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TIME, COST AND CO_2 EFFECTS OF RESCHEDULING FREIGHT DELIVERIES

***Andrew Palmer*[1], *Maja Piecyk*[2]**
[1]*Cranfield University, Cranfield*
[2]*Heriot-Watt University, Edinburgh*

Introduction

Traffic congestion can significantly impair the efficiency and performance of logistics systems. As transport infrastructure reaches its capacity, ensuring a smooth, reliable and cost-effective road freight operation is one of the main challenges faced by logistics managers. Between 2004-5 and 2007-8 the total delay to all journeys in England increased by 8.1%, followed by a decline of 10.5% in 2008-9. Even though this gives an overall decline of 3.3% from the 2004-5 baseline year, it is likely to be a temporary result of a recent decrease in vehicle traffic caused by difficult economic situation. According to Department for Transport (2009), “2008 saw the first year on year fall in overall motor vehicle traffic (0.8 per cent) since the 1970s. This fall was probably due to a combination of higher fuel prices, which peaked in July, and the economic slowdown which turned into a recession during the second half of the year” (p.10). Once the economic situation improves again, the traffic volumes and associated congestion levels are likely to reverse back to their long-term upward trends. This view is consistent with an official forecast compiled by the UK Department for Transport. In the central scenario, congestion (measured as seconds lost per vehicle km relative to free flow speeds) across the English network is expected to increase by about 37% between 2003 and 2025. This represents an average increase in time spent travelling of 6% (4 seconds for each kilometre travelled) (Department for Transport, 2008a).

Faced with a constrained capacity of existing transport infrastructure, road network users need to modify their travel behaviour. According to Crowley (1998), transport users may adjust their travel pattern to the network congestion in the following ways:

- Absorbing delays on the routes chosen;
- Re-routing to alternative, indirect routes;
- Changing destinations;
- Postponing travel to off-peak times;
- Not travelling at all.

As the main objective of logistics systems is to ensure a cost-effective, smooth and reliable “procurement, *movement* and storage of materials, parts and finished inventory (…) through the organisation and its marketing channels” (Christopher, 2005, p.4), the opportunities for eliminating the need for freight transport are largely limited. Although some physical goods may be substituted by their virtual equivalents (e.g. CDs, DVDs, newspapers and magazines, etc.), the vast majority of products continue to have a material dimension inflicting a need for travel as they pass along the supply chain.

Changing destinations is also not a viable option in the freight transport sector. Goods need to be delivered to where they are required and altering destination points would imply a long-term change in internal network or customer base configurations. Logistics systems tend to have relatively fixed structures and any changes to locations of company’s premises are a result of decisions taken at higher levels in the organisational hierarchy (Piecyk and McKinnon, 2010). Day-to-day transport management issues such as congestion are unlikely to result in modifications to the network design. In the case of outbound distribution, goods need to be delivered to customers’ premises thus opportunities for influencing locations of these are even more limited.

Freight transport operators may also choose to absorb congestion-related delays and revise their delivery schedules to accommodate longer transit times. In practice, however, congestion also causes variability in journey times from day to day, reducing the reliability of transport operation. Research shows that predictability of journey times is far more important than the extra time associated with a congested infrastructure. A high level of certainty as to the expected arrival time is crucial to ensure effective utilisation of a fleet (Fowkes et al., 2004). A similar argument is developed by McKinnon et al. (2009). They argue that if traffic congestion were regular and predictable, companies could mitigate its effects at little additional cost by building extra slack into their operation schedules. However, traffic flow on a congested road network becomes “unstable and much more sensitive to incidents such as accidents, breakdowns, road works and bad weather. Transit time variability then increases and the reliability of deliveries deteriorates. Most of the adverse effects of congestion on logistics performance are associated with this unreliability” (McKinnon et al., 2009, p. 331).

Re-routing of delivery vehicles is one of the options. However, there are some limitations to using alternative routes. For example, an alternative route may be too long, not suitable for increased HGV traffic, subject to HGV access restrictions etc. Also, if too many vehicles use the diverted route, it eventually becomes congested and the operator is faced with the initial problem.

Postponing travel to off-peak times enables transport operators to use their vehicles more efficiently by taking advantage of free-flow traffic conditions. The issues associated with off-peak delivery operations are discussed in the next section.

Night-time / off-peak deliveries

As mentioned above, one way of absorbing network congestion is to reschedule travel to avoid peak traffic periods. The percentage of lorry-kms run between 8pm and 6am increased from around 8% in 1985 to almost 20% in 2005 (McKinnon et al., 2009). However, much of this growth occurred before the early 2000s. There has been virtually no change in the distribution of truck traffic by time of day and day of week over the last decade (Figure 1).

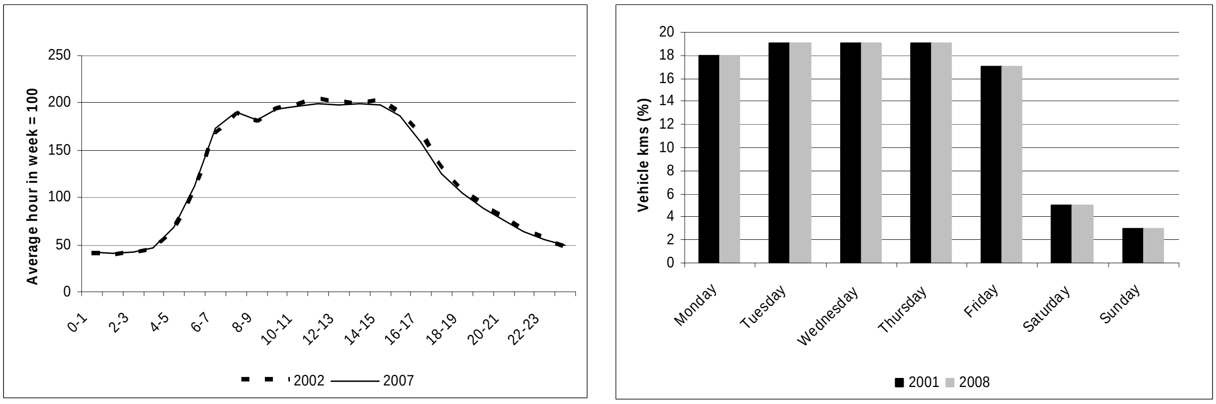

Figure 1. Hourly distribution of HGV traffic (weekdays) and weekly distribution of distance travelled by HGVs

The benefits of rescheduling road freight transport operations are usually considered in the context of urban distribution. Deliveries, especially in urban areas, can be subject to several different types of time restrictions such as night-time restrictions imposed by authorities at the point of delivery, access time restrictions in pedestranised areas, area-wide loading and unloading time restrictions on the kerbside or delivery time restrictions imposed by the receiving unit (Browne et al, 2006). Thus, delivery schedules need to accommodate a number of constraints, which quite often leads to a sub-optimal utilisation of vehicle fleets. Reduced delivery cost, better environmental performance, improved levels of customer service are amongst the most often listed potential benefits from relaxing these constraints and rescheduling road freight transport operation to off-peak times (Holguin-Veras, 2008).

However, only limited attempts have been made to directly quantify the benefits of rescheduling deliveries. Cooper and Tweddle (1990) present a comparison of two hypothetical fleets: one operated on a basis of a single day shift and one where vehicles are operated for two shifts per 24 hours. They prove that there is a clear financial benefit from operating vehicles on a 24 hour basis but acknowledge that it results mainly from a reduced fleet size rather than from lower fuel consumption and transit times. Their calculations are also sensitive to a number of assumptions, particularly as to the frequency of vehicle replacement, residual values of vehicles and uncertainty over levels of future costs incurred by the company. A recent three-month night-time delivery trial undertaken at Sainsbury's supermarket in Wandsworth, in cooperation with the UK Freight Transport Association and the Noise Abatement Society, resulted in reduced journey times (60 minutes per trip), delivery costs (£16000 per annum) and CO_2 emissions (68 tonnes per annum) while no noise-related complaints were reported (Freight Transport Association, 2009). Also, Fisher et al (2010) estimated that, in the UK, even a 1% increase in out-of-hours deliveries would generate £18 million savings per annum in external costs associated with congestion, accidents and noise.

Several studies, nonetheless, question the environmental benefits of rescheduling deliveries. Based on his analytical models, Campbell (1995) concludes that it is not clear that switching to off-peak operation would reduce environmental performance of trucks and improve air quality. A more recent research warns that there may be some unintended environmental impacts of night-time freight activities due to lower temperatures decreasing the speed at which pollutants are dispersed to higher altitudes. This may result in an overall increase in 24-hour average concentrations of diesel exhaust pollutants in many locations (Sathaye et al., 2010). This paper examines the time, cost and CO_2 benefits of rescheduling more freight deliveries to off-peak times. In terms of environmental impacts, it focuses on direct tailpipe CO_2 emissions and does not consider meteorological conditions.

In order to quantitively assess the time, distance and CO_2 implications of rescheduling deliveries, a computer model was developed, using a modified shortest path algorithm with the ability to examine variable journey start times (VST). This model incorporates a road network with hourly traffic volumes for each of the links in the road network. Speed flow formulae are applied to these traffic volumes to obtain a unique speed by time of day. Road freight movements between source and destination locations are then input to the model to find the optimum routes based on defined minimisation criteria of time, distance or CO_2, for different journey start times ranging from 5am to midnight. The hours of 1am to 4am were omitted because any routes starting in the early morning hours before 5am are unlikely to be congested and would therefore produce the same results for each start time. However, the model still allowed for vehicles to travel during these omitted hours if a journey started at, say, midnight.

Methodology

Traditional vehicle routing and scheduling (VRS) software consist of algorithms that attempt to optimise the routing of vehicles so that deliveries (or collections) are made in the most efficient sequence minimising either the time taken, distance travelled or cost. This is achieved by calculating delivery routes based on a matrix of times and/or distances between all delivery locations and depots. This matrix will have been derived from a digitised road network containing a series of nodes (points on a map) and links (roads connecting those points). The nodes would correspond to some location on the road network such as a motorway exit, junction, roundabout, traffic lights. The links would contain information about the road between the nodes. Typically this would be a distance and a road category against which a constant average speed would be applied in order to calculate the time to drive that distance. The times and distances for each link would be applied to a shortest path algorithm, to produce a matrix of the quickest or shortest routes between locations. Most VRS packages allow for a speed reduction, as a percentage of the standard speeds, at certain times of the day thereby allowing for rush hour congestion. Speed reductions can also be applied by area, such as town centres. Despite this, the use of fixed speeds by road category means that all links in a road network having the same road category and distance will produce the same time to travel that distance. In reality, those same links will each have different combinations of congestion levels at different times of the day, and delays associated with road furniture such as traffic lights and roundabouts, and road topography and geometry such as inclines and bends. All this will cause variations in the average speed and therefore produce different times over links with the same road category and distance.

The model developed for this study uses Highways Agency (HA) sensor data from over 4,500 detector loops on the major roads throughout England. This data was aggregated to show the average hourly traffic volumes for a typical weekday, with a standard deviation to indicate the variability of the traffic volumes. A digitised road network of the UK consisting of nodes and links was also used in the model. The hourly traffic volumes from the HA sensors were allocated to the appropriate links in the road network. Any link without a sensor was allocated traffic volumes typical for the type of road. Each link also represented a two way flow so the direction of road travel for the traffic volumes was also considered. Using HA speed flow formulae (Highways Agency, 2003) which calculates a speed for a given traffic volume on a specific type of road, each link in the road network was then given a series of speeds which was used to calculate the time for a vehicle to travel along the length of the link depending on the time of day on which the link is used. However, as a vehicle travels from one link to another, the speed of the vehicle will change to reflect traffic volumes for the new link, and the time of day. If the road type of the new link is different from the one just used, there is an assumption in the model that the node connecting the two links corresponds to either a roundabout, traffic lights or junction, in which case the vehicle will slow down to a halt. The model takes into account this reducing speed and that a vehicle will remain stationary for a period between 10 seconds and 4 minutes depending on the traffic volumes on the link section just travelled, i.e. the level of congestion. These speeds and link distance were also used to calculate the fuel consumed by a vehicle, so that CO_2 emissions could be calculated for any route.

For a given journey start time at a node in the road network, Dijkstra's shortest path algorithm was then adapted to take into account the arrival time at subsequent nodes in a potential route, and therefore the consequent speeds and vehicle travel times on the following links in the network, to reach a destination node.

There were three sets of freight data analysed by the model. The first set comprised of 21 source and destination locations used in a previous ITF/OECD study (McKinnon et al, 2009). That study also used the same road network and HA sensor data to look at transit time variability, but the analysis was based on an overall average daily traffic volume on a link rather than hourly changes in traffic volumes. The second set of data were 23 source and destination locations based on the largest inter regional flows as defined by the Continuing Survey of Road Goods Transport (DfT, 2008a). A regional centroid was selected for each of the nine regions considered by weighting the population and coordinates of the major locations in a region. This centroid was then allocated to the nearest node on the road network. One of the important issues arising out of the model results is the reliability of the output. Consequently, a third set of data were obtained from a major retailer. This data showed planned start and finish times, and distances, produced by the companies VRS software, and the actual times and distances achieved by the vehicles. A selection of 12 source and destination locations were analysed in the VST model.

Effects of rescheduling deliveries

Time minimised routes - combined analysis

In the first instance, because the general pattern of results for each of the three datasets were very similar, the outcomes have been combined. The graphs below show the best and worst start times for all 56 journeys modelled, compared with the average distance travelled.

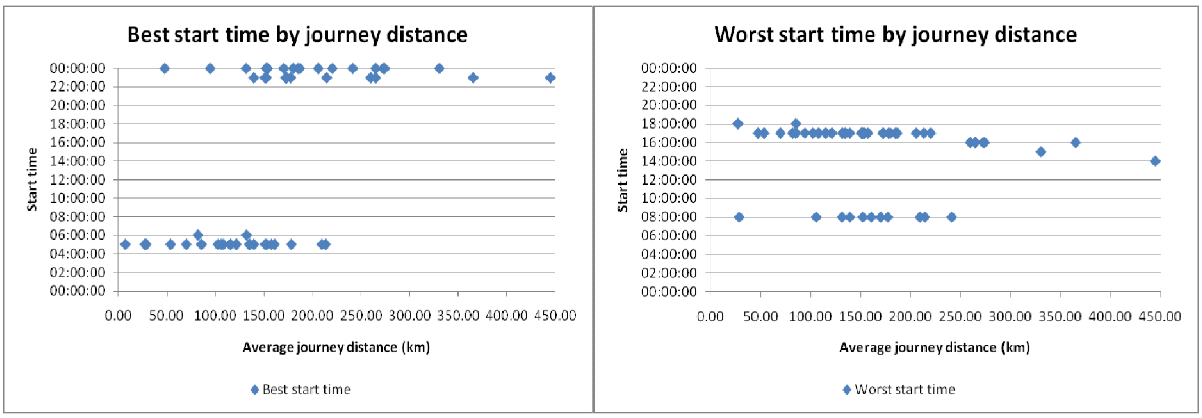

Figure 2. Profile of journey start times

All the model results indicate that the best start times occur just before midnight or during the early hours of the morning. Longer journey distances tend to show start times around midnight. This is a fairly obvious outcome since congestion is unlikely during these times and vehicles would be able to travel at optimum speeds. The worst start times all occur across the morning or evening peak periods.

For distances in excess of 250km the evening peak period is more likely to be the worst time to start a journey with start times moving towards late afternoon as distances become greater. A typical journey profile is shown in the graphs below.

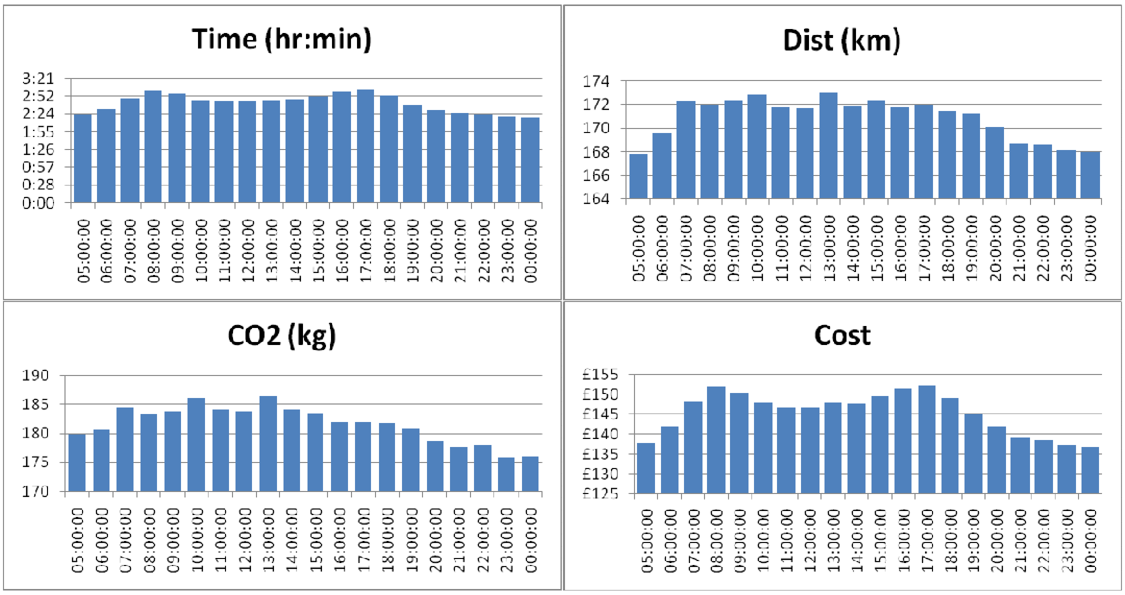

Figure 3. Profile of a typical journey based on different start times

The time graph shows that midnight is the best start time for this particular route producing a distance of 168km and lasting 2.3 hours. The worst times are clearly shown during the morning and evening peak hours, with the worst case travel time being nearly 3 hours over a distance of 170km. Even the off peak daytime hours incur higher journey times than the early morning or late evening start times. Based on all 56 journeys there is a difference of 29% in the travel time between the fastest journeys, typically starting in the early morning hours, compared to the slowest journey times, typically starting during the morning and evening peak hours. There is a 16% reduction in travel time when comparing the fastest journey with an average journey time.

In the example above the average journey distance is 171 km, but varies by +/- 3km depending on the start time. The varying distances show that different routes are being chosen to minimise the travel time depending on the start time of the journey. This example shows a relatively small variation in comparison to other routes as can be seen in figure 4 below. Journeys starting in the early hours of the morning or late evening show a lower overall distance as well as time which means, because of the light traffic, that vehicles have the opportunity of taking a more direct route. The routes taken at peak and off peak start times during the day are both longer in hours and distance reflecting the vehicles taking circuitous journeys to avoid congestion. The costs for the routes at different start times reflect the time taken and distance travelled. With the time related costs of a vehicle being about two thirds of a vehicle operating cost, the profile of costs for different start times are very similar to the route time profile, with the lowest costs occurring during the early morning and late evening. No allowance for increased out of hours driver's costs have been considered.

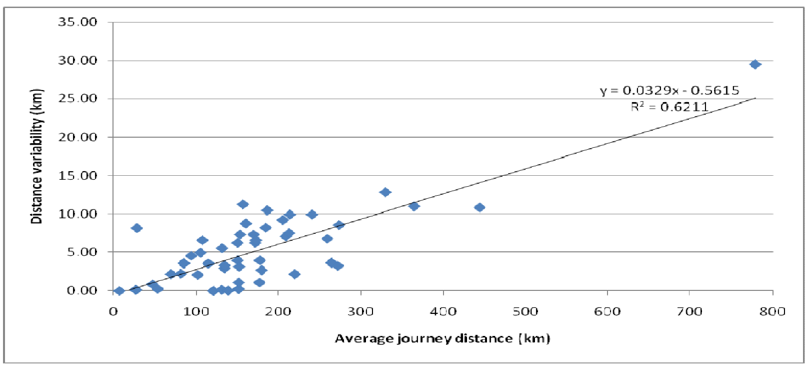

Figure 4. Start time distance variability against average distance travelled

The CO_2 emitted reflects the speed of the vehicle on each road link and the distance travelled along the link. There is a variability which shows higher CO_2 emissions for the longer route distances such as those journeys starting between 7am and 7pm. The optimum start time for minimising CO_2 is after 11pm. As with time, based on all 56 journeys, there is a difference of 11% in the CO_2 emitted between the fastest journey and the slowest journey times. There is a 6% reduction in CO_2 emitted when comparing the fastest journey with an average journey time.

Some of the route distances differ significantly by time of day as can be seen in the graph below which shows the level of distance variability against the average route distance.

Figure 4 shows that there is some correlation between the length of a journey and the variability in the route distance. There are exceptions such as one route with an average distance of 28km varied by as much as 8km in an attempt to minimise the route time. Generally, shorter journeys are likely to have less flexibility in changing to different routes.

Time minimised analysis - ITF study routes

The original study results were based on a stochastic simulation of traffic volume on each link in the road network. This variability of traffic produced a range of speeds on each link, but were not based on hourly volumes. Twenty one fixed routes were simulated between 7km and 780km producing trip times between 9 minutes and 13 hours. In this study the VST model decided on the optimal time minimised routes between each of the 21 source and destination locations, for journeys starting each hour between 5am and midnight. Thus there were 420 routes produced for this dataset. An ANOVA test between the maximum trip times and the minimum trip times from results of this and the ITF studies show a relationship between the groups. The ITF maximum trip times were higher than those in this study because the VST model was reacting to the need to minimise time and avoiding congested routes. The minimum trip times were significantly lower than those in the ITF study because the model was able to find quicker routes during off peak periods. The table below shows the comparative differences.

	Current VST study			ITF Study		
Route number	Average dist (km)	Max Trip Time (mins)	Min Trip Time (mins)	Average dist (km)	Max Trip Time (mins)	Min Trip Time (mins)
1	7.00	8.00	8.00	7.0	10.4	7.9
2	28.47	41.00	28.00	31.5	46.0	31.5
3	47.44	52.00	40.00	47.0	93.6	64.5
4	53.55	61.00	45.00	60.7	97.9	77.2
5	69.81	75.00	60.00	74.2	108.0	81.2
6	81.87	93.00	67.00	87.9	124.3	96.5
7	94.35	112.00	79.00	102.2	124.4	106.3
8	102.31	104.00	84.00	116.8	181.1	149.0
9	131.38	140.00	112.00	131.2	269.8	219.6
10	131.77	153.00	108.00	146.6	256.1	196.4
11	160.71	172.00	123.00	162.1	193.8	163.9
12	170.09	188.00	134.00	179.5	335.7	280.6
13	205.64	212.00	155.00	196.7	257.5	224.1
14	209.28	213.00	172.00	215.3	252.8	216.0
15	241.12	256.00	186.00	235.8	281.5	244.8
16	220.15	236.00	180.00	259.4	285.7	256.4
17	259.58	269.00	220.00	287.1	530.1	461.6
18	330.36	341.00	253.00	320.3	517.0	445.2
19	365.09	393.00	295.00	367.7	414.4	352.5
20	444.77	477.00	360.00	454.5	600.4	521.7
21	779.25	806.00	599.00	773.3	834.3	764.1

Figure 5. Differences between ITF and current study results

Time minimised analysis - CSRGT derived inter-regional routes
The top 23 flows between the regions, as defined by the DfT (2008b), were identified as a reasonable sample for analysis by the VST model. These flows, highlighted in bold, were as follows:

Origin	North East	North West	Yorkshire and the Humber	East Midlands	West Midlands	East of England	London	South East	South West
North East		5	**10**	1	1	-	-	-	-
North West	7		**15**	**9**	**15**	4	1	4	3
Yorkshire and the Humber	**10**	**18**		**18**	7	7	2	3	1
East Midlands	2	**14**	**19**		**19**	**17**	5	**11**	4
West Midlands	1	**12**	5	**16**		8	3	7	6
East of England	-	3	5	**15**	8		**21**	**18**	3
London	-	1	1	3	2	**11**		**13**	1
South East	-	3	2	8	8	**11**	**16**		**11**
South West	-	3	1	2	7	2	2	**9**	

Figure 5. Goods lifted by origin and destination region of goods: 2008 (million tonnes)
Source: Table 1.33: Continuing Survey of Road Goods Transport, DfT

These flows represented a total of 328 million tonnes of goods moved between the 9 regions analysed in this dataset, accounting for about 68% of all goods moved. Based on a vehicle with a capacity utilisation of 20 tonnes, this represents 16.4 million vehicle movements, by nearly 12,000 vehicles. With a potential time saving of 16% when comparing the fastest journey during the night, with an average journey time, this could reduce the number of vehicles travelling between regions by nearly 2,000, and reduce CO_2 emissions by 6%.

Time minimised analysis - retailer modelled routes
The retailer provided a sample of routes with times and distances between depot and delivery points. Start times for these routes ranged from 6am to 11pm. These were compared with the routes produced by the VST model, for the same start times as specified by the retailer. The results showed that the VST model generated routes with an overall difference of 2.6% less time than the retailer routes, although individual route times varied by between +/-15%. The retailer could not provide the actual routes used between locations, so it was not possible to assess why or how these variations occurred. When the routes produced by the VST model for the retailers start times were compared with the best start times, there was an opportunity to save 10.6% in travel time. There was also a reduction of 3.6% in CO_2 emissions by changing to the optimum start times.

Conclusions
This paper examines the opportunities companies have to mitigate the adverse effects of congestion on their road freight transport operations by rescheduling more of their traffic to off-peak times. Based on 56 sample journeys, it demonstrates that significant time, cost and CO_2 savings can be achieved by increasing the percentage of vehicles operating at off-peak times. In terms of minimising the travel time, for journeys up to 100km early morning (around 5am) prevails as the best start time. For journeys between 100 and 200km best start times occur either early in the morning or around midnight, while for distances over 200 km night-time operation is most time-effective. Morning and evening peak times are the worst start times for trips up to 250km and late afternoon for journeys above that. Additionally, for a typical journey modelled for the purpose of this research there was up to 2% variation in the distance travelled, 6% in cost, 15% in time and 5% in CO_2 depending on the start time.

As the average distance travelled by trucks in the UK is currently 87km, this research suggest that rescheduling more road freight traffic to early morning hours would allow companies to benefit from minimum transit times and increased reliability of deliveries. However, detailed analysis of an individual company's circumstances is recommended to identify best operating schedules and optimum routes.

A practical relevance of the modelling work presented in this paper was validated by replicating the results based on theoretical routes derived from the CSRGT data and previous ITF study, with 'real-world' operational data obtained from a large retailer. More research is currently underway to examine additional routes provided by other companies.

Further research is also being undertaken to examine best and worst start times when minimising CO_2 is the optimisation criterion. So far, early indications for CO_2 minimised routes show a potential of 3.1% saving in emissions between the time and CO_2 minimisation options, with variations between 1.6% and 5.1% depending on whether the best or worst start times are used. Initial results also suggest that free – flow driving conditions do not necessarily lead to the best performance in terms of fuel consumption and related CO_2 emissions. Operating trucks during congestion – free periods, especially at night-time when there are only very few other vehicles on the roads, is likely to result in higher driving speeds. When vehicle speeds increase above a certain level (i.e. around 75 km/hr for a 44 tonne lorry), fuel efficiency and environmental performance deteriorate rapidly. These conclusions, however, still need validating.

In the light of results presented in this paper, it is surprising that the proportion of vehicles operating at off-peak times stabilised in early 2000s and has not increased since. It suggests that there are a number of different operational constraints preventing companies from shifting more transport to off-peak times. Further research is currently underway to investigate causes of this situation.

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