Prescott-Gagnon et al. (2010). The approaches for Canadian and Australian regulations presented by Goel and Rousseau (2011) and Goel et al. (2012) were based on the assumption that all time values are a multiple of 15 minutes. We modified these approaches in such a way that arbitrary time values can be used. This is achieved by increasing the completion time of any partial schedule to a multiple of 15 minutes whenever a driver is released from duty. By this, all off-duty periods start and end at a multiple of 15 minutes, and the modified approaches can be used without further changes.

4.6. Addressing the challenge of computational efficiency

Hybrid genetic algorithms are known to rely on a large number of route evaluations, especially due to the local search-based *Education* and *Repair* procedures. One major algorithmic result is to show that, even in presence of computationally expensive route evaluations and scheduling procedures, an efficient overall hybrid genetic method can be developed. Essential components for this are adequate memory structures, neighborhood pruning, and schedule pruning procedures.

Memories. Since early research on VRP variants, it has been observed that the same customer sequences appear in many solutions generated throughout the solution process. Adequate data structures on partial routes can thus lead to notable computational savings (Savelsbergh 1985, 1992). To illustrate this, consider the evaluation of a 2-opt* neighborhood, which involves to replace two arcs (r_i, r_j) and $(r'_{i'}, r'_{j'})$ from two different routes r and r', by arcs $(r_i, r'_{j'})$ and $(r_{i'}, r'_j)$. As illustrated in Figure 4, the partial route $(r_1, \ldots, r_i)$ appears several times in the neighboring solutions. Hence, a large number of redundant computations are avoided by storing partial truck driver schedules associated to such subsequences.

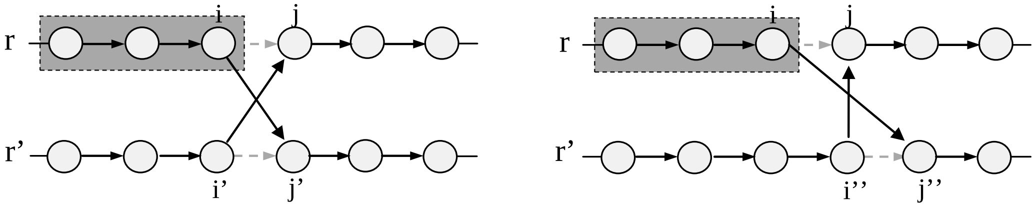


Figure 4 **Common subsequences through 2opt move evaluations**

Furthermore, memories for move and route evaluations are used to avoid redundant computations. During the local search, moves are sorted relatively to the nodes and the routes they impact. The evaluation $f(x, r, r')$ of any move x between routes r and r' is stored, along with a *chronological* information indicating *when*, for example at which iteration of the local search, this value has been calculated. Similarly, chronological information indicates for each route *when* this route has been last modified. A move is not evaluated if none of the routes it impacts has been modified since its last evaluation.

We observed that the *Education*, *Repair* and *Split* procedures, when applied to different individuals, are naturally bound to evaluate some identical routes. High-quality routes are particularly likely to appear in many individuals. To avoid redundant computations, we added a *long-term global memory* to store the results of the route evaluations. This memory is implemented as a hash-table. To limit memory usage, each route evaluation is stored along with a counter for frequency of appearance. Whenever 5 million route evaluations are stored, the half least frequently encountered route evaluations are discarded. This long-term memory led to an algorithm speed-up ranging from 2 to 10 relatively to the instances used.

Local search restrictions and search tree reductions. Local search moves have been restricted to pairs of related customers, which are spatially close, or require service in close periods of time (Vidal et al. 2011a). The resulting neighborhood size, once pruned, is $O(\Gamma n)$, where Γ is a method parameter representing the number of close customers to consider. Thanks to memory structures, each of the $O(\Gamma n)$ moves is evaluated at most once, and upon the application of a move, $O(2\Gamma \bar{n})$ moves must be recomputed, $\bar{n}$ representing the average number of customers in a route. The total number of route evaluations during a local search is thus $O(\Gamma n + \alpha^{\text{IMP}}(n)\Gamma \bar{n})$, where $\alpha^{\text{IMP}}(n)$ is the number of moves before reaching a local optimum.

Fast route evaluations are crucial for the overall running time of the HGSADC. As the search tree generated during route evaluations may grow very large for some of the regulations, various techniques for limiting its size have been applied. For Canadian and Australian regulations, Goel and Rousseau (2011) and Goel et al. (2012) presented heuristic forward labeling methods which only generate a small subset of all possible partial schedules, thus reducing the size of the search tree significantly. In the European Union, the possibility of reducing the duration of rest periods and extending the amount of driving time between rest periods results in a dramatic increase in the size of the search tree. To speed up route evaluations in this case, the size of the search tree has been reduced using a combination of two techniques. First, we use a heuristic dominance relationship which does not take into account the number of reduced rests and extended driving periods. Second, the number of different schedules in $\mathcal{S}_i$ at each iteration i of the truck driver scheduling method is limited to at most $\Gamma' = 5$. To do so, the set of non-dominated partial schedules $\mathcal{S}_i$ is ordered by completion time, and only the schedules at positions $1 + \lfloor (j-1)(|\mathcal{S}_i| - 1)/(\Gamma' - 1) \rfloor$ for all $1 \leq j \leq \Gamma'$ are kept.

All these elements lead to rapid *Split* and local search-based *Education* procedures for the VRTDSP, and thus enable to efficiently apply the HGSADC framework to this difficult problem.

5. Computational experiments

Extensive computational experiments have been conducted to evaluate the performance of the proposed algorithm, and to assess the impact of different hours of service regulations world wide. These experiments are based on the 56 benchmark instances for the VRTDSP proposed by Goel (2009), which are derived from the VRPTW benchmarks of Solomon (1987). The instances are grouped into six classes. In classes R1 and R2 customers are randomly distributed in a square region. In classes C1 and C2 customers are clustered, and in classes RC1 and RC2 the customer distribution is mixed. In all instances, 100 customers with a demand of at most 50 units must be served. In the R1, C1, and RC1 classes the capacity of each vehicle is 200 units, in the R2 and RC2 classes the capacity of each vehicle is 1000 units, and in the C2 class the capacity of each vehicle is 700 units. The average size of time windows per instance ranges from less than 7 hours to more than 107 hours. The service time at every customer is set to one hour. The planning horizon is 144 hours and the maximum required driving time (without compulsory breaks and rests) to go from one point in the square region to another is approximately one day.

To demonstrate the performance of the proposed method, the solutions obtained by HGSADC on these original instances were compared with the solutions of the best current methods. To assess the impact of different hours of service regulations world wide, we also derived a modified instance set to improve realism. As time window requirements of customers are usually tied to business hours and most customers cannot be visited in the night, we removed the time between 8.00 PM and 8.00 AM from time windows in the original VRTDSP instances. However, to maintain feasibility of the instances, the night time of time windows with a duration of 24 hours or less was not removed. Thus some customers have a single time window and others have multiple time windows tied to business hours. Any feasible solution of a modified instance is obviously feasible for its original counterpart.

For all experiments, the HGSADC parameters proposed by Vidal et al. (2011a) are used, with the exception of the population size parameters $\mu^{\text{MIN}} = 10$, $\mu^{\text{GEN}} = 5$, and the neighborhood pruning parameter $\Gamma = 10$, which are set to small values to quickly converge towards high quality solutions. The termination criterion is set to $\lambda^{\text{IT}} = 500$. The algorithm has been implemented in C++, and run on an Intel Xeon X7350 2.93 Ghz processor.

5.1. Comparison with best known solutions

The most advanced method for solving the VRTDSP known to the authors is the approach presented by Prescott-Gagnon et al. (2010) which combines column generation techniques with large neighbourhood search. This approach was tested on the instances presented by Goel (2009) for different subsets of rules applicable in the European Union. The authors used a hierarchical objective with the primary goal of minimizing the size of the vehicle fleet and the secondary goal of minimizing the total travel distance. We addressed this hierarchical objective by setting a constraint on the fleet size of 20 vehicles, and then iteratively decrementing the fleet size constraint whenever a feasible solution is found with HGSADC.

Tables 2 and 3 show the results for two subsets of rules in the European Union. The subset labeled *EU (All)* contains all the rules described in Section 2.3. The subset labeled *EU (No split)* contains all the rules except for those allowing to split breaks and rest periods and those allowing to reduce the duration of daily rest periods or to extend the accumulated amount of driving time between two rest periods. As in Prescott-Gagnon et al. (2010), five runs of HGSADC have been performed for each instance and each set of rules. The tables report for each method and each problem class the average and best solution values with respect to the hierarchical objective, i.e. the accumulated fleet size and the accumulated distance. The best solutions are indicated in boldface. The last lines report the accumulated fleet size and distance on all instances, the average computation time per instance, and the processor used. Detailed results per instance are reported in the Appendix.

Table 2 Method performance on Goel (2009) instances - EU (No split)

	Prescott-Gagnon et al. (2010)				HGSADC			
	Avg. Fleet	Avg. Dist.	Best Fleet	Best Dist.	Avg. Fleet	Avg. Dist.	Best Fleet	Best Dist.
R1	98.40	11855.28	98.00	11855.34	98.80	11769.13	**98.00**	**11835.89**
R2	64.40	10341.83	63.00	10262.50	62.60	10294.36	**62.00**	**10279.25**
C1	90.00	7628.71	**90.00**	**7628.47**	90.40	7630.25	90.00	7628.73
C2	39.40	5847.00	40.00	5792.67	40.00	5754.04	**40.00**	**5753.30**
RC1	72.00	8945.84	72.00	8903.44	72.00	8915.07	**72.00**	**8892.74**
RC2	52.50	8938.95	50.00	8976.28	50.00	8960.99	**50.00**	**8917.25**
All	416.70	53557.61	413.00	53418.70	413.80	53323.84	**412.00**	**53307.16**
	Avg. CPU: 11 min (OPT 2.3 Ghz)				Avg. CPU: 54 min (XE 2.83 Ghz)			

Table 3 Method performance on Goel (2009) instances - EU (All)

	Prescott-Gagnon et al. (2010)				HGSADC			
	Avg. Fleet	Avg. Dist.	Best Fleet	Best Dist.	Avg. Fleet	Avg. Dist.	Best Fleet	Best Dist.
R1	97.00	11710.92	97.00	11659.63	96.20	11800.47	**96.00**	**11806.72**
R2	62.40	10208.45	60.00	10273.19	59.80	10177.15	**59.00**	**10153.30**
C1	90.00	7628.56	90.00	7628.47	90.00	7444.86	**90.00**	**7444.86**
C2	37.00	5559.58	37.00	5519.58	36.00	5505.79	**36.00**	**5501.50**
RC1	72.00	8890.88	72.00	8858.12	72.00	8834.31	**72.00**	**8806.01**
RC2	49.20	8772.75	49.00	8726.37	49.00	8654.63	**49.00**	**8604.17**
All	407.60	52771.14	405.00	52665.36	403.00	52417.21	**402.00**	**52316.56**
	Avg. CPU: 88 min (OPT 2.3 Ghz)				Avg. CPU: 228 min (XE 2.83 Ghz)			

For both sets of rules, the proposed method produces solutions of higher quality than the approach of Prescott-Gagnon et al. (2010), which was designed specifically for European Union regulations. For the *EU (No split)* set of rules, HGSADC produces new best known solutions for 29 of the 56 instances and obtains equally good solutions for 22 of the instances. For the *EU (All)* set of rules, HGSADC produces new best known solutions for 43 of the 56 instances and obtains equally good solutions for nine of the instances. For these rules, the average solution quality is better than the best solution quality found by Prescott-Gagnon et al. (2010).

Computation times are higher than those of Prescott-Gagnon et al. (2010), but still of the same order of magnitude. As our main goal is to assess the impact of hours of service regulations world wide, a special emphasis has been put on the quality of the scheduling methods. Smaller CPU times could thus be achieved by using faster heuristic scheduling procedures within route evaluations.

A Wilcoxon test on the 112 average solution pairs from HGSADC and Prescott-Gagnon et al. (2010) confirms with high confidence ($p < 0.0001$) the statistical significance of the solution quality improvements. In average, on the subset of 106/112 instances for which the minimum fleet size was obtained on all five runs, the standard deviation on distance measures is +0.21%, thus illustrating the good reliability of the method.

5.2. An international comparison of hours of service regulations

To assess the impact of different hours of service regulations world wide, we conducted experiments for the different regulations described in Section 2 on the modified Goel (2009) instances obtained by removing the night time from long time windows. As most fleet operators have a fixed fleet size which cannot be increased or reduced on a weekly basis, the minimization of distance has been selected as the primary objective in the experiments described in this section. For each instance, we associated a fleet size limit which is a few vehicles larger than the minimum feasible value obtained in preliminary experiments. The fleet size limit for each of the instances is reported in Tables 8 to 10 in the Appendix.

Table 4 reports for each class of instances and each type of regulation the best solution found in five runs of our algorithm. The last lines indicate respectively the cumulated distance (CTD) on all instances, the percentage of increase in total distance in comparison to the case in which no hours of service regulations are considered (Inc %), the cumulated number of vehicles (CNV), and the computation time (CPU) averaged on all instances and runs.

The column titled *US (current)* reports the results obtained using the exact truck driver scheduling method presented by Goel and Kok (2011) for current hours of service regulations in the United States with a limit of 60 hours of on-duty time within 7 days. The column titled *US (2013)* reports the results obtained using the exact truck driver scheduling presented by Goel (2012b) for the new regulations in the United States, becoming effective in July 2013. Due to the complexity of Canadian regulations, using an exact approach for truck driver scheduling results in prohibitively slow running times. Therefore, the heuristic truck driver scheduling procedure *CAN2* introduced in Goel and Rousseau (2011) was used. The columns titled *EU (No split)*, *EU (Split)*, and *EU (All)* report the results obtained for European Union regulations. For *EU (No split)* and *EU (All)* the same scheduling methods as in Section 5.1 are used. For *EU (Split)* the exact truck driver scheduling method presented by Goel (2010) is used which considers all rules except for those allowing to reduce the duration of daily rest periods and to extend the amount of driving time between rest periods. The columns titled *AUS (Std.)* and *AUS (BFM)* report the results obtained for the standard option and the BFM option of Australian regulations. For both options, the heuristic truck driver scheduling procedure *AUS1* introduced in Goel et al. (2012) is used. Finally, the column titled with *None* reports the results obtained by our approach without considering hours of service regulations. All algorithms were modified as described in Section 4.5.

It must be noted that the approach for Australian regulations does not consider the 36 hour limit on long/night work of the BFM option. Although the limit could theoretically have an impact for the benchmark instances considered in this paper, we observed that for all solutions obtained in our experiment a feasible schedule with respect to all rules is found.

Table 4 Best solutions found for modified Goel (2009) instances

	US		CAN	EU			AUS		None
	(current)	(2013)		(No split)	(Split)	(All)	(Std.)	(BFM)	
R1	11666.19	11690.82	11688.77	11817.42	11764.29	11748.14	11819.65	11752.88	11620.10
R2	10078.91	10123.65	10074.01	10276.13	10232.13	10181.37	10261.73	10180.27	10002.36
C1	7447.15	7447.15	7447.14	7637.43	7636.20	7451.15	7625.02	7447.15	7447.15
C2	5427.60	5655.66	5124.82	5857.09	5677.43	5533.44	5466.39	5153.82	4730.51
RC1	8856.83	8863.28	8868.42	8945.68	8922.60	8892.30	8921.56	8890.82	8821.35
RC2	8540.56	8653.45	8552.40	8916.51	8827.14	8710.67	8878.58	8634.84	8325.21
CTD	52017.23	52434.00	51755.55	53450.26	53059.78	52517.07	52972.93	52059.78	50946.68
Inc %	+2.1%	+2.9%	+1.6%	+4.9%	+4.2%	+3.1%	+4.0%	+2.2%	+0.0%
CNV	432	437	430	452	447	440	444	432	411
CPU	11 min	21 min	64 min	23 min	180 min	228 min	26 min	19 min	7 min

With a value of 1.6%, the smallest increase in total distance compared to the case without hours of service regulations is obtained for Canadian hours of service regulations. Current U.S. hours of service regulations result in an increase of 2.1%, which becomes 2.9% when the 2013 rule change is enforced. In the European Union a similar increase of 3.1% is obtained when exploiting all rules of the regulations. The regulations give a strong incentive of exploiting the possibilities of reducing the duration of rest periods to 9 hours and extending the driving time between rest periods to 10 hours. Without these optional rules, the total distance increases by 4.2% if the possibility of taking break and rest periods in two parts is exploited and by 4.9% otherwise. One might think that the intention of European lawmakers was to give motor carriers the possibility of reacting on unforeseeable traffic conditions by allowing to reduce the duration of rest period and to extend the driving time between rest periods on some days of the week. However, if this was the case, these optional rules are unlikely to fulfill this purpose as economic pressure can force motor carriers to exploit these options on a regular basis and not only in the case of unexpected delays. Australian motor carriers without accreditation have with 4.0% the highest increase in total distance. As travel distances only increase by 2.2% when using the BFM option, there is a strong incentive for Australian motor carriers to be accredited for the BFM option.

To further analyze the impact of hours of service regulations, we determined for each of the routes of the best solutions a schedule with minimal duration using the iterative dynamic programming approach of Goel (2012a). Table 5 reports for each set of solutions the cumulated schedule duration (CSD), the average percentage of on-duty time with respect to the schedule duration (OD), and the average amount of on-duty time between two long rest periods (OBR). Time values are reported in hours and minutes (hh:mm).

Table 5 Schedule characteristics

		US		**CAN**	**EU**			**AUS**		**None**
		(current)	**(2013)**		**(No split)**	**(Split)**	**(All)**	**(Std.)**	**(BFM)**	
R1	CSD	7701:17	7781:22	7614:30	8493:44	8226:12	7897:22	8791:03	8203:23	6976:20
	OD	45.72%	45.31%	46.30%	41.81%	43.04%	44.79%	40.40%	43.13%	50.34%
	OBR	9:01	8:56	9:04	7:56	8:20	8:46	7:47	8:19	
R2	CSD	6676:13	6866:41	6654:21	7487:26	7296:31	7051:50	7652:05	7482:32	6423:20
	OD	46.50%	45.34%	46.64%	41.99%	42.97%	44.31%	41.05%	41.76%	48.10%
	OBR	9:23	8:59	9:27	8:29	8:33	9:05	8:01	8:09	
C1	CSD	7110:20	7152:27	6973:48	7572:27	7476:26	7308:34	7404:59	7237:57	7054:48
	OD	33.55%	33.35%	34.21%	32.01%	32.41%	32.65%	32.70%	32.96%	33.82%
	OBR	6:42	6:33	6:57	6:11	6:14	6:26	5:17	5:22	
C2	CSD	4025:31	4645:37	3564:01	4945:59	4875:29	4508:54	4631:22	3814:39	2951:55
	OD	46.71%	41.45%	51.06%	39.75%	39.59%	42.17%	40.77%	47.86%	58.98%
	OBR	10:37	9:31	11:10	8:32	9:03	9:32	9:05	10:31	
RC1	CSD	5022:03	5201:13	5052:00	5784:08	5673:59	5204:16	5816:18	5391:15	4607:28
	OD	51.09%	49.36%	50.84%	44.67%	45.45%	49.44%	44.34%	47.72%	55.54%
	OBR	9:42	9:27	9:25	8:17	8:21	9:08	8:03	8:48	
RC2	CSD	5386:09	5535:45	5347:53	6075:56	5952:10	5541:58	6058:10	5639:57	4753:37
	OD	46.47%	45.62%	46.85%	42.43%	43.01%	45.77%	42.43%	44.71%	51.74%
	OBR	9:36	9:26	9:28	8:34	8:41	9:19	8:34	8:56	
All	CSD	5986:56	6197:11	5867:46	6726:37	6583:28	6252:09	6725:39	6294:57	5461:15
	OD	45.01%	43.41%	45.98%	40.44%	41.08%	43.19%	40.28%	43.02%	49.75%
	OBR	9:10	8:48	9:15	7:60	8:12	8:43	7:48	8:21	

As illustrated in Table 5, schedule characteristics appear to be consistent with the properties of the regulations. The impact of hours of service regulations on the total schedule duration, average on-duty ratio, and duty time between rests periods is evidenced. Exploiting the optional rules in the European Union leads to reduced schedule durations and to increased on-duty ratios and on-duty time between rests. Similar observations can be made when comparing AUS (Std.) with AUS (BFM) regulations, and US (2013) with US (current). Overall, the highest on-duty ratio (45.98%) is achieved for Canadian regulations followed by the current regulations in the United

States (45.01%). On-duty ratios for the new regulations in the United States (43.41%), European Union regulations (43.19%) and the rules of the BFM option in Australia (43.02%) are comparable.

It is also worth noting that hours of service regulations do not have a high impact on distances for the C1 class. Analyzing the schedules, we observe that only one third of the time spent by the drivers in the solutions for the C1 class is on-duty time. Consequently, there is plenty of time available that potentially can be used for taking breaks and rest periods. For the C2 class, on the other hand, we obtain a high on-duty ratio of 58.98% and an average amount of on-duty time per vehicle above 72 hours when not considering hours of service constraints. As the average amount of on-duty time exceeds the weekly limits of the regulations and as less time can be used for taking breaks and rest periods, the impact of hours of service regulations is the highest for the C2 class.

Although the fleet size is not considered in the objective function, fleet sizes differ in the solutions as a result of minimizing the total distance. The largest increase in fleet size compared to the case without regulations is obtained for the instances in the C2 class. For most other instances and most of the regulations, at most one additional vehicle is required. Again, CAN, US (current), and AUS (BFM) regulations lead to the smallest fleet sizes.

To evaluate the impact of hours of service regulations on road safety we used the fatigue and risk index calculator available from Health and Safety Executive (2006). This calculator can be used to estimate the average risk of the occurrence of an accident given a specific work schedule and is described in Spencer et al. (2006). The risk indices are calculated from separate components considering the amount of sleep loss that is likely to accumulate throughout the course of a work schedule, the effect of start time and length of the individual daily shifts, and the break patterns within these shifts. When using the calculator to assess the risk associated to the solutions obtained by our method, we interpreted any off-duty period of at least 7 hours duration as the end of a daily shift and specified the required input accordingly. Table 6 shows the average risk indices obtained for the different hours of service regulations. The indices represent the estimated relative accident risk and an index of two represents a twice as high average accident risk as an index of one. We normalized the risk indices with respect to the average risk associated to the *EU (No split)* rule set.

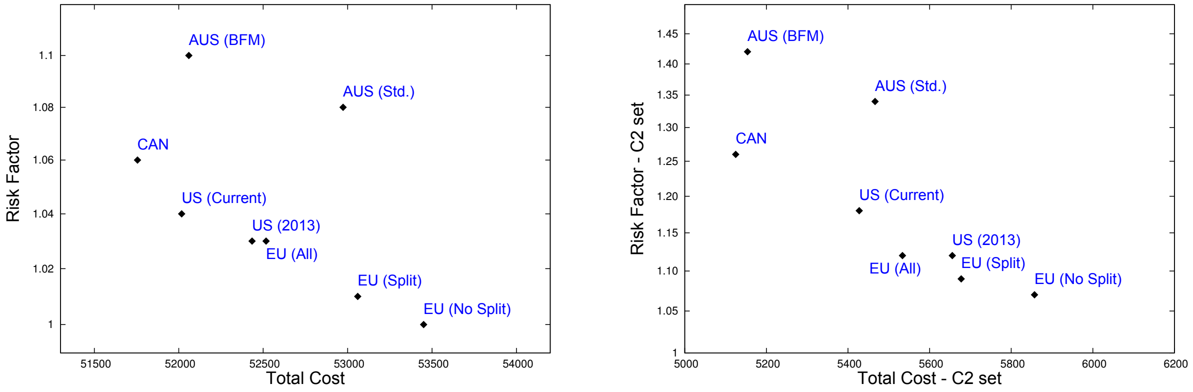
For European Union rules we observe that the possibility of taking breaks and rest periods in two parts and the respective reduction in the minimum duration of rest periods has only little impact on the average risk. When exploiting all optional rules in the European Union, the risk is 3% higher compared to the basic set of rules. Looking at the individual risk components it appears that this increase in risk is mainly related to an increased duration of daily shifts. In the United States, the additional break requirement that will be enforced in 2013 will reduce the risk by approximatley 1%, reaching a value comparable to the risk in the European Union when all optional rules are

Table 6 Average risk indices

	US		CAN	EU			AUS	
	(current)	(2013)		(No split)	(Split)	(All)	(Std.)	(BFM)
R1	1.03	1.04	1.07	0.99	0.99	1.03	1.11	1.14
R2	1.08	1.05	1.11	1.02	1.02	1.04	1.11	1.13
C1	0.93	0.92	0.88	0.92	0.95	0.94	0.85	0.86
C2	1.18	1.12	1.26	1.07	1.09	1.12	1.34	1.42
RC1	1.06	1.05	1.08	1.00	1.00	1.04	1.10	1.15
RC2	1.08	1.07	1.11	1.03	1.04	1.08	1.16	1.21
All	1.04	1.03	1.06	1.00	1.01	1.03	1.08	1.10

exploited. The risk associated to Canadian regulations is notably higher compared to regulations in the United States and the European Union. The standard and the BFM rules of Australian regulations have the largest risk indices. It appears that due to the short minimum rest duration of seven hours in Australia and eight hours in Canada, the risk resulting from likely accumulated sleep loss throughout the course of a work schedule is the largest contributor to this increase in risk.

Figure 5 Costs vs. risks



As for the economic impact analyzed earlier, the largest variation in risk indices is observed for the C2 set. For this set the BFM rules in Australia result in a risk index of 1.42 which is 33% higher than the minimum average risk index for this set. Furthermore, the 2013 rule change in the United States leads to a risk reduction of 5% for this set. Figure 5 illustrates the tradeoff between total costs and average risks associated to the different rules. The graph on the left illustrates the respective values for all of the instances whereas the graph on the right illustrates the values for the instances of set C2. We can see that except for Australian regulations, there is no clear dominance of one set of rules over another. The rules resulting in small operating costs are associated with a higher risk index and rules associated with a small risk index have higher operating costs. Australian rules, however, appear to result in unnecessarily high risk levels in relation to the economic impact of these regulations. Apparently, the break requirements of Australian regulations are not sufficient to compensate the negative impact of short rest periods on associated risk values.

6. Conclusions

In this paper we proposed a hybrid genetic search with advanced diversity control (HGSADC) for solving the combined vehicle routing and truck driver scheduling problem. By combining the exploration capacities of population-based approaches, the quick improvement abilities of local search, along with efficient procedures for checking compliance with hours of service regulations, the proposed approach outperforms all current methods designed for this difficult family of problems. Our approach is the first which is not specifically designed for a particular set of rules and can be a valuable tool for transport operators world wide.

We conducted extensive experiments to assess the impact of hours of service regulations in the United States, Canada, the European Union, and Australia. The results indicate that Australian regulations have unnecessarily high risk levels with respect to the resulting operating costs. For the other regulations, average accident risk rates appear to be negatively correlated to operating costs. European Union rules lead to the highest safety, while in terms of economic efficiency Canadian regulations are the most competitive. The recent rule change in the United States will bring a reduction in accident risks. The largest decrease in the associated accident risk of the new rules can be observed for the set of instances in which the previous rules had the largest associated risk indices.

Our optimization-based approach can be used to realistically assess the impact of hours of service regulations from a carrier-centric point of view. The decision whether the economic impact of hours of service regulations is justified by improved road safety is a question that has to be discussed and answered by society, policy makers, transport operators, and truck drivers. Our optimization-based approach to analyze the impact of hours of service regulations can be an important building block in such a discussion.

Where transport operators can choose among alternative rule sets our approach can bring important insight concerning the best choice of rules to operate under. Our experiments indicate that accreditation for the BFM option can bring significant advantages for transport operators in Australia. Furthermore, we observed that there are strong economic incentives for European operators to exploit all optional rules of the regulations, in particular, reducing the duration of rest periods and extending driving times.

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Appendix

Table 7 presents detailed results of our experiments conducted on the Goel (2009) instances. The table shows the average fleet size and distance as well as the best fleet size and distance obtained from the five HGSADC runs. Tables 8, 9, and 10 present detailed results of our experiments on the modified instances with multiple time windows. The tables report the average distance and fleet size as well as the best distance and fleet size obtained from the five HGSADC runs, for regulations in North America, Europe, and Australia, as well as the results obtained without hours of service constraints.

Table 7 Detailed results for Goel (2009) instances and European Union regulations

	EU (No split)				**EU (All)**			
Instance	Avg Fleet	Avg Dist.	Best Fleet	Best Dist.	Avg Fleet	Avg Dist.	Best Fleet	Best Dist.
R101	10.00	1332.93	10.00	1326.78	8.20	1452.47	8.00	1482.44
R102	8.80	1196.98	8.00	1283.86	8.00	1187.97	8.00	1176.58
R103	8.00	979.00	8.00	977.25	8.00	966.62	8.00	965.92
R104	8.00	859.96	8.00	859.27	8.00	853.26	8.00	852.99
R105	8.00	1114.32	8.00	1109.96	8.00	1095.53	8.00	1093.63
R106	8.00	1018.79	8.00	1017.71	8.00	999.53	8.00	997.83
R107	8.00	900.93	8.00	900.93	8.00	900.99	8.00	898.05
R108	8.00	839.30	8.00	838.54	8.00	839.63	8.00	837.99
R109	8.00	930.03	8.00	928.43	8.00	923.12	8.00	922.40
R110	8.00	885.03	8.00	881.30	8.00	876.75	8.00	875.80
R111	8.00	880.54	8.00	880.54	8.00	874.84	8.00	873.93
R112	8.00	831.31	8.00	831.31	8.00	829.75	8.00	829.14
R201	7.00	1261.50	7.00	1256.06	7.00	1210.10	7.00	1205.42
R202	6.00	1120.13	6.00	1116.22	6.00	1091.54	6.00	1087.36
R203	6.00	921.35	6.00	918.82	5.00	926.25	5.00	921.72
R204	5.00	776.27	5.00	774.96	5.00	771.22	5.00	770.21
R205	6.00	1018.80	6.00	1011.29	6.00	1000.76	6.00	997.44
R206	5.60	945.67	5.00	958.59	5.20	942.83	5.00	943.83
R207	5.00	857.69	5.00	854.01	5.00	835.75	5.00	830.96
R208	5.00	745.52	5.00	745.15	5.00	742.61	5.00	742.61
R209	6.00	905.89	6.00	904.21	5.00	926.08	5.00	910.70
R210	6.00	943.64	6.00	943.64	5.60	946.54	5.00	959.58
R211	5.00	797.92	5.00	796.30	5.00	783.46	5.00	783.46
C101	10.40	928.70	10.00	931.37	10.00	828.94	10.00	828.94
C102	10.00	908.70	10.00	904.52	10.00	828.94	10.00	828.94
C103	10.00	833.19	10.00	833.19	10.00	827.34	10.00	827.34
C104	10.00	819.81	10.00	819.81	10.00	819.81	10.00	819.81
C105	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94
C106	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94
C107	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94
C108	10.00	827.38	10.00	827.38	10.00	827.38	10.00	827.38
C109	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65
C201	6.00	853.12	6.00	852.94	5.00	802.65	5.00	800.18
C202	5.00	811.71	5.00	811.15	5.00	692.66	5.00	692.66
C203	5.00	695.54	5.00	695.54	4.00	660.07	4.00	660.07
C204	4.00	661.57	4.00	661.57	4.00	651.91	4.00	650.28
C205	5.00	683.75	5.00	683.75	5.00	678.33	5.00	678.33
C206	5.00	680.78	5.00	680.78	4.00	675.27	4.00	675.27
C207	5.00	693.97	5.00	693.97	5.00	672.42	5.00	672.42
C208	5.00	673.61	5.00	673.61	4.00	672.49	4.00	672.30
RC101	9.00	1314.22	9.00	1305.09	9.00	1296.37	9.00	1286.03
RC102	9.00	1185.39	9.00	1180.34	9.00	1172.32	9.00	1159.33
RC103	9.00	1081.36	9.00	1080.40	9.00	1076.59	9.00	1075.81
RC104	9.00	993.19	9.00	993.19	9.00	993.13	9.00	993.13
RC105	9.00	1228.41	9.00	1227.14	9.00	1205.77	9.00	1203.02
RC106	9.00	1097.79	9.00	1093.62	9.00	1092.98	9.00	1092.80
RC107	9.00	1027.98	9.00	1027.89	9.00	1017.46	9.00	1016.96
RC108	9.00	986.73	9.00	985.05	9.00	979.69	9.00	978.93
RC201	8.00	1385.00	8.00	1384.01	7.00	1375.75	7.00	1344.99
RC202	7.00	1193.72	7.00	1193.12	7.00	1162.65	7.00	1162.28
RC203	6.00	1040.33	6.00	1036.96	6.00	1015.51	6.00	1012.13
RC204	5.00	878.88	5.00	877.17	5.00	860.81	5.00	860.17
RC205	7.00	1328.51	7.00	1313.71	7.00	1230.56	7.00	1228.09
RC206	6.00	1168.93	6.00	1160.40	6.00	1128.02	6.00	1124.17
RC207	6.00	1087.30	6.00	1079.01	6.00	1046.74	6.00	1038.04
RC208	5.00	878.32	5.00	872.87	5.00	834.60	5.00	834.30
All	413.80	53323.83	412.00	53307.16	403.00	52417.21	402.00	52316.57

Table 8 Detailed results for modified Goel (2009) instances and U.S. and Canadian regulations

Instance & Fleet size		**US (current)**				**US (2013)**				**CAN**			
		Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet
R101	12	1286.39	11.00	1285.50	11.00	1288.27	11.00	1285.50	11.00	1288.38	10.80	1287.09	11.00
R102	10	1163.08	9.20	1160.90	9.00	1168.72	9.20	1166.59	9.00	1171.53	10.00	1169.13	10.00
R103	10	985.53	9.00	985.34	9.00	985.34	9.00	985.34	9.00	986.16	9.00	984.43	9.00
R104	10	855.38	8.00	855.13	8.00	855.74	8.00	855.13	8.00	855.72	8.00	855.13	8.00
R105	10	1069.05	9.00	1068.77	9.00	1073.37	9.00	1071.85	9.00	1075.34	9.00	1073.83	9.00
R106	10	998.42	8.00	994.03	8.00	998.00	8.20	994.48	8.00	1006.43	8.20	1000.98	8.00
R107	10	904.27	8.00	900.90	8.00	905.73	8.00	901.72	8.00	905.94	8.00	902.03	8.00
R108	10	838.30	8.00	837.99	8.00	838.14	8.00	837.99	8.00	841.65	8.00	839.87	8.00
R109	10	973.74	9.00	967.95	9.00	975.91	9.00	969.65	9.00	970.86	9.00	962.40	9.00
R110	10	887.15	8.00	886.63	8.00	899.52	8.00	896.72	8.00	890.15	8.00	890.05	8.00
R111	10	895.70	8.00	893.07	8.00	896.17	8.00	893.68	8.00	894.73	8.40	893.86	8.00
R112	10	831.65	8.00	829.98	8.00	833.39	8.00	832.15	8.00	830.08	8.00	829.98	8.00
R201	9	1171.68	9.00	1171.68	9.00	1171.68	9.00	1171.68	9.00	1170.93	9.00	1168.57	9.00
R202	8	1063.43	8.00	1063.34	8.00	1065.31	8.00	1064.50	8.00	1053.40	8.00	1048.86	8.00
R203	7	898.56	6.40	895.14	6.00	915.60	7.00	910.07	7.00	908.88	6.60	899.85	6.00
R204	7	763.59	6.00	762.73	6.00	769.69	6.20	766.78	6.00	762.97	6.00	762.73	6.00
R205	7	1020.70	7.00	1018.51	7.00	1027.42	7.00	1021.96	7.00	1020.57	7.00	1017.57	7.00
R206	7	937.24	6.00	935.21	6.00	944.06	6.80	942.37	6.00	937.28	6.00	935.84	6.00
R207	7	840.54	6.00	834.44	6.00	841.99	6.00	840.37	6.00	842.50	6.00	840.37	6.00
R208	7	747.44	5.20	742.64	5.00	746.48	5.00	746.24	5.00	744.38	5.00	742.43	5.00
R209	7	918.23	6.20	916.33	6.00	920.37	6.40	918.15	6.00	918.06	6.00	917.88	6.00
R210	7	937.93	7.00	937.63	7.00	941.07	7.00	940.99	7.00	940.19	7.00	938.65	7.00
R211	7	803.77	6.00	801.26	6.00	801.65	5.80	800.54	5.00	802.30	6.00	801.26	6.00
C101	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C102	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C103	12	828.06	10.00	828.06	10.00	828.06	10.00	828.06	10.00	828.07	10.00	828.07	10.00
C104	12	819.81	10.00	819.81	10.00	819.81	10.00	819.81	10.00	819.81	10.00	819.81	10.00
C105	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C106	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C107	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C108	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C109	12	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00
C201	8	826.42	6.00	826.42	6.00	828.93	6.00	828.93	6.00	651.83	4.00	651.83	4.00
C202	7	755.92	5.00	753.59	5.00	769.14	5.60	761.88	5.00	647.41	4.00	647.41	4.00
C203	6	658.00	4.00	658.00	4.00	688.91	5.00	688.74	5.00	636.92	4.00	636.92	4.00
C204	6	638.00	4.00	638.00	4.00	680.35	4.80	666.74	4.00	634.17	4.00	634.17	4.00
C205	6	638.57	4.00	638.57	4.00	677.44	5.00	677.44	5.00	638.57	4.00	638.57	4.00
C206	6	637.33	4.00	637.33	4.00	676.72	5.00	676.25	5.00	638.57	4.00	638.57	4.00
C207	6	638.36	4.00	638.36	4.00	679.94	5.00	679.82	5.00	638.79	4.00	638.79	4.00
C208	6	637.70	4.00	637.33	4.00	676.35	5.00	675.85	5.00	638.57	4.00	638.57	4.00
RC101	11	1264.32	10.00	1260.57	10.00	1263.74	10.00	1263.21	10.00	1260.10	10.00	1259.30	10.00
RC102	11	1163.56	10.20	1157.66	10.00	1160.93	10.40	1157.66	10.00	1160.54	10.20	1157.67	10.00
RC103	11	1085.87	9.20	1080.70	9.00	1082.65	9.00	1080.70	9.00	1086.07	9.00	1082.67	9.00
RC104	11	993.13	9.00	993.13	9.00	993.13	9.00	993.13	9.00	993.13	9.00	993.13	9.00
RC105	11	1199.93	10.00	1197.25	10.00	1200.60	10.00	1200.60	10.00	1204.41	10.20	1201.23	10.00
RC106	11	1137.82	9.60	1132.84	9.00	1138.56	9.40	1132.84	9.00	1136.29	9.00	1134.90	9.00
RC107	11	1055.24	9.40	1045.69	9.00	1049.56	9.00	1045.69	9.00	1051.91	9.00	1049.76	9.00
RC108	11	989.86	9.00	988.98	9.00	990.41	9.00	989.44	9.00	989.77	9.00	989.77	9.00
RC201	9	1297.39	9.00	1296.88	9.00	1308.87	9.00	1308.37	9.00	1300.02	9.00	1299.09	9.00
RC202	8	1127.71	8.00	1127.68	8.00	1142.08	8.00	1142.08	8.00	1142.08	8.00	1142.08	8.00
RC203	7	999.28	7.00	998.46	7.00	1018.33	7.00	1017.34	7.00	995.68	7.00	995.68	7.00
RC204	7	846.89	6.00	846.09	6.00	857.26	6.00	856.46	6.00	848.74	6.00	847.73	6.00
RC205	7	1246.51	7.00	1239.91	7.00	1268.97	7.00	1268.16	7.00	1233.31	7.00	1231.23	7.00
RC206	7	1137.40	7.00	1133.52	7.00	1145.78	7.00	1144.94	7.00	1126.45	7.00	1126.45	7.00
RC207	7	1054.76	7.00	1048.07	7.00	1062.02	7.00	1054.39	7.00	1064.60	7.00	1062.27	7.00
RC208	7	849.94	6.00	849.94	6.00	862.39	6.00	861.70	6.00	849.11	6.00	847.87	6.00
All	508	52118.84	434.40	52017.23	432.00	52533.82	441.80	52434.00	437.20	51832.56	431.40	51755.55	430.00

Table 9 Detailed results for modified Goel (2009) instances and European Union regulations

Instance &		**EU (No split)**				**EU (Split)**				**EU (All)**			
Fleet size		Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet
R101	12	1300.78	12.00	1299.62	12.00	1294.23	11.00	1293.92	11.00	1290.68	11.00	1290.06	11.00
R102	10	1181.60	10.00	1173.01	10.00	1175.05	9.40	1172.56	9.00	1174.94	9.80	1173.56	9.00
R103	10	1006.61	10.00	1006.61	10.00	998.69	10.00	998.69	10.00	998.54	9.00	997.34	9.00
R104	10	864.61	9.00	864.61	9.00	863.23	8.00	862.92	8.00	860.87	8.00	860.54	8.00
R105	10	1093.31	9.00	1092.52	9.00	1084.13	10.00	1082.55	10.00	1084.64	9.20	1081.70	9.00
R106	10	1025.89	9.00	1021.10	9.00	1006.51	8.20	1001.86	8.00	1003.50	8.00	1001.57	8.00
R107	10	910.36	8.00	906.60	8.00	908.16	8.00	903.18	8.00	909.28	8.00	902.32	8.00
R108	10	843.51	8.00	838.54	8.00	838.35	8.00	837.99	8.00	837.99	8.00	837.99	8.00
R109	10	985.75	9.00	983.05	9.00	981.81	9.00	981.81	9.00	979.87	9.00	977.56	9.00
R110	10	908.49	8.00	901.45	8.00	908.28	8.00	901.45	8.00	906.75	8.00	901.09	8.00
R111	10	900.68	8.20	898.17	8.00	897.32	8.00	895.20	8.00	894.80	8.00	892.25	8.00
R112	10	833.98	8.00	832.16	8.00	833.44	8.00	832.16	8.00	834.54	8.00	832.16	8.00
R201	9	1189.68	9.00	1189.07	9.00	1188.18	9.00	1185.36	9.00	1181.30	9.00	1181.30	9.00
R202	8	1083.18	8.00	1082.86	8.00	1080.53	8.00	1080.42	8.00	1075.02	8.00	1069.76	8.00
R203	7	942.22	7.00	940.03	7.00	938.28	7.00	936.64	7.00	922.40	7.00	918.59	7.00
R204	7	777.94	6.20	775.16	6.00	775.27	6.20	770.59	6.00	770.24	6.00	768.57	6.00
R205	7	1054.68	7.00	1048.32	7.00	1037.79	7.00	1036.49	7.00	1036.90	7.00	1036.32	7.00
R206	7	951.25	7.00	948.79	7.00	946.68	7.00	945.08	7.00	944.67	6.80	942.81	7.00
R207	7	854.76	7.00	854.65	7.00	854.27	6.80	853.26	6.00	850.32	6.60	846.06	6.00
R208	7	753.56	6.00	750.96	6.00	754.67	6.00	750.96	6.00	753.26	5.00	750.33	5.00
R209	7	924.54	7.00	924.49	7.00	923.16	7.00	922.83	7.00	922.96	7.00	922.81	7.00
R210	7	950.49	7.00	947.88	7.00	947.79	7.00	946.13	7.00	943.60	7.00	943.05	7.00
R211	7	817.28	6.00	813.93	6.00	805.89	6.00	804.37	6.00	801.78	6.00	801.78	6.00
C101	12	920.37	11.00	920.37	11.00	920.41	11.00	920.37	11.00	828.94	10.00	828.94	10.00
C102	12	909.81	10.00	905.48	10.00	906.02	10.00	904.25	10.00	828.94	10.00	828.94	10.00
C103	12	834.75	10.00	834.75	10.00	834.75	10.00	834.75	10.00	828.06	10.00	828.06	10.00
C104	12	829.58	10.00	829.58	10.00	829.58	10.00	829.58	10.00	823.81	10.00	823.81	10.00
C105	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C106	12	834.79	10.00	834.79	10.00	834.79	10.00	834.79	10.00	828.94	10.00	828.94	10.00
C107	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C108	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C109	12	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00
C201	8	852.94	6.00	852.94	6.00	756.52	6.00	756.52	6.00	745.37	6.00	745.37	6.00
C202	7	798.37	6.00	798.37	6.00	758.38	6.00	758.38	6.00	734.37	5.60	731.09	5.00
C203	6	741.78	5.00	738.79	5.00	717.07	5.00	717.07	5.00	672.85	4.00	672.31	4.00
C204	6	716.48	5.00	711.43	5.00	702.01	5.00	701.08	5.00	680.38	4.60	672.66	4.00
C205	6	683.70	5.00	683.70	5.00	683.70	5.00	683.70	5.00	675.85	5.00	675.85	5.00
C206	6	694.90	5.00	694.10	5.00	691.43	5.00	691.43	5.00	680.42	5.00	680.03	5.00
C207	6	694.42	5.00	694.42	5.00	687.36	5.00	685.90	5.00	680.28	5.00	680.28	5.00
C208	6	683.65	5.00	683.34	5.00	683.55	5.00	683.34	5.00	675.85	5.00	675.85	5.00
RC101	11	1272.29	10.60	1268.97	11.00	1266.67	10.20	1266.32	10.00	1267.32	10.40	1264.96	10.00
RC102	11	1177.54	10.80	1175.75	10.00	1176.32	10.20	1175.37	10.00	1165.47	10.20	1162.65	10.00
RC103	11	1090.28	9.00	1088.59	9.00	1088.83	9.20	1085.73	9.00	1086.83	9.00	1083.62	9.00
RC104	11	993.30	9.00	993.30	9.00	993.30	9.00	993.30	9.00	994.08	9.00	994.08	9.00
RC105	11	1223.34	11.00	1223.34	11.00	1217.54	11.00	1213.76	11.00	1210.48	11.00	1208.42	11.00
RC106	11	1158.17	9.80	1147.20	9.00	1150.45	9.60	1139.92	9.00	1145.33	9.60	1137.08	9.00
RC107	11	1060.94	9.60	1058.07	9.00	1060.87	9.40	1057.72	9.00	1052.05	9.00	1052.05	9.00
RC108	11	990.94	9.00	990.47	9.00	991.09	9.00	990.47	9.00	990.16	9.00	989.44	9.00
RC201	9	1341.41	9.00	1340.63	9.00	1336.93	9.00	1336.93	9.00	1321.58	9.00	1320.71	9.00
RC202	8	1182.32	8.00	1179.05	8.00	1165.93	8.00	1164.41	8.00	1154.67	8.00	1152.92	8.00
RC203	7	1042.01	7.00	1041.49	7.00	1027.60	7.00	1027.13	7.00	1022.19	7.00	1017.34	7.00
RC204	7	869.17	6.00	869.17	6.00	867.32	6.00	867.23	6.00	857.45	6.00	857.45	6.00
RC205	7	1371.62	7.00	1371.62	7.00	1332.10	7.00	1328.00	7.00	1274.00	7.00	1273.66	7.00
RC206	7	1163.19	7.00	1162.27	7.00	1159.25	7.00	1154.98	7.00	1149.34	7.00	1148.95	7.00
RC207	7	1090.68	7.00	1074.65	7.00	1082.71	7.00	1072.58	7.00	1074.38	7.00	1068.64	7.00
RC208	7	882.27	6.40	877.63	6.00	876.95	6.20	875.89	6.00	873.36	6.00	870.99	6.00
All	508	53572.62	454.60	53450.26	452.00	53153.59	450.40	53059.78	447.00	52614.07	443.80	52517.07	440.00

Table 10 **Detailed results for modified Goel (2009) instances and Australian regulations and without regulations**

Instance & Fleet size		**AUS (Std.)**				**AUS (BFM)**				**None**			
		Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet	Avg Dist.	Avg Fleet	Best Dist.	Best Fleet
R101	12	1297.58	12.00	1297.56	12.00	1288.55	11.00	1288.55	11.00	1282.59	10.40	1278.95	10.00
R102	10	1178.81	10.00	1176.51	10.00	1175.12	10.00	1174.74	10.00	1160.75	9.40	1156.73	9.00
R103	10	1002.15	9.60	1000.08	9.00	1000.56	9.00	1000.43	9.00	981.99	8.20	981.51	9.00
R104	10	865.46	8.40	864.44	8.00	861.23	8.20	859.19	8.00	855.15	8.00	855.13	8.00
R105	10	1097.66	10.00	1097.12	10.00	1082.89	9.00	1078.67	9.00	1059.69	8.20	1056.52	8.00
R106	10	1023.13	8.80	1018.23	9.00	1007.05	8.20	1003.94	8.00	988.09	8.00	983.06	8.00
R107	10	911.82	8.00	908.46	8.00	905.50	8.00	901.29	8.00	902.87	8.00	900.03	8.00
R108	10	842.69	8.00	838.54	8.00	840.62	8.00	838.54	8.00	838.96	8.00	837.99	8.00
R109	10	985.61	9.00	983.94	9.00	981.34	9.00	976.66	9.00	968.59	9.00	962.40	9.00
R110	10	911.32	8.20	904.75	8.00	911.69	8.00	904.75	8.00	885.87	8.00	885.54	8.00
R111	10	899.12	8.00	897.61	8.00	898.18	8.00	893.96	8.00	893.70	8.00	892.26	8.00
R112	10	834.56	8.00	832.41	8.00	832.16	8.00	832.16	8.00	831.00	8.00	829.98	8.00
R201	9	1188.74	9.00	1188.27	9.00	1181.50	9.00	1179.79	9.00	1161.66	8.00	1159.14	8.00
R202	8	1085.24	8.00	1081.06	8.00	1068.09	8.00	1062.97	8.00	1044.94	7.60	1042.41	7.00
R203	7	937.05	7.00	935.60	7.00	926.13	7.00	922.60	7.00	892.50	6.20	890.85	6.00
R204	7	773.79	6.00	769.50	6.00	764.33	6.00	761.57	6.00	761.77	6.00	758.45	6.00
R205	7	1039.16	7.00	1038.09	7.00	1031.57	7.00	1028.97	7.00	1016.61	7.00	1013.37	7.00
R206	7	948.23	7.00	946.67	7.00	945.10	7.00	944.03	7.00	935.86	6.00	934.38	6.00
R207	7	855.64	7.00	854.40	7.00	854.03	7.00	852.28	7.00	827.18	6.00	827.18	6.00
R208	7	758.39	5.40	752.71	5.00	755.75	5.20	753.77	5.00	733.72	5.00	733.51	5.00
R209	7	924.24	7.00	924.18	7.00	922.83	7.00	922.83	7.00	913.79	6.00	911.96	6.00
R210	7	951.07	7.00	948.92	7.00	943.44	7.00	942.97	7.00	932.08	7.00	930.48	7.00
R211	7	823.50	6.20	822.33	6.00	811.91	6.20	808.51	6.00	802.52	5.80	800.63	5.00
C101	12	920.37	11.00	920.37	11.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C102	12	904.72	10.00	904.69	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C103	12	834.75	10.00	834.75	10.00	828.06	10.00	828.06	10.00	828.06	10.00	828.06	10.00
C104	12	823.81	10.00	823.81	10.00	819.81	10.00	819.81	10.00	819.81	10.00	819.81	10.00
C105	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C106	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C107	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C108	12	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00	828.94	10.00
C109	12	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00	825.65	10.00
C201	8	706.26	5.00	706.26	5.00	639.40	4.00	639.40	4.00	588.88	3.00	588.88	3.00
C202	7	730.26	5.00	728.82	5.00	664.66	4.00	664.66	4.00	588.88	3.00	588.88	3.00
C203	6	703.14	5.00	702.99	5.00	652.60	4.00	652.20	4.00	593.41	3.00	593.41	3.00
C204	6	669.32	4.00	669.32	4.00	646.87	4.00	646.70	4.00	593.03	3.00	593.03	3.00
C205	6	664.34	5.00	664.08	5.00	626.63	4.00	626.63	4.00	588.49	3.00	588.49	3.00
C206	6	669.16	4.20	667.32	4.00	641.26	4.00	640.89	4.00	588.49	3.00	588.49	3.00
C207	6	662.62	5.00	662.62	5.00	628.72	4.00	628.72	4.00	588.29	3.00	588.29	3.00
C208	6	665.87	4.60	664.98	4.00	654.62	4.00	654.62	4.00	601.05	3.00	601.05	3.00
RC101	11	1270.83	11.00	1270.15	11.00	1265.29	10.00	1263.82	10.00	1246.06	9.80	1243.20	9.00
RC102	11	1175.26	10.20	1173.04	10.00	1167.75	9.40	1164.55	9.00	1162.36	9.80	1156.30	9.00
RC103	11	1091.86	9.20	1088.18	9.00	1085.24	9.00	1084.06	9.00	1072.22	9.00	1072.22	9.00
RC104	11	993.30	9.00	993.30	9.00	993.14	9.00	993.13	9.00	993.13	9.00	993.13	9.00
RC105	11	1211.72	10.00	1208.22	10.00	1203.59	10.00	1203.38	10.00	1188.34	10.00	1186.15	10.00
RC106	11	1146.96	9.60	1139.01	9.00	1142.78	9.60	1134.71	9.00	1135.07	9.00	1132.52	9.00
RC107	11	1062.89	9.40	1060.22	9.00	1060.66	9.20	1057.72	9.00	1053.60	9.40	1049.76	9.00
RC108	11	990.22	9.00	989.44	9.00	989.75	9.00	989.44	9.00	989.44	9.00	988.09	9.00
RC201	9	1344.55	9.00	1342.10	9.00	1310.98	9.00	1307.20	9.00	1270.16	8.60	1266.50	9.00
RC202	8	1172.76	8.00	1171.30	8.00	1142.78	8.00	1142.78	8.00	1104.42	8.00	1103.98	8.00
RC203	7	1042.57	7.00	1042.57	7.00	1019.07	7.00	1017.77	7.00	958.40	5.20	954.86	5.00
RC204	7	870.87	6.00	870.67	6.00	860.73	5.80	859.57	5.00	812.18	5.00	812.18	5.00
RC205	7	1360.45	7.00	1339.21	7.00	1254.43	7.00	1243.12	7.00	1170.36	7.00	1170.36	7.00
RC206	7	1165.65	7.00	1161.43	7.00	1140.71	7.00	1138.82	7.00	1119.73	7.00	1118.13	7.00
RC207	7	1086.28	7.00	1078.14	7.00	1071.50	7.00	1062.89	7.00	1056.45	7.00	1051.32	7.00
RC208	7	876.44	6.00	873.15	6.00	868.36	6.00	862.70	6.00	849.52	6.00	847.86	6.00
All	508	53093.57	447.80	52972.93	444.00	52168.24	434.80	52059.78	432.00	51030.98	414.60	50946.68	411.00

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