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Driver scheduling for vehicle schedules using a set covering approach: a case study*

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Abstract

For transport companies, one important aspect is to decrease their operational costs. This can be done by somehow optimizing the routes of their public transport services. Usually the overall operational cost of the transportation consists of the cost of the vehicles used and their drivers. Solving such a task is rather complex and usually the optimized planning process is divided into several phases. These might be the vehicle scheduling, driver scheduling and driver rostering. First the journey tasks are assigned to vehicles, and then these vehicle schedules are divided into driver schedules, which are usually shorter, because of driving time restrictions. Next, the driver schedules are assigned to individual drivers. In the article, we will focus on the second part, i.e. with driver scheduling for given vehicle schedules. It is NP-hard to find the optimal driver schedules [8]. Here, we will use the well-known set covering approach to model the problem. It will be formally expressed as an integer programming problem, which can be solved by column generation. To generate the new columns, a time-space network based generator network is used, as proposed by Gintner et al. [8], and Steinzen et al. [14]. Here, we present a case study of how we applied these techniques to real data supplied by the Szeged public bus transport company.

Keywords: Operations Research, Integer Programming, Driver Scheduling

MSC: 90B06, 90C10

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1. Introduction

In the paper, we will be concerned with an important part of the operative planning of public transport service, namely that of driver scheduling. The solution method applied below is for public bus transport, but the principles are the same for other areas of public transport.

The planning aspect of public transport can be divided into different parts. The first part is that of strategic planning. Generally, the design of bus routes is an important part of this phase. The second and third parts are to determine the frequencies and timetables, respectively, both of them being part of tactical planning. These three problems are generally specified by the local council. The fourth and fifth parts – namely, vehicle scheduling, driver scheduling and rostering – belong to the operative planning part. A detailed description of the phases, models and so on for these can be found, for instance, in [6].

Finding a solution to the problems of operative planning is the task of the public transport companies. A significant aspect of the transport companies is to reduce their operational costs. Usually the operational cost of the transportation consists of the cost of the vehicles used and their drivers.

The operative planning (i.e., the scheduling of the vehicles and drivers) is typically divided into four phases (see, e.g. [1,3]). These phases are vehicle scheduling, vehicle assignment, driver scheduling and driver rostering.

The task of *vehicle scheduling* (see, e.g. [5]) is the designing of the schedules (vehicle shifts) for each day based on the vehicle park, such that each timetabled trip is covered. Deadhead trips (without passengers) are also allowed between two timetabled trips t_1 and t_2, if they are *compatible*, i.e. the journey time of the deadhead trip is less than or equal to the difference between the departure time of t_2 and arrival time of t_1. A deadhead trip is made between two geographical points: the arrival station of t_1 and the departure station of t_2. Roughly speaking, vehicle scheduling produces suitable vehicle schedules that meet the timetable requirements.

The *vehicle assignment* step assigns particular buses to schedules catering for special requirements (e.g. refueling of natural gas buses, where the maximum distance without refueling is given [2]). In this phase, we assign a specific bus to each vehicle scheduling (vehicle shift).

The *driver scheduling* step [15] produces working shifts that respect daily constraints. These constraints include certain rules regarding the driving time, resting time, working time in a day, as well as breaks between two work pieces. The maximum driving time without a break and the maximum working time per a day are prescribed.

The task of *driver rostering* is to assign drivers to shifts subject to constraints of the planning in the given planning period. The length of the planning period is usual several weeks or months, and the task is to make the scheduling of the shifts of each day, including days off. The minimum number of days off, including Sundays is prescribed. The shifts are usually of different types.

All in all, there are different software modules for the support of phases of operative planning. This can be realized in an automatized or interactive way. Normally, these are parts of a decision support system.

It should be mentioned here that there are several integrated models available for the operative planning of public transport, which handle some parts of the above steps together (see [6,9,12,16]). But usually the size of the problem is restricted (e.g. to a medium-sized problem) or the rules of the drivers are simplified, or their total number is reduced. However, to find an efficient driver scheduling is an important task from an operative cost perspective. In the 1980-s, Bodin et al. discussed its importance. Based on North-American public transport examples, the authors of [4] argued that the biggest part of the operative costs is the cost of the drivers; and it is generally higher than the average cost of the vehicles.

2. The solution for the construction of vehicle schedules

Next, we will describe the construction of the vehicle schedules. The first step is the so-called theoretical vehicle schedules. The second step is to assign real vehicles to these, which is called vehicle assignment. In our system, these two steps are the task of the vehicle scheduling module, and vehicle assignment module, respectively. The input for the vehicle scheduling module is:

- the data of the trips (their departure and arrival time, departure and arrival stations as geographical places, vehicle-type requirements for the trips),
- data of the vehicles (type of the vehicle, cost data, etc.),
- other geographical data (e.g. data concerning depots).

A vehicle scheduling (the scheduling of a vehicle) contains some *events*, such as the trips, and the deadhead trips.

Generally speaking, the definition of the vehicle scheduling part is to give the scheduling of the vehicle park for a day, using vehicles got from given depots (multiple-depot vehicle scheduling problem). The number of vehicles of each vehicle type is a given constraint. For example, the type of a vehicle might be a regular (normal), low floor, long vehicle. A vehicle scheduling has to be created that fulfils the following constraints:

- each trip must be covered by exactly one vehicle,
- the vehicle schedules must be realizable: a schedule starts from and ends at the same depot, each task is performable in time (there can be no collisions in time),
- the capacity of the depots,

- and the depot-trip compatibility requirements must be met.

In general, the objective of the vehicle scheduling problem is to:

- minimize the number of vehicles,
- minimize the total length of the distances of the deadhead trips, or the total length of their time intervals,
- or find an optimal (minimum) weighted sum of the above costs.

In our cost model, there is a cost of the vehicle (assigned to the pull-out from the depot): it means a general cost even for the usage of a vehicle in a day. In our model, this cost depends of the vehicle type. It may be different for vehicles of different type, but it is the same for any two vehicles if their type is the same. We have an additional cost, namely the cost of a unit-distance-journey of a vehicle or a calculated cost per kilometer. The objective function is the sum of the above costs, and the goal is to minimize it.

For the solution of vehicle scheduling problem, many papers have been published in the past few decades using different models (see a review of these in [6] and a comparison of the different models and methods available in [13]). The so-called multi-commodity flow minimization model of the multiple vehicle scheduling problem (MDVSP) has two general formulations. The first one is the connection-based network model (Andreas Löbel, 1997, [11]) and the second one is the time-space network model (Natalie Kliewer et al., 2006, [10]). Both of them solve an IP-model, but in [10] the number of arcs is reduced in the network. Here, we applied the latter method for the scheduling of the vehicle shifts in a day.

In the vehicle assignment module of our system we apply a special assignment model, solving the resulting problem via LP-formalization [2]. In this part, we examine the refueling requirements as well. The input data values of the assignment module are the so-called theoretical vehicle shifts of the vehicle scheduling module, data for the given vehicles and geographical places. The fuel type of the vehicles is included as well.

The output of the vehicle assignment module contains vehicle schedules, where the vehicle is precisely identified. In addition, the vehicle shifts contains specific vehicle events like the events of parking and maintenance. The constraints of the problem are the current state of the vehicle (e.g. the number of distance kilometers traversed since the last refueling and the time of the last maintenance) and parameters for the vehicle (e.g. the maximum distance without refueling). The vehicle assignment step and module were elaborated on in an earlier paper of ours [2].

After the steps of vehicle scheduling and vehicle assignment, the output of these steps is the input of driver-scheduling. It should be added that the input for driver scheduling phase is the output of the vehicle scheduling phase; that is, the vehicle schedules are given in advance.

3. The solution of the driver scheduling problem

Now we will introduce some notions concerning driver scheduling and the prescribed working rules of the drivers. After, we will present the solution method for driver scheduling.

3.1. Working rules, as constraints for the driver scheduling

We begin with some basic notions and definitions regarding the working rules of the drivers. Work piece mean a valid sequence of trips and deadhead trips. Here, the term valid means that this sequence can be executed by one driver without a break. In a schedule of a driver there are some events. Events are the driving parts and the breaks of the schedules, the time interval of vehicle maintenance, and special events at the start and the end of a schedule. In general there might be some other rules and compulsory requirements concerning the daily, weekly, monthly work of the drivers. Some additional, specific requirements may need to be taken into account like the necessary driving licence types for some shifts.

In the driver scheduling part, we have to take into consideration some rules defined by the EU such as the

- maximum number of working hours (per day),
- rules for the maximum driving time,
- minimum lengths of breaks, resting time, etc.

and local rules, such as types of the events and shifts, additional local rules for the breaks, etc.

In the following, we overview the set of working rules we took into account.

The diameter of the schedule, which is the time between the beginning and the end, is at most 20 hours and the total driving time is at most 10 hours. Once a week the driving time may be longer than 10 hours, but at most 11 hours. And it may be longer than 10 hours only if the next day of the week is a day-off.
The rules for the breaks that we need to consider are the following:

- The length of a *break* is at least 15 minutes and at most 30 minutes; and the breaks may be given only in specific places (stations),
- A driver has to start their first work break after a maximum of 5 hours and 59 minutes,
- If the schedule is longer than 8 hours, then the driver has to start their second break after a work period of at most 8 hours and 59 minutes,
- If the schedule is longer than 9 hours, then the driver has to start their third break after a work period of 9 hours and 59 minutes,

- There is exactly one break in a given time period of a schedule (the time periods are the first 6 hours, second 2 hours, third one hour), and there cannot be two breaks in any period,
- If the schedule ends before the end of a time period, then it is not necessary to give the driver a break for the driver if a rest period commences before that time.

Additional working rules:

- After a shift there is a resting period, which is at least 12 hours (if there was not 2 hours or more resting time in the schedule). If there was a minimum 2 hour resting time in the schedule, then the resting time after the schedule must be at least 9 hours; but in this case the sum of the length of the longest resting time in the schedule and the resting time after the schedule must be at least 12 hours.
- In the case of a split schedule between any two schedule parts, the driver must have a resting time of at least 80 minutes. A split schedule must not contain any short breaks. If a schedule contained a break of at least 80 minutes, then it must be declared to a split schedule. A split schedule may contain two or more parts. In the latter case there must be a resting time of at least 80 minutes between any two consecutive schedule-parts, but the total length of these resting time intervals must not be longer than 5 hours.
- There is an administrational time at the beginning and at the end of a schedule for the driver. Both of them are of 15-15 minutes, except in the case of a split schedule. In the case of a split schedule, there is an administration time at the start and one at the end of *each* schedule-part. Their lengths are 5-5 minutes. There is also an administration period of 5 minutes for a change of driver.
- In a schedule, there are some cost events
  a) a vehicle maintenance period of 30 minutes,
  b) a special administration period of 10 minutes, and these events may be divided into 5-minute-long intervals.
- Before the beginning and after the end of each trip, there are two 2-minute-long intervals for passengers getting and getting off a bus.

Furthermore,

- if the period of a schedule is less than 4 hours, then the 4-hour working time has to be paid.

Below, we applied our method to regional public transport as well.
Driver rules for regional public transport include the following:

- Driver schedules are differentiated based on the lengths of the trips. If there is a trip longer than 50 km in a schedule, then we call it *long-trip schedule*; otherwise it is a *short-trip schedule*.
- For long-trip schedules, a work break of at least 45 minutes should be given after a 4.5 hours of continuous driving. This break may be separated into two parts, one being at least 15 minutes and the second being at least 30 minutes. The order cannot be changed, but the each time period may be longer.
- The daily maximum driving time is 9 hours, which may be 10 hours 3 times a week. The weekly maximum driving time is 56 hours and it is 90 hours in two weeks.
- The daily resting time is at least 11 hours in a 24-hour period. It may be divided into a minimum of 3 hours and 9 hours.
- The weekly resting time is at least 45 hours, which may be reduced to 36, but it should be compensated for in the 3 weeks following.

3.2. Our method for finding the solution to the driver scheduling problem

Next, we introduce the specification and optimization criteria of our driver scheduling module. The *input* of this module consists of the:

- vehicle schedules,
- vehicle data,
- driver data (driving licence types, contract types),
- geographical locations,

and its *output* is the driver schedules generated, which must be consistent with the set rules. So it means that our task is to *schedule the events*, i.e. the work pieces and the other daily events, subject to the *restrictions* (daily rules).

The cost model in the driver scheduling is generally a weighted sum of drivers' fee and the number of schedules. Our *objective function* simply minimizes the total cost, i.e. the simple sum of the driving costs and the cost arising from the number of schedules.

3.3. The mathematical model applied for driver scheduling: a set covering formulation

The most commonly used mathematical model for driver scheduling in the literature is the set covering approach or a very similar set partitioning approach. The solution of the driver scheduling problem got via this approach can be found in many papers (see, for example, [6,7,14]).

Using the set covering model for driver scheduling, we can formalize it as a 0-1 programming problem; namely

$$\sum_{d\in D}\sum_{k\in K^d} c_k^d x_k^d \to \min,$$
$$\sum_{d\in D}\sum_{k\in K^d(t)} x_k^d \geq 1 \text{ for } \forall\, t\in T,$$
$$x_k^d \in \{0,1\}\ ,\ d\in D,\ k\in K^d,$$

where

- T is the set of timetabled trips to be covered,
- D is the set of depots,
- K^d is the set of possible driver schedules from depot *d*,
- K^d*(t)* is the set of driver schedules covering trip t from depot *d*,
- $c_k^d$is the cost of schedule k from depot *d*.

By solving the set covering model of the problem defined in the above way, the main difficulty we encounter with this is that the number of possible driver schedule combinations is huge. Hence, it is not possible to generate them directly. Each driver schedule should just satisfy all the rules and requirements. For this reason, we applied a column generation approach to solve the problem. It is a general method applied in the literature, and it has a variety of applications.
The algorithm we applied to solve this problem is the following:

Solution algorithm

Step 1 Construct an initial column set by generating all possible work piece combinations from the vehicle schedules.

Step 2 Solve a relaxed master problem using the current column set K. Store the current lower bound and dual programming information.

Step 3 Solve the pricing problem and generate new columns with a negative reduced cost. Add the new columns to the current column set.

Step 4 If there is a significant improvement in the lower bound, then continue with Step 2.

Step 5 Construct an integer solution using branch and bound.

We will solve a so-called pricing problem applied in Step 3 to choose the new columns. For this, we solve a resource constrained shortest path problem on a specific network *(N,E)* with a given resource set R. This problem can be stated as:

$$\sum_{e\in E} \tilde{c}_e x_e \to \min,$$

supposing that

$$\sum_{e\in n^+} x_e^d - \sum_{e\in n^-} x_e^d = \begin{cases} 1, & \text{if } n \text{ is a source,} \\ 0, & \text{if } n \in N \text{ and } n \text{ is not source and not destination} \\ -1, & \text{if } n \text{ is a destination,} \end{cases}$$

$$a^r \leq \sum_{e\in E} d_e^r x_e \leq f^r, \text{ for each } r \in R,$$

$$x_e \in \{0,1\}, \text{ for each } e \in E.$$

The resources are used express some of the rules, i.e. the maximum working time, schedule duration, number of work pieces and so on. Other procedures are used in the pricing problem to check the validity of the generated schedules based on the drivers' rules. Invalid schedules are left out; they are not included in the generator.

3.4. An application of our driver scheduling method

As an application of the above method, we applied our method to the regional and the local public transport cases as well. Our initial results look promising.

The following table lists the results of the calculations that we made for the regional bus transport company in Szeged. We had to solve several different problems.

Problem	Number of trips	Number of vehicles	Number of drivers
#1	830	100	220
#2	902	105	226
#3	900	105	226
#4	951	104	196
#5	1465	175	303
#6	1467	175	280
#7	1483	174	300

4. Summary and future work

We presented a solution for the driver scheduling problem, based on the given vehicle schedules. The method we used was an integer programming formulation of a set covering approach. To demonstrate that our solution is not only realistic, but the approach is an application-oriented one, we applied this method to solve a concrete problem. The method presented is included in the software package developed for the Szeged public bus transport company, for operation management optimization.

As regards possible directions for future study, three issues that deserve a mention. The first issue is how to develop a method that fully integrates vehicle and driver scheduling and works effectively for real-world instances. The second is how to develop other efficient and good heuristics for the problem. And the third one is how to find a model that better handles specific requirements of a real-life scheduling problem.

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