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Proving the Versatility of Automatic Driver Scheduling on Difficult Train and Bus Problems✠

by

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Abstract

TRACS II is a driver scheduling system developed originally for the U.K. rail industry. It embodies a new shift generation approach, and recent research has enhanced the Integer Linear Programme solver. The system itself and some of the earlier exercises conducted were reported by Kwan et al. (1999). The ability of TRACS II to solve very complex rail problems enables it to become a generic tool for solving a wide range of driver scheduling problems including those relating to buses.

Bus and rail operators are devising imaginative and complex labour agreements that are attractive and acceptable to the drivers and attain maximum efficiency. The increasing use of computer assisted scheduling has enabled operators to extend the scope of their existing agreements. In the past two years, the applications of TRACS II have been extended to cover bus problems. There are many similarities between bus driver scheduling and train driver scheduling. However it has generally been believed that the bus driver scheduling problem is a special case of train driver scheduling because it is usually less difficult than the train problem. This paper will describe two complicated driver scheduling problems, one of which is a bus driver scheduling problem that is far more complex than usual for problems of its type. The other problem is a rail problem which is the largest and the most complex problem that has ever been tackled by TRACS II.

1. Introduction

TRACS II is a driver scheduling system which has been developed from an earlier system to schedule bus drivers. Its initial application was in the scheduling of train drivers for which special algorithms were developed. The system itself and some of the earlier exercises conducted are reported by Kwan et al. (1999), while the mathematical processes used are reported by Fores et al. (1999, 2000). The ability of TRACS II to solve very complex problems presented by rail operators is of great benefit to bus companies whose operations are usually less constrained. However they do present aspects of operation which are unique to the bus industry. The use of one system to produce schedules for both of these scenarios presents a serious technical challenge to the algorithms employed.

In a changing bus and rail world, operators must be able to react quickly to the forces of competition. While the geography of the network may govern what can be achieved feasibly on the ground, the manipulation of the drivers to produce efficiency and savings is one area over which an operator may have more control. Thus very many different rules are being devised, especially by bus operators, to try and put these savings into practice.

For the rail operator, the network of train work to be considered is often much larger than that for the bus operator. This implies the use of a great many places where drivers may be relieved and a large number of depots where drivers can be based. It also means that the type of operation, very rural through to very intensive urban, is often well mixed within the same schedule. The use of many more types of traction and the greater diversity of routes imposes more constraints upon the system than in the case of bus operators. Drivers from any depot will know only a subsection of routes and traction types, and these subsections can overlap. Nevertheless, train operators are compiling imaginative rules to overcome these problems, yet retaining and improving the working efficiency of their schedules.

Two of the recent applications of TRACS II which have successfully addressed these issues have been to a bus company based in Norwich, UK, and to the whole operation of one UK-based train operating company. These particular applications tested the computer algorithms to their utmost and have subsequently laid the basis for further research into the solution of large and difficult problems.

2. The TRACS II system

The TRACS II system has been described in Kwan et al. (1999), and Fores et al. (1999). A brief description is as follows. From a list of vehicle work for which drivers are to be provided, together with the necessary allowances for moving them around the network and a list of scheduling rules, a process which we call BUILD forms a large number of potential shifts which between them cover all the given vehicle work (generally many times over) and obey all the rules by which the driver schedule should be constructed. A specifically developed integer linear programming (ILP) process then selects that subset of shifts which covers all the work in the most suitable way.

3. Application of TRACS II in the bus situation – First Eastern Counties

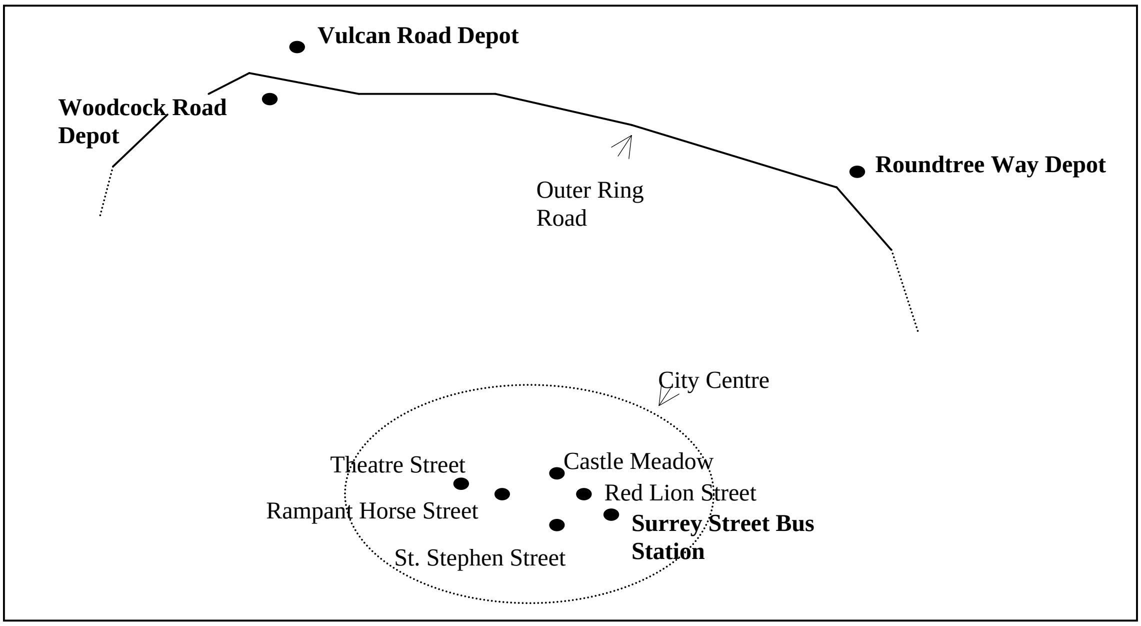

Figure 1: Locations of the Norwich Depots

Distances

Vulcan Road – Surrey Street 4 km

Roundtree Way – Surrey Street 5.3 km

Woodcock Road – Surrey Street 4.8 km

In the spring of 1999, FirstGroup set out a bus and driver scheduling exercise for potential suppliers of computer-aided scheduling systems. Meilton (2000) gives a detailed description and background of the test exercise. Briefly, the driver scheduling exercise was based on four possible scenarios derived from the Norwich Monday to Friday operations on the bus network provided within that city in Autumn, 1998. The network of services was operated by two classes of vehicle, namely, Super Low Floor Buses (SLF) and Conventional Buses. The time allowed to solve the whole problem, including the bus scheduling part was limited to 6 weeks. The driver schedule was to be based upon the bus schedule produced as part of this scheduling exercise. The bus schedule was produced three weeks before the deadline.

There were three depots located outside Norwich city centre: Roundtree Way, Vulcan Road and Woodcock Road which was a sub-depot of Vulcan Road. See Figure 1 for the locations of these. All vehicles returning to Woodcock Road at the end of service run via Vulcan Road depot to be refuelled and cleaned. A bus station at Surrey Street in central Norwich was also used as a driver signing on and off point. The existing operating conditions required drivers signing on and off at the same point. Hence there were effectively four driver depots.

671	Bus	Time	Route	From	To	Time	Duty	
Start				Roundtree Way Depot			671	
1203				Start & proceed to Ring Road (15 mins)				
		1218	27	Travel Passenger by service 1 to	St. Stephens Street	1241	671	
		1252	26	Stand By to Take over			671	
	9	1254	27	St. Stephens Street	University	1310	671	
	9	1315	26	University	Hellesdon	1402	671	
	9	1404	26	Hellesdon	St. Stephens Street	1444	671	
					Proceed to Red Lion Street		671	
		1532		Stand By to Take over			671	
	44	1534	19	Red Lion Street	Heartsease Estate, Sale Road	1554	671	
	44	1555	19	Heartsease Estate, Sale Road	Costessey, Longwater Lane	1664	671	
	44	1646	19	Costessey, Longwater Lane	Red Lion Street	1714	671	
					Proceed to Castle Meadow		671	
		1747		Stand By to Take over			671	
	23	1749	20	Castle Meadow	Costessey, Longwater Lane	1818	671	
	23	1819	LT	Costessey, Longwater Lane	Bowthorpe, Harpsfield	1824	671	
	23	1830	22	Bowthorpe, Harpsfield	Old Catton, Lodge Lane	1913	671	
	23	1915	21	Old Catton, Lodge Lane	St. Stephens Street	1938	671	
		2020		Stand By to Take over				
	19	2022	19	St. Stephens Street	Costessey, Longwater Lane	2042	671	
	19	2045	19	Costessey, Longwater Lane	Heartsease Estate, Sale Road	2129	671	
	19	2130	20	Heartsease Estate, Sale Road	Costessey, Longwater Lane	2212	671	
	19	2215	20	Costessey, Longwater Lane	Heartsease Estate, Sale Road	2259	671	
	19	2300	19	Heartsease Estate, Sale Road	Costessey, Longwater Lane	2342	671	
	19	2343	19	Costessey, Longwater Lane	Gatehouse	2354	671	
	19	2355	LT	Gatehouse	Roundtree Way Depot	2405	671	
	19	2405		Refuel, Park Car & Cash In			671	
					Off Duty	2420	671	
					Pay Hours			12:17

Start	**Finish**	**Spell**	**Break**	**Spreadover**
12:03	12:41	0:38	0:11	
12:52	14:44	1:52	0:48	
15:32	17:14	1:42	0:33	
17:47	19:38	1:51	0:42	
20:20	0:20	4:00		
		10:03	**2:14**	**12:17**

Figure 2: Example of a Norwich shift

There were two types of shifts: 'five day week' shifts which had a maximum length of 8 hours 30 minutes and 'four day week' shifts which were between 9 hours 45 minutes and 12 hours 59 minutes. There were no spreadover (split) shifts, i.e. a shift with a long spreadover and a long break in the middle. Figure 2 is an example of a four day week shift from the manual schedule. This is a typical example of the complexity of shift type in the Norwich schedule.
Shift 671 is one of the many four spell shifts in the manual schedule and can be interpreted as follows:

Start of Shift	1203
15 minutes is allowed to walk to Ring Road	1218
Travel passenger on route 27 to St. Stephens Street arrive	1241
11 minutes short break	1252
2 minutes is allowed to stand by to take over	1254
Take bus 9 at 1254 on route 27 and drive journeys as detailed until	1444 at St. Stephens Street
48 minutes mealbreak, during which walk to Red Lion Street	1532
2 minutes is allowed to stand by to take over	1534
Take bus 44 at 1534 on route 19 and drive journey as detailed until	1714 at Read Lion Street
33 minutes mealbreak during which walk to Castle Meadow	1747
2 minutes is allowed to stand by to take over	1749
Take bus 23 at 1749 on route 20 and drive journeys as detailed until	1938 at St. Stephens Street
42 minutes mealbreak	2020
2 minutes is allowed to stand by to take over	2022
Take bus 19 on route 19 and drive journeys as details until	2405 at Roundtree Way Depot
5 minutes to Refuel Bus	2410
5 minutes to Cash In	2415
5 minutes to garage car at end of shift	2420
END OF SHIFT	2420

The exercise involved producing schedules according to four different scenarios and each of these scenarios was treated as an independent problem. A detailed description of the operating conditions of each scenario can be found in Meilton (2000).

- Scenario one

This aimed to replicate the present operating conditions, and the schedule produced provided a comparison with the manual schedule. There was a desire to maintain the same number of shifts, which included the same distribution of 'four day week' shifts and 'five day week' shifts at two of the outer depots.

- Scenarios two, three and four

The objectives of these scenarios were to evaluate the cost implications of potential changes to the operating agreements.

3.1 Tackling the problem

3.1.1 Multi-depot

Unlike the usual practice in the U.K. bus industry where drivers were usually restricted to driving vehicles from their home depots, drivers in this exercise could work on vehicles from any of the depots subject to some restrictions on the classes of vehicle that could be driven. This implied that the problem had to be solved as a single problem. It would have been very difficult to sub-divide it effectively into four different sub-problems and inefficient schedules would have resulted.

TRACS II has the capability of tackling multi-depot problems since it was originally designed to solve rail problems in which the presence of many depots was a common feature. During the shift building process of TRACS II when all the possible shifts satisfying the user-defined parameters were being considered, an individual shift was assigned to that depot which gave the lowest cost for the shift. It was therefore necessary for the user to define the different allowances for each depot.

3.1.2 Drivers travelling as passenger

Since there were three out-of-town depots, and drivers were required to sign on and sign off at the same point (except Scenario Three and Four), drivers of these outer depots starting or finishing at the city centre had to be ferried on company buses between the depots and the city centre. Furthermore, in some cases a fifteen minute walking allowance was given to a driver who had to walk from the depot to a place on the Ring Road where he/she could travel on a bus to the city centre; the same applied in the reverse direction. For drivers who were travelling back from city centre to out-of-town depots, a further two minutes waiting allowance was given before the departure of the bus. This is illustrated in Figure 2. The driver signs on at Roundtree Way (no allowances) and 15 minutes allowance is given for walking from Roundtree Way to a point on Ring Road for the bus which arrives at there at 12:18. The bus arrives at St. Stephen Street in the City Centre at 12:41 and the driver has a short relief of 11 minutes before he/she takes over bus 9 as a driver. Passenger travel is also known as nominated travel in some bus operations in which the journey details of the passenger travel of the shift is to be determined.

There were two additional buses which were used to ferry drivers between the depots and the city centre during the day, and there was also a minibus available in the evening at the city centre which needed to be returned to one of the out-of-town depots. There were no fixed times for these buses to run and the objective of the exercise was to schedule their movements in the most efficient way.

Unlike rail operation where passenger travelling is used extensively within a shift, travelling was only required at the start or end of a shift and was not required during mealbreak or short relief which were usually in the city centre.

TRACS II contains a module called TRAVEL for finding all the possible passenger travelling trips for each relief opportunity. Finding the passenger travel trips from, say, Vulcan Road to Surrey Street in the city centre, involves two similar but separate searches: a *forward search* and a *backward search*. A forward search involves finding the earliest arrival time at Surrey Street, and the journey details, leaving at or after a specified start time at Vulcan Road. A backward search involves finding the latest departure time from Vulcan Road, and the journey details, to arrive at Surrey Street at or before a specified end time. In both searches, the exact times of departure and arrival of the relevant buses as in the timetable must be used and enough walking time (15 walk to Ring Road) must be allowed to change buses. The algorithm of TRAVEL, briefly, performs the two types of search for each relief opportunity to or from every other relief point. All the possible passenger travelling details are output to a file which is used by the subsequent shift building process, BUILD.

As for the minibus and two other bus journeys described above, however, there is no facility in TRACS to schedule a vehicle with no fixed arrival and departure time. We had to fix the times of these bus journeys as at current situation and then adjust the times manually after the schedule was obtained in order to link trips more efficiently.

3.1.3 Depot constraints on vehicle types and shift types

In Scenarios One and Two, there were complex restrictions on which types of vehicle the driver from a particular depot could drive. In addition, in some depots, the drivers could drive both types of vehicle, but not within the same shift.

For Scenario One, there were more complicated restrictions on the type of shift for each driver from a particular depot driving a certain type of vehicle. For example, drivers of Roundtree Way depot driving Conventional buses must be on a ‘four day week’ shift; Surrey Street Bus Station drivers who could drive on both types of vehicle must be assigned a ‘five day week’ shift.

In order to model these constraints precisely, it was necessary to use some artificial depot points so that, for example, there would be a Roundtree Way depot for driving Conventional buses only and another Roundtree Way depot for driving SLF only. Restricting the types of vehicle to a particular depot could be modelled in the same way as traction knowledge in rail problems. However, at that time, there was no facility in TRACS to restrict additionally the type of shifts formed for a particular depot and this facility had to be added to TRACS during the exercise.

3.1.4 ‘period of work’

There was a restriction on the maximum length of a ‘period of work’ to 4 hours 8 minutes. A ‘period of work’ could contain as many spells as possible separated by short reliefs of at least 15 minutes. The length of a ‘period of work’ was the total ‘wheel turning’ time only. There must be a mealbreak following or preceding a ‘period of work’ and a shift could have a maximum of three mealbreaks. Hence, in theory, a shift could have more than four spells on different vehicles and this would have increased the number of potential shifts enormously.

Instead of ‘work period’, TRACS previously used the concept of a ‘stretch’ to describe the work from the start of a shift to a mealbreak, or from a mealbreak to the end of a shift. However, the maximum number of spells in a stretch formed by TRACS was limited to two. A shift was formed by combining two stretches together separated by a mealbreak which was called a ‘main mealbreak’. Hence the maximum number of spells in a shift was four and in cases of four spell shifts, the second break had to be a mealbreak. However, some of the manual shifts in this exercise had three spells in a ‘period of work’ which is then followed by a mealbreak. Modification had to be made to TRACS so that when two stretches were combined to form a shift, the gap could either be a short relief or a mealbreak. If the gap separating the two stretches was a short relief and if either the first stretch or the second stretch also contained a short relief, then there would be three spells, all separated by a short relief, either preceded or followed by a mealbreak in a shift. This modification enabled more varieties of shifts to be formed, some of which turned out to be crucial in the final schedules.

3.1.5 Variable mealbreak length

In Scenario One, the mealbreak length for the ‘four day week’ shift could be variable. For instance, shifts that were over 11 hours long required two meal breaks totalling at least 80 minutes, of which each mealbreak had to be at least 30 minutes long. This was a feature which was new to TRACS. For the purpose of this exercise, the facility of having variable mealbreak length was added to TRACS.

3.1.6 Extra non-driving allowances

Different allowances were given to drivers taking over buses from the garage depending on the time of day. A longer allowance was given for the first journey of the bus from the garage at the beginning of an early shift; a shorter allowance was given otherwise. Likewise, different non-driving allowances were given to the driver at the end of shift depending on the location. Shifts finishing at all the out-of-town depots included a ‘cash in’ allowance and shifts finishing at the out-of-town depots with a bus were given additional allowances for parking and re-fuelling the vehicle.

All these extra non-driving allowances were being modelled as non-driving work, as in the train situation. There are four types of non-driving work in the train situation: preparation, disposal, mobilisation and immobilisation. Preparation is the work needed for preparing a train unit before it leaves the train depot; disposal includes work for disposing a train at the end of a day’s operation; mobilisation involves work for starting a train after it is left unattended at a platform or siding; immobilisation is the work of temporarily shutting a train unit which will then be left unattended. The allowances for these four types of work vary according to the traction type in the train situation. Although the actual work involved in this exercise was somewhat different to that involved in the train situation, the same basic ideas still applied. In order to model the different allowances for different types of bus starting from different depots, some artificial vehicle types had to be created. For example, vehicle type 1 referred to SLF buses starting from Vulcan Road while vehicle type 2 referred to SLF buses starting from Roundtree Way and so on. The extra allowance involved in taking a bus out from the garage was the ‘preparation’ and the ‘re-fuel, park and cash in’ became the disposal work.

3.1.7 Problem size

The manual schedule had 70 shifts which is a medium size problem in terms of number of shifts. However, there were many relief opportunities around city centre points. Also, because of the wide range of spreadovers allowed (up to 13 hours), while the maximum length of a period of work was only 4 hours 8 minutes, shifts usually contained four spells of work. In a few cases in the manual schedule there were even five spells. In Scenario One which contained the largest number of relief opportunities (887), an initial shift building process in the early stage of the exercise produced more than 600,000 potential shifts satisfying the parameters. In order to reduce this to a manageable size, some of relief opportunities had to be eliminated. There is a program module which can automatically de-select some relief opportunities, but it does not work well with a multi-depot problem and it was not possible to update it in time within the deadline. Some relief opportunities were therefore de-selected manually using the existing schedule as a guide.

Eventually, the problem was solved by deselecting manually about half of the relief opportunities. The problem size was therefore substantially reduced and TRACS II was able to produce good solutions. An effort was made to bring the de-selection program up-to-date and some of the de-selection strategies were changed as a result. This produced very comparable results to the manual de-selection process.

3.2 Results

The only comparison that could be made against any existing schedule was on Scenario One. The manual schedule had 70 shifts costing 764:49. The schedule for the base scenario produced by TRACS II had 69 shifts with a total cost of 756.25, which is cheaper than the manual schedule, and all the shifts conformed to the conditions stated.

In examining the existing manual schedule, there were a number of instances where shifts did not adhere to the existing conditions of Scenario One. For example, some of the shifts exceeded the maximum of 4 hours 8 minutes in one work period, some of the short reliefs were shorter than the minimum of 15 minutes. Had the computer system been allowed to break these conditions as in the existing schedule, TRACS II would probably have produced even more efficient schedules. Another observation of the manual schedule was that there were a number of shifts with five spells of work. The shifts which TRACS II produced have a maximum of four spells, which is desirable for operational reasons.

In summary, the results obtained by TRACS II for the four scenarios are summarised in Table 1.

Problem	**Number of Depots**	**Relief opportunities**	**No. of RO's used**	**Manual solution (cost)**	**TRACS II solution (cost)**
Scenario 1	4	887	440	70 (764:49)	69 (756:25)
Scenario 2	4	846	387	-	65 (702:08)
Scenario 3	2	846	387	-	77 (614:07)
Scenario 4	2	846	387	-	73 (669:19)

Table 1: Summary of results for First Eastern Counties.

Analysis of these results by FirstGroup, and further exploratory work reported by Meilton (2000), led to TRACS II being chosen as the driver scheduling system to be implemented throughout the Group, together with other components of the Schedules Office system. Meilton reports that in the further tests, savings of up to 4% of payable hours were achieved where scheduling had previously been done without the aid of computers, and over 1% in locations where previous computer systems were in use. The solutions were all considered operable by staff with local knowledge.

4. Application of TRACS II in the train situation – ScotRail

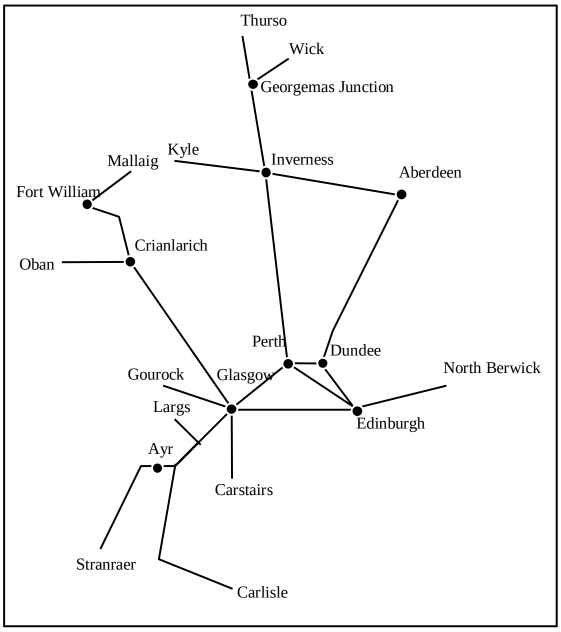

Figure 3: The ScotRail network

Distances
Edinburgh – Glasgow 75 km
Glasgow – Carlisle 184 km
Glasgow – Mallaig 263 km
Edinburgh – Inverness 302 km
Inverness – Wick 258 km
Inverness – Aberdeen 173 km
Inverness – Kyle 132 km

ScotRail operates a vast network service covering the whole of Scotland. Its network is shown in outline in Figure 3. It has a diverse operation comprising rural, inter-urban and very intensive urban operations. Its intercity service between Glasgow and Edinburgh operated a service with a train every 30 minutes at the time of this exercise. The operation in the Strathclyde area around Glasgow and the south west is not shown in the figure, but is very intensive and generates a large proportion of ScotRail's business. Apart from the Glasgow, Edinburgh and the southern part of the region, much of ScotRail's operation can be classed as very rural. For example, the 263 km from Glasgow to Mallaig was served by only four daily return trips, the 258 km between Inverness and Wick/Thurso had three daily return trips. It provides socially necessary services to some of the remotest parts of Scotland.

In 1998, ScotRail commissioned an exercise to use TRACS II to produce three sets of schedules, namely Monday to Friday (SX), Saturday (SO) and Sunday (SU) for their whole service network.

The data was based on the winter timetable of 1998. There were 19 driver depots throughout Scotland ranging in size from two drivers at Kyle, Mallaig, Oban and Stranraer to 73 drivers at one of the four Glasgow Depots giving a total of 365 drivers for Monday to Friday, 334 drivers on Saturday and 156 drivers on Sunday. In total, 64 relief points were identified, although it would have been beneficial to have had more for operational accuracy. There were 75 different routes and 25 different traction types.

For the Monday to Friday situation a total of 3,445 relief opportunities were noted with 3094 relief opportunities for Saturday and 1260 for Sunday.

For each of these schedules, because the problem was larger than could be tackled by TRACS II at that time, it was necessary to divide it into sub-problems. It was easy to form three self-contained problems comprising Glasgow North Clyde, South and West region of Glasgow and the rest of Scotland. This latter group was still too large for the capability of the system and it was not obvious how to divide it. Trains from Glasgow and Edinburgh serve Perth and Dundee, Aberdeen, Inverness and beyond, while trains from Glasgow serve Crianlarich and beyond. Initially services running beyond Perth were placed into a North area division with other services running to Dundee, while the rest was placed into a Central division. However some difficulties were encountered in that some of the north group of services were interworked with the central group and it was necessary to move some portions of train work around between the two divisions. Eventually a satisfactory division was achieved.

The four sub-problems based on different regions were thus:

1. South and West region of Glasgow;
2. North and East of Edinburgh;
3. Glasgow North Clyde;
4. Central, West Highland and Stirling

and each was run separately. As we were working to strict deadlines these four schedules were tackled concurrently by four different people. Work started with the Monday to Friday schedule which was the most difficult.

4.1 Data

The data for this exercise was already available on ScotRail's own computer system, which is a standard system used throughout the rail industry in the UK. We were able to gain access to this data through one of our industrial partners who also have facilities for converting the data into a format suitable for TRACS. ScotRail provided the scheduling rules and time allowances for signing on, signing off, walking where applicable, taxi rides, etc. ScotRail also provided the existing driver schedules. With such a large and diverse operation there were unfortunately discrepancies between the times in the data collected automatically and those in the existing schedules, usually just a few minutes, but sufficient to cause some existing shifts to be illegal unless times were changed.

4.2 Scheduling conditions

The scheduling conditions of ScotRail are very similar to other train operating companies in the UK:
- shift lengths can vary from 6 hours to 10 hours (except in four depots where the length could be up to 11 hours)
- there is a limit of 4 hours 30 minutes on continuous driving
- any turnround time which is less than 10 minutes is counted towards the continuous driving otherwise periods of greater than 10 minutes had to be subtracted from the running time between adjacent relief opportunities
- minimum times for signing on and off, dependent on location and traction type
- all shifts sign on and sign off at their home depot
- no depot should have more shifts than the current schedule
- drivers can travel between relief points as passengers on scheduled trains, or in certain cases by taxi

- no train can be left unattended unless it has been immobilised; special time allowances exist for immobilisation and mobilisation
- drivers require at least 10 minutes to change trains
- there can be up to three meal breaks in a shift
- meal breaks take place between the *m*th and *p*th hour, depending on shift duration
- the lengths of the meal break vary depending on the shift length. For shifts whose spreadover was longer than 9 hours and with three meal breaks, their meal breaks can be of different lengths, e.g. two 15 minutes meal breaks plus one 30 minutes meal break.

This latter condition caused a problem for the shift generation process as it did not cater for different meal break lengths in a shift at that time. However, after inspecting ScotRail's existing schedule, only four shifts out of the about 400 shifts had three meal breaks and most of these four shifts violated the precise combinations of break lengths permitted according to the conditions specified to us. In view of this it was decided that no special arrangement for different meal break lengths was to be implemented in this exercise.

After the first set of results was produced from TRACS II, some re-grouping of work between the sub-problems was needed in order to achieve the same distribution of shifts amongst the depots as in the manual schedule. For example, the TRACS II results produced a total of 29 shifts assigned to Perth depot whereas the manual schedule had 26 shifts at Perth and there were 36 Glasgow Queen Street shifts in the TRACS II solutions compared to 47 in the manual schedules. Hence work originally falling in the North and East of Edinburgh (sub-problem 1) had to be re-assigned to the Central sub-problem (sub-problem 4). There was some other similar re-distribution of work in the other depots. Details of how the division was made can be found elsewhere in Fores et al. (2000).

4.3 Calibration

It is important when conducting a scheduling project for a new client that the system should be used first with existing train schedules and existing rules, so as to ensure that schedules can be produced which are comparable with (hopefully better than) existing schedules. The first task is to ensure that existing driver schedules adhere to the given rules. Inevitably, many shifts violate some rules, or use relief times that contradict the train schedule. The rules then have to be amended to reflect the situation in practice.

Schedules are then produced according to the rules as now perceived, and checked against the existing schedules. If the computer-produced schedule is inferior to the manual one in any respect, it is necessary to determine whether any given rule is still violated in the manual schedule. If the computer schedule is better, it is necessary to determine whether the shifts formed can actually be operated.

4.4 Problems

There were many problems encountered in this exercise. Many of them were attributed to data errors. In addition, there were some computational difficulties. The ILP process as it existed at the time (see Fores et al., 1999, 2000) had difficulties in finding any solution for the North Clyde Saturday data. Several ILP runs were tried with different target numbers of shifts but each time there was no solution found in the branch and bound process. Considerable experiments had to be undertaken in order to refine the parameters before TRACS II produced an acceptable solution. The Edinburgh data demonstrated very similar difficulties. The most difficult problem in running TRACS in a multi-depot rail or complex bus situation is probably determining the minimum number of shifts for which a solution can be obtained by the ILP. Whereas in our traditional bus driver scheduling work, an integer solution has almost always been attainable at the target level (relaxed total rounded up if necessary), this is seldom possible in rail operations. The difficulty in setting the target arises, at least in part, from the fact that it may be necessary to round up each depot separately from the relaxed solution. This will give an "ideal" solution. However, even if the ideal is known, it is often very difficult to find it.

There were also problems in dealing with the very special mode of operation which occurs in the running of the more remote services north of Glasgow and Inverness. For example:

- on the service which operates between Glasgow and Crianlarich and beyond, the southbound train stops at Ardlui from 0940 to 0944, and the northbound train stops there from 0941 to 0943. During this short time period the drivers change trains, so that the driver from Glasgow on the northbound train may return there within his shift time by exchanging with the Fort William (or Oban) driver on the southbound train, who may also return to his base depot within his shift length. However the scheduling rules did not allow this type of operation. (No train can be left unattended unless it is immobilised, and no driver can change trains in less than 10 minutes.) At Ardlui (and some other places, including Aberdeen) these two rules have to be waived.
- In a similar way these rules have to be waived at Crianlarich, the next station along the line from Ardlui. Here the northbound train divides with sections to Oban and Mallaig. Normally the Oban section was shown as a separate train, and so should have required a 10 minute changing time, but often it was that section that should be driven by the through driver.
- At Garve, on the Inverness to Kyle of Lochalsh line, an Inverness-bound driver changes over with a Kyle-bound driver, and if this is not done, an extra shift is needed. However Garve is not a designated relief point. The solution was to modify the train data to pretend that the train from Kyle turned back at Garve, returning to Kyle, and similarly with the train from Inverness.

4.5 Overcoming the problems

Nearly all the scenarios studied involved running the BUILD process several times with the parameters set differently to generate different mixes of shifts, and then merging the results of these separate runs before proceeding to the ILP process. Typically there would be a run to build two part shifts, then a run to build three and four part shifts; this was sometimes followed by another run to generate shifts with different characteristics to those generated earlier. The reason for having separate BUILD processes was due in part to the limits imposed by the software at the time that the work was being undertaken, but also ensured that a wide range of possible parameters could be considered.

4.6 Project timetable

The project started in late October 1998, and after overcoming these problems, the first satisfactory Monday to Friday schedule was finalised in late November. Work was started immediately on the Saturday schedule followed by the Sunday schedule. The Saturday schedule was produced in December and the Sunday schedule was produced in early January 1999.

4.7 Results

Date	Problems	Depots	Relief opportunities	Manual solution	TRACS II solution	Savings %
Nov 1998	SX	19	3445	365	350	4.1
Dec 1998	SO	19	3079	334	314	6.0
Jan 1999	SU	19	1264	156	141	9.6

Table 2: Summary of results for ScotRail

The results of the exercise are summarised in Table 2. It will be seen that on each of the three sets of schedules, TRACS II yielded considerable savings over the manual process. This demonstrates that although it was necessary to divide the whole of Scotland into four sub-problems, TRACS II can still produce schedules that are considerably better than those achieved by manual schedulers who generally cannot examine all the complexities, and are restricted to even smaller sub-areas.

Although TRACS II in some cases has used more shifts at some depots than were used previously, there were many cases where a shift could be worked from either one of several depots. TRACS II has always chosen the depot which can work the individual shift most economically. If this requires too many shifts at some depot, the possibility of using another depot can be considered, although in some cases the operator would be prepared to exceed the previous number in the interests of efficiency. Wherever TRACS II produced more shifts than previously at some depot, the possibility of using another depot was considered. If this was not possible, then a constraint was set on the number of shifts at the offending depots, and the ILP part of the system was re-run. Generally this was not necessary. For example, on Saturdays, three of the shifts assigned to Inverness either started at Inverness and finished at Aberdeen, with drivers returning to Inverness as passengers, or vice-versa. These three shifts could be assigned to Aberdeen at a small increase in cost.

5. Conclusions

The application of the TRACS II scheduling system to these two complex problems has demonstrated that the system is flexible and able to accommodate all manner of difficult operating strategies. The two problems are very different: one having relatively straightforward scheduling conditions but with a vast operating network bringing with it all the problems of validating and consistency of data; while the other had a relatively modest network serving a city with a population of 173,000, but exhibiting types of scheduling rules which were not easy to implement with the system as it was at the start of the project. That both projects were completed against a strict deadline proves in itself that the system is versatile and able to be applied in all types of situation.

Using the system in such a way has been invaluable in providing material and expertise to develop the system further so that problems of this type can be solved as a matter of routine. Fores et al. (2000), describe how the ScotRail problem has been used in exactly this way. We were able to demonstrate satisfactorily to FirstGroup that the system was flexible enough to accommodate all the subtleties of a complex operational strategy, and work has now commenced on installing the system throughout the 26 companies of FirstGroup, operating about 9,000 buses between them.

6. References

Fores, S., Proll, L., Wren, A. (1999): An improved ILP system for driver scheduling. In: Wilson, N.H.M. (Ed): Computer-Aided Transit Scheduling. Springer-Verlag. pp. 43-61.

Fores, S., Proll, L., Wren, A. (2000): Experiences with a flexible driver scheduler. Presented at CASPT2000 – the 8th International Conference on Computer-Aided Transit Scheduling, Berlin.

Kwan, A.S.K., Kwan, R.S.K., Parker, M.E., Wren, A. (1999): Producing train driver schedules under different operating strategies. In: Wilson, N.H.M. (Ed): Computer-Aided Transit Scheduling. Springer-Verlag. pp. 129 – 154.

Meilton, M (2000): Selecting and implementing a computer aided scheduling system for a large bus company. Presented at CASPT2000 – the 8th International Conference on Computer-Aided Transit Scheduling, Berlin.