To team up or not – single versus team driving in European road freight transport

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The last decades have seen a tremendous amount of research being devoted to effectively managing vehicle fleets and minimizing empty mileage. However, in contrast to, e.g., the air transport sector, the question of how to best assign crews to vehicles, has received very little attention in the road transport sector. The vast majority of road freight transport in Europe is conducted by single drivers and team driving is often only conducted if there are special circumstances, e.g., security concerns. While it is clear that transport companies want to avoid the costs related to additional drivers, vehicles manned by a single driver sit unused whenever the driver takes a mandatory break or rest. Team drivers, on the other hand, can travel a much greater distance in the same amount of time, because mandatory breaks and rests are required less frequently. This paper investigates under which conditions trucking companies should use single or team driving to maximize their profitability.

Key words: Hours of service regulations; vehicle routing; truck driver scheduling; crew optimization

1. Introduction

Competition in the road freight sector has led to very low profit margins close to three percent in Europe (European Commission 2008), on average. With low profit margins, companies are forced to make the best possible use of their resources. Since truck drivers have limited working hours and regularly must take breaks and rests in order to be able to safely operate their vehicles, many trucks are unproductive for significant periods. Truck drivers in the European Union are legally required to take a rest of eleven hours after nine hours of driving. Therefore, a truck with a single driver spends less time on the road than in the parking lot. One way to increase the productivity of vehicles is to assign a team of two drivers to a truck. The total daily driving time can then be doubled, and one driver can take a break while the other is driving. Thus, a truck with two drivers can cover a much larger distance in a single day than a truck with a single driver. On the other hand, only one of the two drivers is actually driving while the other is unproductive. In some cases, service tasks, e.g. loading and unloading the vehicle at customer locations, can be parallelized, and team driving can therefore reduce service durations. This can make it possible to serve more customers in the same amount of time. In other cases, service durations are independent of the number of drivers available and there is no benefit of having two drivers available during service tasks. Transport companies are thus confronted with the question of whether or not to increase the productivity of the trucks at the expense of the reduced productivity of the drivers.

The team driving question is relevant both at the operational level, where drivers must be assigned to routes to be conducted in the near future, and at the tactical level. As a supplier of optimization software and analytics solutions, ORTEC develops, amongst other solutions, decision support systems designed to assist with various tactical decisions. Given the plethora of interrelated tactical decisions, these systems are often based on scenario-based analyses in which a combination of simulation and optimization is used. Some tactical decisions are given as input by the user, and others are optimized subject to the relevant constraints and interrelations. For example, some of ORTEC's customers have to take tactical decisions concerning the fleet composition, visit days and time windows, or the assignment of customers to distribution centers (DCs). After selecting the respective parameters, they obtain a scenario for which resulting operational costs must be assessed and compared with other scenarios. Obviously, the operational costs depend on the characteristics of the routes to be conducted in the scenario. Ideally, the team driving question, which has a large impact on the route characteristics, can be answered for each scenario by an appropriate methodology. To date, the current state-of-the-art in transportation research is lacking sophisticated methods for determining the best driver composition, and companies like ORTEC have a strong demand for appropriate approaches that can be included in their decision support systems.

This paper seeks to develop a better understanding of the factors influencing the decision on whether or not a team of two drivers shall be assigned to a truck. After an overview of related studies, the paper discusses the impact of hours of service regulations on crewing decisions. Then, a combined approach for crew assignment, routing, and scheduling is presented, and an experimental analysis is conducted on selected cases to determine when a trucking company should use single or team driving. This approach can be used for operational route planning as well as within a scenario-based tactical decision support system. The paper concludes with some managerial insights from our analysis.

2. Related work

Crewing problems in transport have been studied intensively in the airline sector (see, e.g., Kasirzadeh et al. 2017, Salazar-González 2014). In air transport, crews consisting of pilots and flight attendants must be assigned to scheduled flights. As in road transport, there are constraints on the crew working hours. Aviation regulations limit the flight time of pilots and impose regular rest periods. Similarly, the working hours of flight attendants are constrained by government regulations and company policies. Typical crewing problems concern the best assignment of crew members to flights in such a way that each scheduled is covered, the regulations are satisfied, and each crew member is assigned to flights forming a round trip. The number of pilots and flight attendants required for each flight is generally given and there is no benefit in assigning additional crew members to a flight. Similar problems can be found for scheduled services for other transport modes, see e.g., Ernst et al. (2004) and Ciancio et al. (2018).

In road freight transport, the working hours of truck drivers are constrained by government regulations specifying minimum break and rest requirements. In contrast to air transport, truck drivers can interrupt a trip to take a break or rest period. Xu et al. (2003) were among the first to explicitly consider such break and rest periods. They study a vehicle routing problem in which hours of service regulations in the United States must be complied with. For a given vehicle route, the problem of determining a truck driver schedule that complies with hours of service regulations in the United States has been tackled by Archetti and Savelsbergh (2009), Goel and Kok (2012b), Goel (2014), and Rancourt et al. (2013). For European Union hours of service regulations, similar approaches have been presented by Goel (2010), Drexl and Prescott-Gagnon (2010), Goel (2012), and Kok et al. (2011).

Besides the aforementioned approach by Xu et al. (2003), a variety of heuristics for vehicle routing and truck driver scheduling problems have been presented by Zäpfel and Bögl (2008), Goel (2009), Ceselli et al. (2009), Bartodziej et al. (2009), Kok et al. (2010), Prescott-Gagnon et al. (2010), Derigs et al. (2011), Drexl et al. (2013), Goel and Vidal (2014), Coelho et al. (2016), Koç et al. (2017) and Bowden and Ragsdale (2018). Exact approaches for vehicle routing and truck driver scheduling problems have been presented by Goel and Irnich (2017), Tilk (2016), and Goel (2018).

All these studies assume that the trucks are manned by a single driver, and the scientific literature considering the possibility of assigning teams of two drivers to a vehicle is scarce. For European Union hours of service regulations, Goel and Kok (2012a) present a model that can be used to determine compliant schedules for given routes performed by team drivers and develop an algorithm for efficiently scheduling the working hours of the teams. Goel (2007) studies a rich vehicle routing problem in which some vehicles are operated by a single driver and some vehicles are operated by a team of two drivers. In this study, the number of drivers assigned to a vehicle is not part of the decision problem and assumed to be given. To our knowledge, the only work studying the question of whether to assign one or two drivers to a vehicle is that by Kopfer and Buscher (2015). They compare the productivities of single drivers and team drivers, assuming that the workload of the drivers is organized in such a way that the main duty is driving over a longer time period. Thus, they assume that driving is only interrupted by breaks and rest periods required by European Union hours of service regulations. They do not consider loading and unloading times and other waiting times during which the vehicle is not moving. Furthermore, certain important European rules on night work (see Goel 2018) are not considered by Kopfer and Buscher (2015).

3. Impact of hours of service regulations on driving patterns

This section describes the European Union (EU) hours of service regulations and analyses the driving patterns of single and team drivers. According to Regulation (EC) No 561/2006, truck drivers must take a 45 minutes break after at most $4\frac{1}{2}$ hours of driving and an 11 hour rest after at most 9 hours of driving. Breaks and rests can also be taken in two parts. If a break is split, the first part must be of at least 15 minutes and the second part at least 30 minutes. If a rest is split, the first part must be of at least 3 hours and the second part of at least 9 hours. The required rest must be taken within 24 hours after the end of the previous rest period. The weekly driving time is restricted to at most 56 hours and the weekly working time (including driving) to at most 60 hours. Furthermore, the bi-weekly driving time is constrained to at most 90 hours. Weekly rest periods of at least 45 hours must be taken starting no later than 144 hours after the end of the last weekly rest.

Additional national regulations, in particular the implementations of Directive 2002/15/EC, must be complied with in each EU member state. These national regulations require that a truck driver must not work for more than six hours without a break of at least 30 minutes and if the total amount of work between two rest periods exceeds 9 hours, the break time must be at least 45 minutes. Furthermore, a driver who performs night work must not work for more than 10 hours in any period of 24 hours (Goudswaard et al. 2006).

Figure 1 shows a reference schedule for a single driver on a daily basis. This schedule comprises two $4\frac{1}{2}$ hour driving periods with an intermediate break of 45 minutes. If the driver is not working at night, a total of $3\frac{1}{4}$ hours can be used for non-driving activities on every day, as long as all necessary breaks are taken. When this pattern is repeated on a weekly basis, a weekly rest period must be taken after five days, so that no more than 45 hours of driving are accumulated in a week.

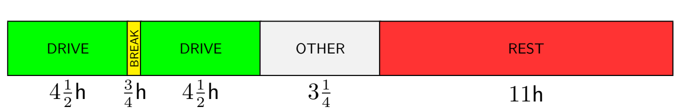

Figure 1 Reference schedule for a single driver.

If a vehicle is continuously manned by a team of two drivers, one driver can take a break while the other is driving. The minimum duration of a rest period for team drivers is 9 hours and both drivers must take the rest simultaneously. Furthermore, the required rest must be taken within 30 hours after the end of the previous rest. Figure 2 shows a reference schedule for team drivers that can be repeated until a weekly rest is taken by both drivers. In this schedule, each driver drives for $4\frac{1}{2}$ hours without a break and after that, the drivers change seats. We assume that the time required for the drivers to switch is negligible so that the vehicle can keep moving without any significant break for a total of 18 hours. Both drivers then take a rest period of 9 hours before repeating this driving pattern. Note that the reference schedule has a total duration of 27 hours including the rest. Therefore, the timing of the rest period of the team drivers would shift by 3 hours for every day. The resulting irregular sleep patterns can be an obstacle to the implementation of such a driving pattern. To maintain a regular sleep pattern, team drivers would need to reduce their daily workload to a value well below the legal limits. However, given the low profit margins in road freight transport, we believe that such a reduction of the daily workload would only be acceptable in very few cases.

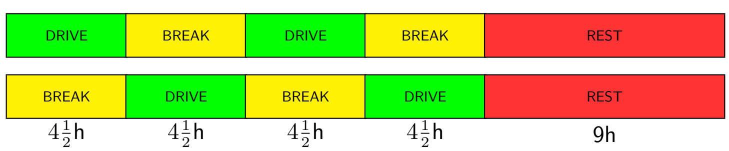

Figure 2 **Reference schedule for team drivers.**

Obviously, the time required to travel the same distance can differ significantly for single and team drivers. Figure 3 shows the time required for single and team drivers for a driving time of up to 90 hours, i.e., the bi-weekly driving limit for a single driver. The gray line illustrates the duration required by a single driver. After five daily driving periods, a single driver reaches the maximum average amount of 45 hours driving per week. The last driving period finishes $4 \cdot 24 + 4\frac{1}{2} + \frac{3}{4} + 4\frac{1}{2} = 105\frac{3}{4}$ hours after the start of the first driving activity. If the driver repeats the same pattern in the subsequent week, i.e., after 168 hours, the driver can take a weekly rest period of $62\frac{1}{4}$ hours after the last driving period.

The black line illustrates the duration required by a team of two drivers. We again assume that the drivers repeat the same pattern in the subsequent week. Therefore, a weekly rest period of 45 hours must be scheduled before the start of the next week and at most $168 - 45 = 123$ hours are available for driving and daily rest periods. Within this time frame, team drivers can have four cycles of 18 hours of driving followed by a rest of 9 hours and another driving period of 15 hours. Thus, team drivers can drive up to 87 hours per week.

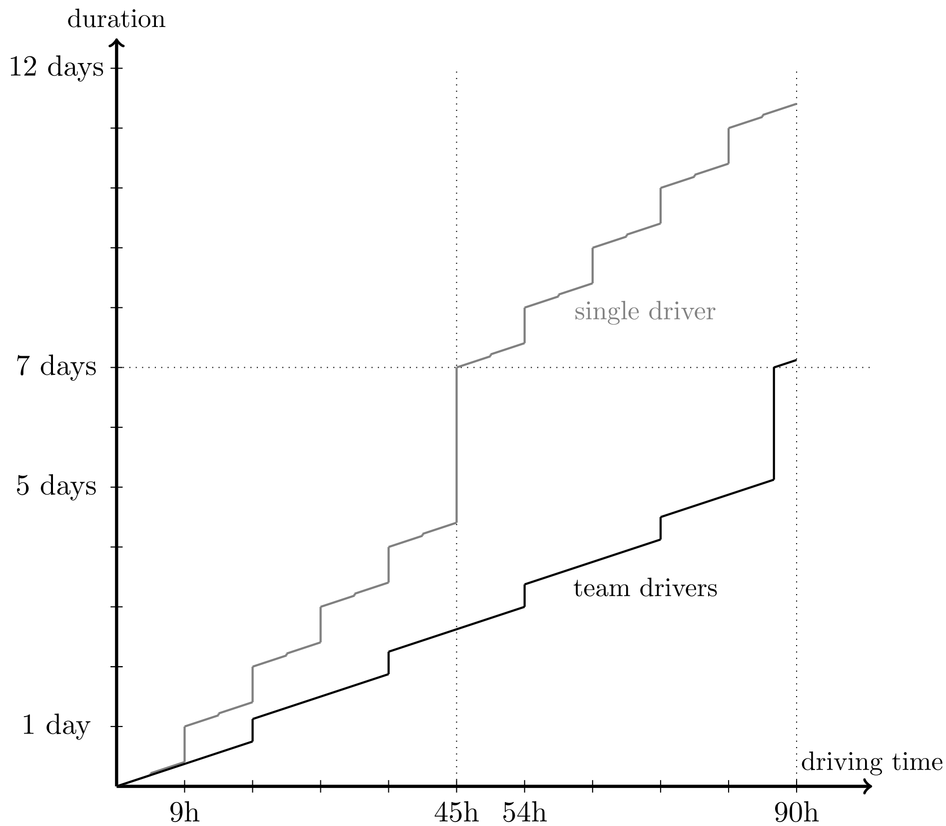

Figure 3 Durations required for single and team drivers.

In this comparison, it must be noted that a single driver has $3\frac{1}{4}$ hours daily that can be used for loading or unloading or other non-driving activities, whereas such activities reduce the amount of driving time that team drivers can conduct within the week.

Depending on the cost structure of the carrier, the question of whether to use a single driver or team drivers may be answered differently. Assuming a daily cost of c^{truck} for the vehicle and c^{driver} for each driver, the time-related cost of operating a vehicle for d^{single} days with a single driver is

$$(c^{\text{truck}} + c^{\text{driver}}) \cdot d^{\text{single}},$$

and the cost of operating a vehicle for d^{team} days with a team of two drivers is

$$(c^{\text{truck}} + 2c^{\text{driver}}) \cdot d^{\text{team}}.$$

Obviously, a single driver is less costly if team driving does not reduce the number of days required to perform a trip, i.e., if $d^{\text{single}} = d^{\text{team}}$. If team driving, however, requires only half of the number of days required by a single driver or less, i.e., if $d^{\text{single}} \geq 2d^{\text{team}}$, then team driving is less costly.

For $d^{\text{team}} < d^{\text{single}} < 2d^{\text{team}}$, the costs for a single driver are the same as the costs for a team of two drivers if

$$\frac{c^{\text{driver}}}{c^{\text{truck}}} = \frac{d^{\text{single}} - d^{\text{team}}}{2d^{\text{team}} - d^{\text{single}}}. \tag{C}$$

For larger values of $c^{\text{driver}}/c^{\text{truck}}$, the costs for a single driver are smaller, and for smaller values, the costs for team drivers are smaller. Table 1 shows the number of days required for single and team drivers depending on the driving time (in hours) and the resulting best crew size.

Driving time	d^{single}	d^{team}	Best crew size
(0,9]	1	1	1
(9,18]	2	1	2
(18,27]	3	2	1 or 2
(27,36]	4	2	2
(36,45]	5	3	1 or 2
(45,54]	6	3	2
(54,63]	7	3	2
(63,72]	8	4	2
(72,81]	9	4	2
(81,87]	10	5	2
(87,90]	10	6	1 or 2

Table 1 Comparison of single and team drivers for trips with different driving times.

For longer routes, team driving is the cheaper alternative for most ranges. For driving times between 18 and 27 hours, a single driver is cheaper if $c^{\text{driver}} > c^{\text{truck}}$, i.e., if the daily cost for the driver is larger than the daily cost of the vehicle. For driving times between 36 and 45 hours and between 87 and 90 hours, a single driver is cheaper if $c^{\text{driver}} > 2c^{\text{truck}}$, i.e. if the daily cost for the driver is larger than two times the daily cost for the vehicle.

4. Impact of operational constraints

The above comparison assumed that the only duty of truck drivers is to drive and there are no other activities such as loading or unloading. Under this assumption, drivers can follow the reference schedules shown in Figures 1 and 2. In this situation, the driving time and the ratio between daily driver wages and vehicle costs are the only factors influencing the decision on team driving. In most transport operations, however, this assumption is overly simplistic because operational requirements concerning business hours of customers, vehicle capacities, service durations etc. can have a significant impact on routes and truck driver schedules.

Figures 4 and 5 show examples of schedules for single and team drivers visiting different customers subject to various operational constraints. These examples were obtained from the experiments described later in this paper. These schedules differ significantly from the reference schedules of Figures 1 and 2. In these examples, the assignment of one or two drivers is not a free choice. In particular, if the route corresponding to the schedule shown in Figure 5 was to be executed by a single driver, the mandatory breaks and rest periods would cause substantial delays, leading to violations of service time-window constraints.

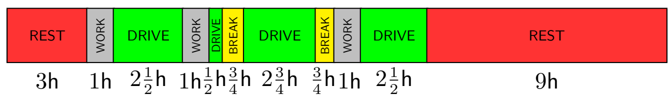

Figure 4 **Example schedule for a single driver.**

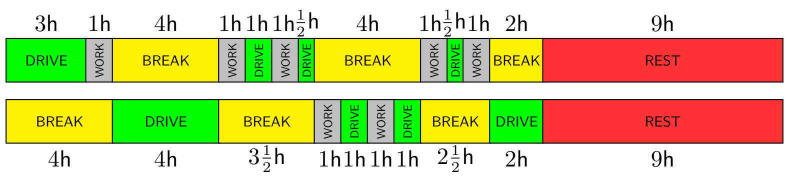

Figure 5 **Example schedule for team drivers.**

To further understand the impact of operational constraints on crewing decisions, consider an example where a transport company has to deliver two half truckloads to two customers who are $4\frac{1}{2}$ hours of driving away from the depot and where the driving distance between the customers is two hours. To fulfill both customer requests and allow the drivers to return to the depot on the same day, two trucks are required if each truck is operated by one driver, whereas a single truck suffices for team driving. Figure 6 illustrates this example. In both cases, two daily salaries would have to be paid. Because team driving only requires one vehicle for a total of 11 hours instead two vehicles for a total of 18 hours, team driving can reduce both cost and distance.

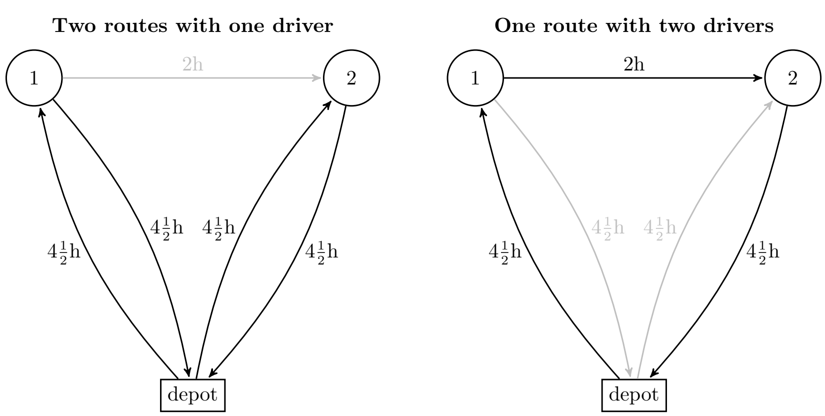

Figure 6 **Team driving can reduce both cost and distance.**

As the above examples show, operational constraints can influence routing decisions and truck driver schedules, and with it, the choice of using single or team drivers. A classification of operational requirements in terms of type of carrier and goods, geographic distribution of customers, distances, service times, time window tightness, transport volumes and capacities, etc. will not help in determining the best crew compositions for the different classes, because the effects of the various requirements on crew size are highly interrelated and of combinatorial nature. For example, geographic proximity of customers and tight time windows may be a reason to use single drivers if the time window tightness results in large waiting times when visiting the customers within the same route. On the other hand, geographic proximity of customers and tight time windows may also be a reason to use team drivers, because a single driver might not be able to visit the customers within the same route due to the additional time required for mandatory breaks and rests. Similar effects can be found for other classification schemes.

In order to adequately consider these interrelated and combinatorial effects, we propose to tackle the team driving question by solving a combinatorial optimization problem considering typical operational requirements. In particular, we propose to solve the combined problem of assigning drivers to vehicles and optimizing routes and schedules. This optimization problem is a variant of the well-known vehicle routing problem with time windows (see, e.g., Bräysy and Gendreau 2005a,b) that aims to find a minimal cost set of routes for a fleet of vehicles such that a given set of customers is visited within given time windows. The problem variant that we consider in this paper is characterized by the additional requirements, that for each route, we must decide whether the vehicle is manned by one or two drivers, and that a schedule satisfying the corresponding hours of service regulations must exist.

Let R_1 represent the set of all feasible routes that can be operated by a single driver, and let R_2 represent the set of all feasible routes that can be operated by a team of two drivers. Single-driver routes in R_1 are distinguished from team-driving routes in R_2, even if the same sequence of customers is visited, such that $R_1 \cap R_2 = \varnothing$. The optimization problem is:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{r \in R_1} (c^{\text{truck}} d_r + c^{\text{driver}} d_r + c^{\text{distance}} k_r) x_r \\
& + \sum_{r \in R_2} (c^{\text{truck}} d_r + 2c^{\text{driver}} d_r + c^{\text{distance}} k_r) x_r && (1) \\
\text{subject to} \quad & \sum_{r \in R_1 \cup R_2} a_{ir} x_r = 1 && \forall i \in V \quad (2) \\
& x_r \in \{0,1\} && \forall r \in R_1 \cup R_2, \quad (3)
\end{aligned}
$$

where d_r and k_r denote the number of days required and the total distance (in kilometers) traveled for route $r \in R_1 \cup R_2$. Furthermore, c^{truck}, c^{driver}, and c^{distance} denote the daily cost for a truck, the daily cost for a driver, and the cost per kilometer. The set of customers is denoted by V, and a_{ir} is a binary parameter set to 1 if and only if customer $i \in V$ is visited by route r. Each binary decision variable x_r is set to 1 if and only if route $r \in R_1 \cup R_2$ is selected in the solution. The objective (1) seeks to minimize the total cost of all the routes, and Constraint (2) ensures that each customer is visited by exactly one route.

The above formulation cannot be directly used to solve the problem because R_1 and R_2 are usually too large. Various heuristic approaches have been developed to find vehicle routes satisfying the time window constraints and hours of service regulations. We use an adaptation of the hybrid genetic search (HGS) presented by Goel and Vidal (2014).

Our HGS is based on the iterative generation of new solutions via a problem-tailored crossover and efficient local-improvement techniques, in combination with population-diversity management strategies that promote the exploration of a wide variety of solutions. It uses the same general-purpose operators as the unified hybrid genetic search (UHGS), which have led to near-optimal solutions for dozens of VRP variants in recent years. We contribute a tailored evaluation procedure for the routes explored during the search. Every route is evaluated twice, first for a team of drivers, and then for a single driver, and the cheaper option is retained. Because the evaluation of each route requires the shortest driver schedule for a given sequence of visits, we apply the labeling algorithm of Goel (2018) for single-driver schedules, and an adaptation of the algorithm of Goel and Kok (2012a) for team-driver schedules.

Note that millions of routes are evaluated during a typical optimization run, due to the use of a local search on each new solution, in which each move evaluation implies one or two new route evaluations. Each route evaluation leads to a time-consuming truck driver scheduling problem. We therefore apply, as in Goel and Vidal (2014), a variety of speed-up techniques. First, we use memories with constant-time hash calculations to store route evaluations, as well as static neighborhood restrictions to avoid evaluating too many moves. Second, we observed that solving the scheduling problem for single drivers takes about 20 times longer than for team drivers because breaks and rest periods can be taken in two parts. Therefore, we exploit *lower-bounds* on move evaluations, as in Vidal (2017), to quickly filter any move that has no chance of contributing to a better solution. We observe that the duration for a team of two drivers will always be a lower bound on the duration for a single driver. We therefore calculate upper bounds on the savings of a local search move, by computing the optimized duration as if a team was driving, but with the cost coefficient for a single driver. A local search move with a negative upper bound on the savings can not improve the incumbent solution. In practice, this strategy filters 90% of the moves on average, considerably reducing the number of calls to the time-consuming single-driver schedule optimization routine. Our adaptations of the HGS allow to quickly find high quality solutions for the combined problem of assigning drivers to vehicles and optimizing routes and schedules subject to respective hours of service regulations.

5. Experimental analysis

To understand under which conditions a trucking company should use single and team driving, we conducted experiments based on instances derived from the planning problem of one of ORTEC's retail customers in Eastern Europe. This retailer is using ORTEC's route optimization engines to construct routes by doing batch optimization runs for three days ahead. So far, the customer is executing all routes with single drivers. Most of the routes are single-day trips, and others are longer multi-day trips.

The instances are grouped in three datasets, each corresponding to a separate DC. Figure 7 illustrates the geographical spread of the addresses in each dataset. For each dataset, we created five instances based on the locations shown in the figure, each time randomly removing 20% of the original addresses to create variability in the customer locations. The planning horizon ranges over three days (Monday till Wednesday) and time window lengths range from 3 to 16 hours, with an average of 9 hours. The original planning problems involve a heterogeneous fleet with small differences in vehicle capacity. To simplify the experimental setting and to focus on the crew size aspects, we assume a homogeneous vehicle fleet with a vehicle capacity set to the largest vehicle type in the original problem. The numbers of customers in each dataset are 60, 70, and 88, respectively. The vehicle capacity is 18 pallets and the average number of pallets demanded by the customers is 7.7 pallets, leading to an average of 2 to 3 stops per trip. The variation in customer demand leads to a mix of short and long routes with one to seven stops per route. The coordinates shown in Figure 7 correspond to real locations (the exact region is not revealed for confidentiality reasons). The maximum distance between any two locations is around 1000 km. Driving distances and durations are based on shortest path distance in the road network and obtained from a geographic information system.

We used our algorithm described in the previous section to solve these instances and determine the least cost routes for the cases where 1) all vehicles are allocated a single driver, 2) all vehicles are allocated a team of two drivers, and 3) the decision on whether to assign one or two drivers to a vehicle is part of the optimization.

Based on realistic cost estimates obtained from ORTEC, we assumed labor costs of €100 per driver per day (compare Comité National Routier 2016), truck costs of €100 per day (excluding fuel costs), and distance-related costs of €0.25 per kilometer (including fuel and toll). Furthermore, we assumed that the time required for loading and unloading the vehicle is independent of the number of drivers assigned to the truck.

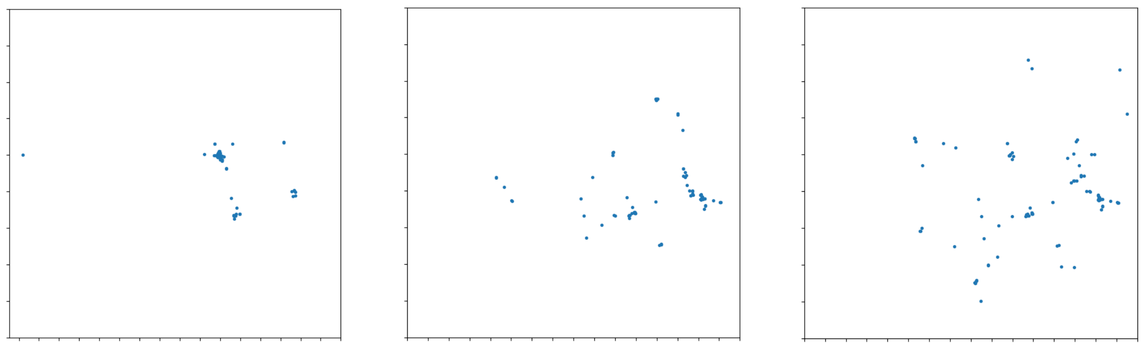

Figure 7 **Customer distribution of real-life instances.**

		Single	Team	Optimized
Set 1	Avg. crew size	1	2	1.035
	Avg. cost	100.8%	138.2%	100%
	Avg. days	1.032	1	1.003
Set 2	Avg. crew size	1	2	1.127
	Avg. cost	103.2%	124.9%	100%
	Avg. days	1.111	1	1.007
Set 3	Avg. crew size	1	2	1.125
	Avg. cost	103.5%	123.9%	100%
	Avg. days	1.114	1	1.001

Table 2 **Impact of crew-size decisions on real-world instances.**

Table 2 shows the results of our experiments for single drivers, team drivers, and an optimized driver assignment. For each set of instances, the table shows the average crew size, the average costs as a percentage of the cost of an optimized crew assignment, and the average number of days required per tour. Most but not all of the 21 to 48 tours in the solutions can be conducted by a single driver on a single day. Relying exclusively on team drivers is clearly not cost-efficient for these instances, and savings of about 1% to 4% can be achieved by assigning team driver to 3% to 13% of the routes. We also observed that the instances of the first dataset, which has highly clustered customer locations, benefited less from using team driving.

We repeated our experiments with different cost parameters and under the hypothesis that the service time at the customer locations can be reduced (by 50% or 25%) if two drivers are available for loading and unloading the vehicle. However, the best crew sizes did not vary much from those reported in Table 2. These experimental results are well aligned with our analysis of normative driving patterns for single and team drivers presented in Section 3, and the insensitivity to the cost parameters is not surprising given the short lengths of the routes.

In general, it can be assumed that transport companies seek to obtain a pool of transportation requests that fit particularly well to the company's way of conducting business. Instead of fulfilling a transportation request that does not fit well, a transport company may either decide to reject the request or to renegotiate some of the requirements if possible and efficiency gains can be generated. In other words, if a transport company is operating all vehicles with a single driver, it will seek to obtain transportation requests that can be nicely combined to cost-efficient single-driver routes, and the company will try to renegotiate, e.g., time constraints on deliveries to certain locations so that nearby customers can be visited by the same driver. When generating instances based on data of companies operating all vehicles with single drivers, as we did for our above experiments, it is likely that these effects create an inherent bias toward single driver routes in optimized crew compositions. To eliminate this bias, we conduct additional experiments on artificial benchmark instances commonly used to evaluate the performance of optimization approaches for vehicle routing problems with time windows. The 56 instances used in these experiments were initially proposed by Solomon (1987) and adapted by Goel (2009) and Goel (2018) for combined vehicle routing and truck driver scheduling problems in the European Union. The instances can be grouped into three classes: in class R the customer locations are randomly distributed; in class C they are clustered; and in class RC the distribution is mixed. Each instance contains 100 customers, and the average size of the time windows per instance ranges from less than 7 hours to more than 107 hours. The planning horizon is 144 hours (6 days) and the maximum driving time (without compulsory breaks and rests) between two customers is approximately one day. Table 3 shows the results of our experiments with the same assumptions as for the real-world instances.

		Single	Team	Optimized
R	Avg. crew size	1	2	1.731
	Avg. cost	107.0%	102.79%	100%
	Avg. days	2.365	1.477	1.507
C	Avg. crew size	1	2	1.475
	Avg. cost	107.2%	105.0%	100%
	Avg. days	2.892	2.762	2.406
RC	Avg. crew size	1	2	1.670
	Avg. cost	105.6%	103.0%	100%
	Avg. days	2.480	1.578	1.667

Table 3 Impact of crew-size decisions on artificial instances.

Under these assumptions, operating each vehicle with two drivers is more cost-efficient than using only single drivers, but the best results are again obtained with an optimized crew composition. We can see that the average tour durations are higher than in the real-world instances, indicating that the driving time in some routes falls into the range where, according to Table 1, the best crew size depends on the cost structure.

We conducted extensive additional experiments with different cost parameters to ensure that our results are not unnecessarily biased by the particular cost structure chosen. In particular, we varied the ratio of the daily driver to the truck cost and and the ratio of the cost per kilometer to the daily truck cost. A factorial design with all 25 possible combinations of parameters $(\frac{c^{\text{driver}}}{c^{\text{truck}}}, \frac{c^{\text{distance}}}{c^{\text{truck}}}) \in \{0.25, 0.5, 1, 2, 4\} \times \{\frac{1}{100}, \frac{1}{200}, \frac{1}{400}, \frac{1}{800}, \frac{1}{1600}\}$ is used. Thus, the daily driver costs range between a quarter and 4 times the daily costs for the vehicle, and the daily truck costs range between the costs for 100 to 1600 kilometers of traveled distance. Furthermore, we made various assumptions about the service durations at customer locations, because in some application scenarios drivers can execute tasks in parallel and in others they cannot. In particular, we assumed that the service duration of team drivers (denoted s^{team}) is 50%, 75%, or 100% of the service duration of a single driver (denoted s^{single}). For each of the 25 cost-parameter configurations and the 3 assumptions on service durations for team drivers, we ran the algorithm 5 times on each of the 56 instances to account for the inherent randomness of the algorithm. The results reported are average results. Furthermore, we repeated the experiments under the assumptions that all vehicles are operated by a single driver and all vehicles are operated by two drivers.

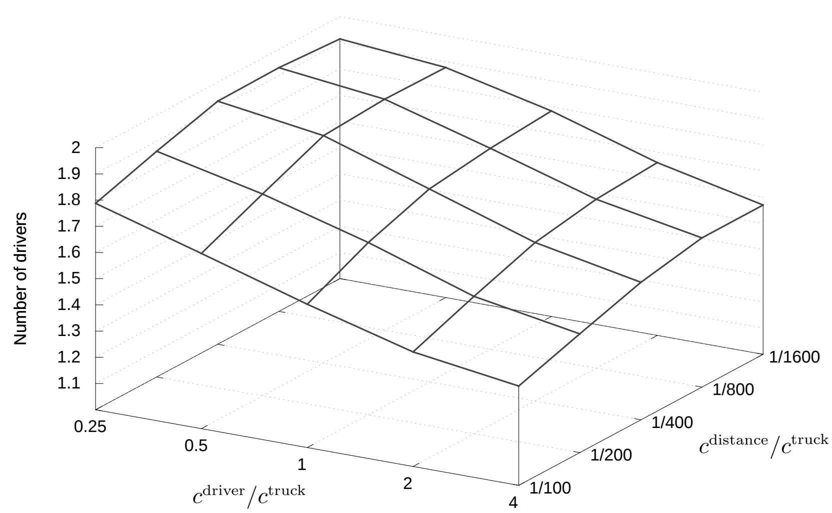

Figure 8 **Average number of drivers for modified Solomon instances for $s^{\text{team}} = 0.5 \cdot s^{\text{single}}$.**

Figures 8 to 10 show the average number of drivers per vehicle in the solutions obtained for the different cost parameters and assumptions on service durations. In the figures, an increase in driver cost corresponds to a move from the left to the right, an increase in mileage cost corresponds to a move to back to the front, and an increase in vehicle cost corresponds to a move from the front right to the back left.

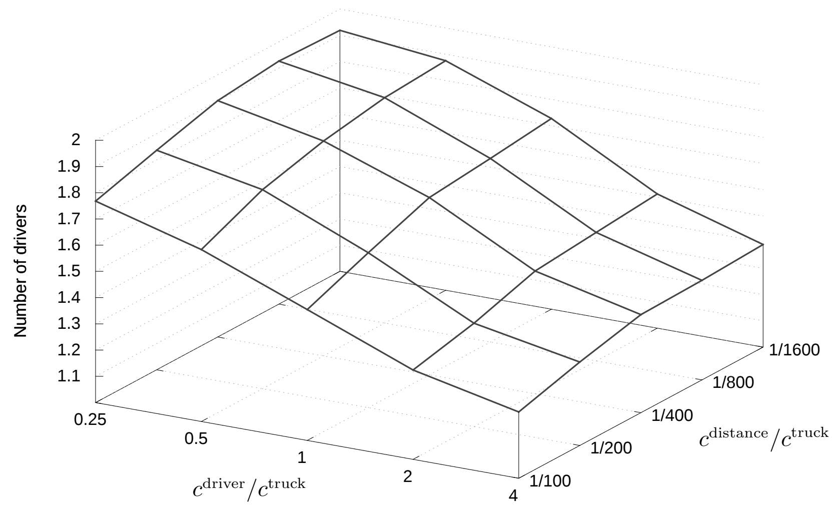

Figure 9 **Average number of drivers for modified Solomon instances for $s^{\text{team}} = 0.75 \cdot s^{\text{single}}$.**

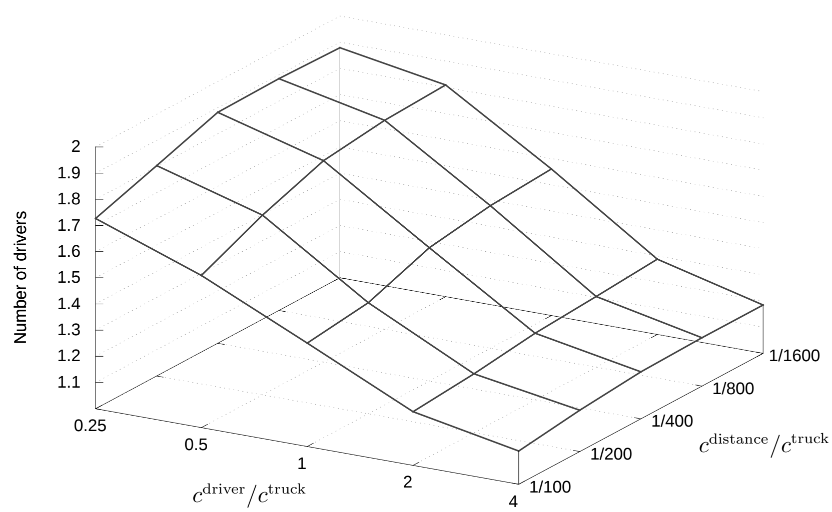

Figure 10 **Average number of drivers for modified Solomon instances for $s^{\text{team}} = s^{\text{single}}$.**

We observe that the highest sensitivity of the optimized number of drivers to a change in driver costs is obtained when $s^{\text{team}} = s^{\text{single}}$. With a Pearson correlation coefficient of -0.77, the share of team drivers has a strong negative correlation with driver wages in this case. Nevertheless, also for $s^{\text{team}} = 0.5 \cdot s^{\text{single}}$ and $s^{\text{team}} = 0.75 \cdot s^{\text{single}}$, the sensitivity to driver wages is clearly visible.

Furthermore, we can see that an increase in truck costs results in a higher share of team drivers. This is because higher truck costs provide a larger incentive for making the most effective utilization of trucks via team driving. We should also note that using team drivers does not necessarily imply that the total driver-related costs increase, because the team drivers do not have to work for the entire planning horizon. Thus, this effect is independent of driver wages.

The effect of mileage costs is less pronounced but still notable and we can see that high mileage costs result in a reduced share of team drivers. For example, we can see a clear decrease in the average number of drivers when going from the point $(\frac{c^{\text{driver}}}{c^{\text{truck}}}, \frac{c^{\text{distance}}}{c^{\text{truck}}}) = (1, \frac{1}{400})$, where traveling 400 kilometers has the same cost as a daily driver shift, to the point $(\frac{c^{\text{driver}}}{c^{\text{truck}}}, \frac{c^{\text{distance}}}{c^{\text{truck}}}) = (1, \frac{1}{100})$, where traveling 100 kilometers has the same cost as a daily driver shift. As expected, we can observe that the traveled distance decreases with higher mileage costs. Although the number of routes also decreases, the number of daily driver shifts is increased. This indicates that routes include more waiting times because of time window constraints at customer locations. It appears that the labor costs related to these waiting times outweigh the potential benefits of reducing mileage by using team drivers, and therefore, their share decreases.

It must be noted that for all values of the cost parameters and the different assumptions on service durations, an average of at least 12.7 per cent of all vehicles are operated by two drivers and an average of at least 7.0 per cent of all vehicles are operated by one driver. This shows that independently of the cost parameters and assumptions on service durations, the best policy overall is to have a mixed composition of single and team drivers.

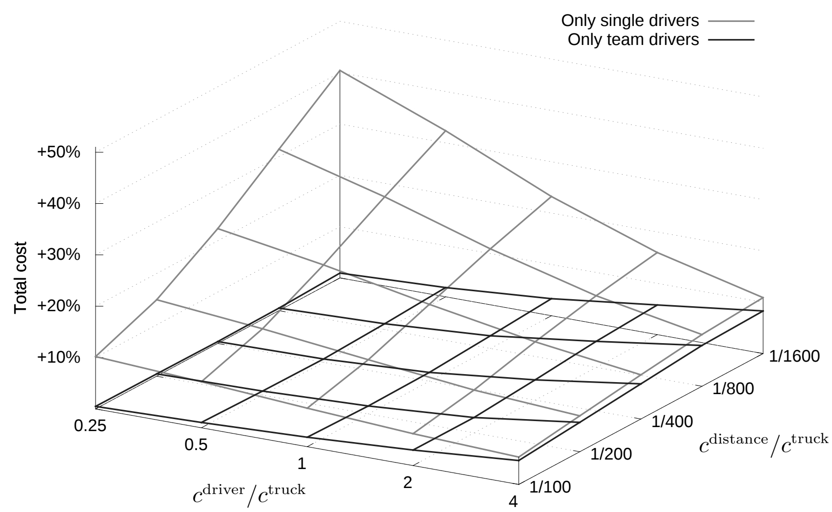

Figure 11 Average cost difference for modified Solomon instances for $s^{\text{team}} = 0.5 \cdot s^{\text{single}}$.

For the different cost parameters and assumptions on service durations, Figures 11 to 13 show the relative cost increase of single and team driving compared to an optimized crew assignment. If team drivers can conduct service tasks completely in parallel (i.e., if $s^{\text{team}} = 0.5 s^{\text{single}}$), team

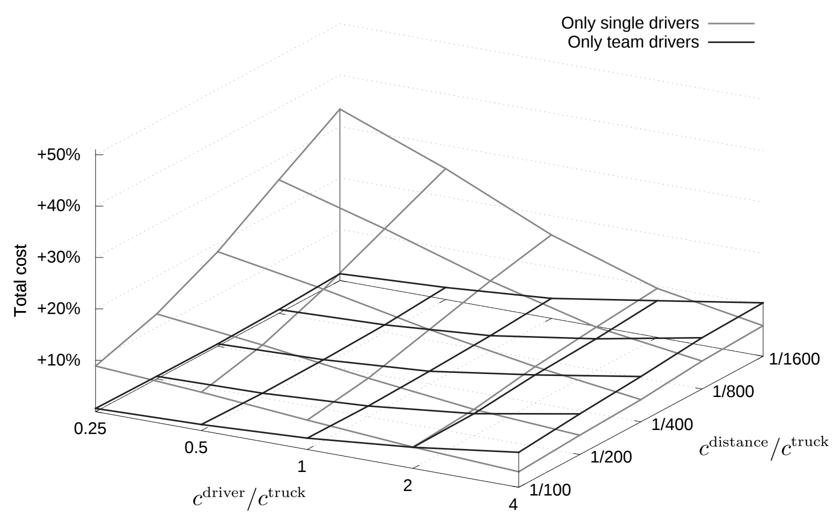

Figure 12 **Average cost difference for modified Solomon instances for $s^{\text{team}} = 0.75 \cdot s^{\text{single}}$.**

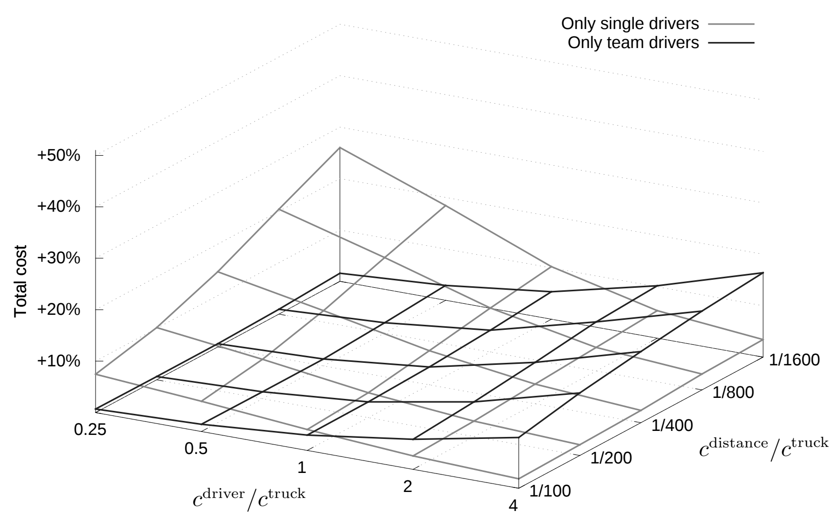

Figure 13 **Average cost difference for modified Solomon instances for $s^{\text{team}} = s^{\text{single}}$.**

driving is particularly attractive, and in our experiments exclusively using team drivers is cheaper for all cost parameters than using only single drivers. Especially with low driver wages and high truck costs, relying solely on single drivers is not competitive. The benefit of an optimized crew assignment compared to a pure strategy depends on the cost structure and can be as much as 5% better compared to the best pure strategy and much higher compared to the other.

6. Managerial insight and conclusion

In this paper, we have evaluated under which conditions trucks should be manned by a single driver or a team of two drivers. Our analysis of normative driving patterns shows that team driving is particularly beneficial for long routes for which route durations can be reduced when using a team of two drivers. For applications where drivers have few other tasks than driving, condition (C) and Table 1 can be used to determine the best crew size depending on the driving time and the ratio of daily labor costs and daily vehicle costs.

Whenever there are operational constraints that have an impact on routes and schedules, crewing decision should not be based on normative driving patterns. To analyze crewing decisions in such cases, we present an approach capable of simultaneously optimizing driver assignments, routes, and schedules. Our approach is based on an underlying genetic algorithm and local search framework that has proven to be extremely flexible with regards to the different operational characteristics that can be found in road freight optimization problems. We added problem-specific lower bounds for move evaluations that help to filter out on average 90% of the time-consuming single-driver route evaluations, thus leading to an effective solution procedure.

We used our approach in various experiments for instances derived from real cases and a collection of artificial instances covering a range of alternative characteristics. A fundamental finding of our experimental results is, that neither single driving nor team driving alone are good management practices, and operating a fleet with a mix of team and single drivers results in lowest operating costs. This finding already contradicts common practice in many transport companies not using team drivers at all.

The best share of team drivers can vary significantly for different use cases. Obviously, if all routes can be operated by a single driver on a single day, it is not possible to reduce costs by using team drivers without changing the routes. On the other hand, if team drivers are required, e.g. due to security concerns or because loading and unloading involves heavy work, there is no choice of using a single driver.

Our experiments on artificial instances show for a wide range of cost factors, how many drivers should be assigned to the vehicles and how much can be saved in comparison with a pure strategy of using only single or team drivers. Not surprisingly the highest cost benefit can be obtained if team drivers can parallelize service tasks. However, an interesting finding of our experiments is that even if team drivers cannot parallelize service tasks and require the same amount of time for servicing customers as a single driver, the cost advantage of team driving can be significant.

As noted in the introduction, crewing decisions can interrelate with other tactical decisions. Our approach can also be used in a what-if analysis, where various tactical decisions interrelating with crewing decisions are evaluated using simulation and optimization. It must be noted that the full potential of team driving may be realized only if certain tactical decisions are changed, making it possible to conduct longer routes with a team of two drivers. Otherwise, the inherent bias resulting from tactical decisions made on the assumption of exclusively relying on single drivers may result in optimized crew sizes involving only a limited number of team drivers. Although the use of single drivers had been the basis for the business of one of ORTEC's customers, our experiments showed that a notable cost reduction can be obtained by assigning team drivers to some of the vehicles.

Obviously, there is a myriad of different operational requirements in road freight transport and it is impossible to conduct experiments that capture all of these requirements in all different combinations. Our hybrid genetic search for simultaneous optimization of driver assignments, routes, and schedules can be used for a large variety of these characteristics. Also, other approaches for route optimization can similarly be extended to also optimize crews. Whenever normative driving patterns cannot be used to decide on single vs. team driving, transport managers should used our approach or a similar adaptation of other approaches to determine how many drivers are required and which routes should be operated by single or team drivers.

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