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CALIBRATION & VALIDATION OF PARKING SEARCH TIME FUNCTION

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ABSTRACT

Large off-street car parks are traditionally modelled as self standing traffic zones representing origins/destinations in standard network assignment models. However, such a treatment precludes the drivers from choosing alternative car parks as it assumes the car parks are their final destinations. This paper discusses the feasibility of bringing car park choice and the effects of capacity within a traditional network assignment model. The search time within car parks depends on the car park occupancy and can be represented by a flow-delay type function on the car park occupancy/capacity. This research calibrates the search time function based on practically observed occupancy, search time at two city centre car parks in Leeds, England. The analysis follows a simple fixed search time method as well as a sophisticated variable search time method. The results are validated against the observed occupancies at the car parks. A Car Park Specific Constant was introduced to account for the unobserved preference for a given type of parking facility. In a multi-period assignment, when car park occupancies are passed on dynamically, both fixed and variable search time approaches are seen as an improvement over the standard approach, with the variable search time outperforming the fixed time approach.

Key words: network assignment, parking location choice, parking search time.

1. INTRODUCTION

Car parks play a critical role in the context of an urban transport policy. It is generally regarded that a policy on limiting the supply of parking and/or increasing parking fees is one of the potential means of restricting car use (IHT, 2005). Restricting the car use at a given location, however, may lead to a diversion of demand to other activity centres and/or nearby car parks in the neighbourhood. It is noted that traditional transport network models do not explicitly include interactions between parking demand/supply. The only option they offer is to treat large off-street parking places as stand-alone traffic zones. Most models do not offer any options to model on-street parking. This approach implies that the drivers do not have a choice of parking location as they get assigned to their respective destination zones. Due to this lack of choice (in the modelling procedure), traffic flows assigned to modelled car park zones may not match with the observed occupancies at car parks resulting in a significant problem with their validation. Moreover, the diversion of demand from competing car parks cannot be studied if the car parks are modelled as isolated traffic zones and another approach is required.

The literature on parking mainly covers two broad research areas (i) economic/behavioural models and (ii) network modelling approaches. Economic models deal with the economics of parking mainly at a macro level (e.g. Arnott and Inci 2006, Shoup 2006) while many others consider the parking choice behaviour of individuals at a micro-level using a discrete choice approach (Hunt and Tepley 1993; Thompson and Richardson 1998; Hensher and King 2001; Bonsall and Palmer 2004; Hess and Polak 2004). Network modelling approaches can be based on a macroscopic approach (Nour Eldin et al 1981, Gur and Beimbourn 1984, Bifulco 1993, Lam et al 2006, Feng and Duangao 2009) or microscopic simulation approach (Belles et al 2007, Benenson et al 2008). Finally, a few other papers address parking policies (Petiot 2004, Marsden 2006) drawing policy conclusions based upon some modelling and/or empirical studies.

Shoup (2006) considers the trade-off between parking for free at an on-street parking site and expensive but quickly available off-street parking, and then discusses pricing strategies to reduce cruising for parking. Arnott and Inci (2006) attempted to derive the traffic speeds from the density of cars in transit/ cruising for parking within a macro-economic framework. On the other hand, network-based approaches focus on representing the network supply to a great detail and aim to assign the demand satisfying certain equilibrium conditions. Gur and Beimbourn (1984) studied the parking location choice using an equilibrium framework and followed a simple static approach. It is noted that the static approach followed by Gur and Beimbourn does not account for time varying occupancy of car parks. Although they attempted to predict the parking allocations by varying the demand levels in a sensitivity test, it was limited to a uniform factor which increases or decreases the demand by a pre-specified factor over the period of analysis. Due to this limitation neither the impact of varying levels of demand over a period of time nor the interaction across the time periods could be studied.

Bifulco (1993) extended the network modelling approach and developed a quasi-dynamic model using the time-slicing method. Lam et al (2006) formulated an equilibrium model which solves user equilibrium flows using a time dependent approach with multiple user classes and multiple parking facilities connected to destinations by walk links. It is assumed that the drivers initially make a joint choice of departure time and parking duration, before deciding on a route that minimises the overall disutility from an origin to a destination, thus replicating a hierarchical choice structure, much in a similar manner to that in Abrahamsson and Lundqvist (1999), for example. The main finding of this study is that the parking behaviour of drivers is significantly influenced by factors such as level of demand, capacity of car parks, parking charges and the distance of car park to the ultimate destination. Both Bifulco (1993) and Lam et al (2006) provided simple numerical examples which are aimed at illustrating the theoretical capabilities of the model and solution properties. However, for the network modelling approach to be brought a step closer to practice, there is a need to apply the model to real networks by calibrating the parking search time function.

The research reported in this paper follows the time dependent approach discussed by Lam et al (2006) and adds to it by calibrating/validating the car park search time function against observed data from a case study of two car parks in Leeds, England. It is noted that while several others (Young et al 1991; Wong et al 2000; Tong et al 2004; Lau et al 2005) have studied the empirical nature of parking accumulation/demand, there is still a need to combine empirical evidence on parking search time within the network modelling approach. Thus, our research adopts an applied path in undertaking a study of search time within car parks. This paper describes the results of calibration/validation of search time functions and presents an analysis of demand based on two separate modelling approaches which use either a simple, fixed or a sophisticated variable search time embedded in assignments undertaken over several successive time periods. It also analyses the empirical significance of search time within a car park relative to the route travel time for some arbitrarily selected OD pairs within the real network.

The rest of this paper is divided into three sections. Section 2 introduces the modelling approach suggested by Lam et al (2006) and outlines the theoretical principles involved. In particular, it focuses on describing the search time function and its inclusion in the generalised cost equation. Section 2 also lists out the steps involved in applying the time dependent method. Section 3 presents the numerical studies and discusses the search time/occupancy profiles at two car parks in Leeds. It also calibrates the search time functions and then validates the occupancy observed at each of the car parks. Finally, Section 4 summarises and concludes the results obtained from the research.

2. MODELLING SEARCH TIME IN CAR PARKS

2.1 Modelling preliminaries

The modelling method considers drivers who have a choice of where to park. Those who do not have a choice of where to park e.g. those who use private non-residential spaces, are still included in the assignment in the traditional manner but are assumed to park at their destination zone as in standard practice. It is assumed that the drivers are rational in their choice of routes and would choose a route which minimises costs including the cost of parking compared to alternative feasible routes. It is also assumed that alternative car parks are available near the destination zones which are well connected by suitable walk links. It is noted that Benbow et al (2008) also connect car parks by walk links, however, they use discrete choice models to estimate the parking location choice. In contrast, we follow a network assignment based on an equilibrium approach following the principles of Wardrop's user equilibrium (Wardrop 1952).

Car park operators may choose to set charges depending on the location and duration of parking, (for example, city car parks may charge more compared to those which are further from the town centre). The choice of a car park from a driver's point of view depends on factors such as the size and type of the car park, its occupancy/search time, parking charge and the distance from the car park to the ultimate destination. This can be formally expressed in the generalised cost equation (measured in time units) as in Lam et al (2006) below:

$$C_r^{kt} = \tau_r^t + \theta_s^k S_p^t + \theta_z^k Z_p^t + \theta_w^k W_p^t + \eta_p \quad (1)$$

where,

τ_r^t = path travel time along route *r* during the departure period *t*

S_p^t = search time in car park *p* during departure period *t*

Z_p^t = parking charges at car park *p* during departure period *t*

W_p^t = walking time from car park *p* to the ultimate destination during departure period *t*

θ_s^k = value of search time relative to the path travel time

θ_z^k = time value of parking charges

θ_w^k = value of walk time relative to the path travel time

η_p = unobservable preference for car park p, if any.

In equation (1), the term representing search time is central to this research and hence merits further explanation here. Firstly, search time can be thought of as dependent on the physical size/shape of the car park. More significantly, the search time depends on the occupancy of a car park relative to its capacity. It is hypothesised that a car park can be represented as if it were a *link* in a network which has a given capacity and a minimum travel time. Consequently, car park capacity can be equated to the *surrogate link* capacity and the minimum search time in the car park can be represented by the free flow (minimum) travel time on the link. The search time function is detailed further in §2.2.

2.2 Search time function

The search time within a car park depends on the occupancy of the car park at any given time and the overall capacity of the car park. In a multi-period context, the occupancy is accumulated over time. Thus the search time within a car park *p* at a given time *t* is defined as a function on accumulated occupancy and capacity as shown below:

$$S_p^t = s_p^0 + \lambda_p \left(\frac{\sum_{i=1}^{t} x_p^i}{Y_p} \right)^{\mu_p} \tag{2}$$

where,

s_p^0 = minimum search time in car park *p*

x_p^i = flow into car park *p* during departure period i

Y_p = capacity of the car park *p*

λ_p, μ_p are the calibration parameters for the car park *p*.

2.3 Incorporating car parks into a network model

As noted earlier, in most network models, large off-street parking facilities are usually defined as traffic zones in their own right. In such cases, road links in a network model are directly connected to the parking zones. However, in the proposed model, we need to modify the existing network by adding a few new links/zone(s) to the network at appropriate locations. Consider the network in Figure 1(a) where there are two competing parking zones which are currently not connected (as in standard practice). Figure 1(b) shows the changes required to implement the proposed approach. Firstly, a link is inserted to represent search times in each car park between the centroid connector of a zone where a car park exists, and the first road link on the road network. Second, walk links are added from the car parks to both ultimate destinations. This will allow the drivers a choice of car park on their way to their ultimate destination. Third, a dummy zone is inserted for each car park to allow for the pre-loading of car park links from previous time periods which accounts for the cumulative parking effect on search times. Finally, each car park link needs to be associated with its properties such as capacity, minimum search time, search time at capacity and a calibration parameter which is based on the outcome of the calibration exercise described later.

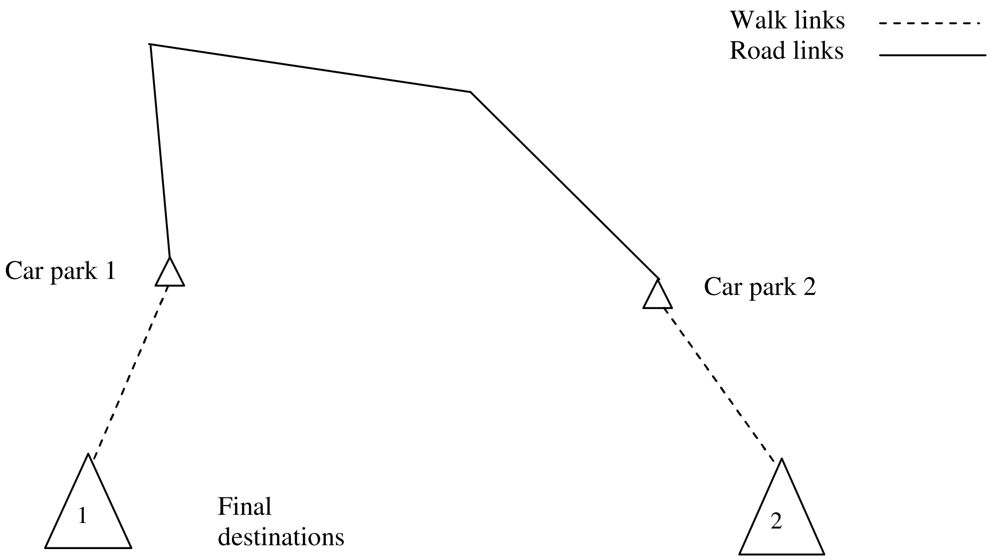


Figure 1(a) Standard Network Model

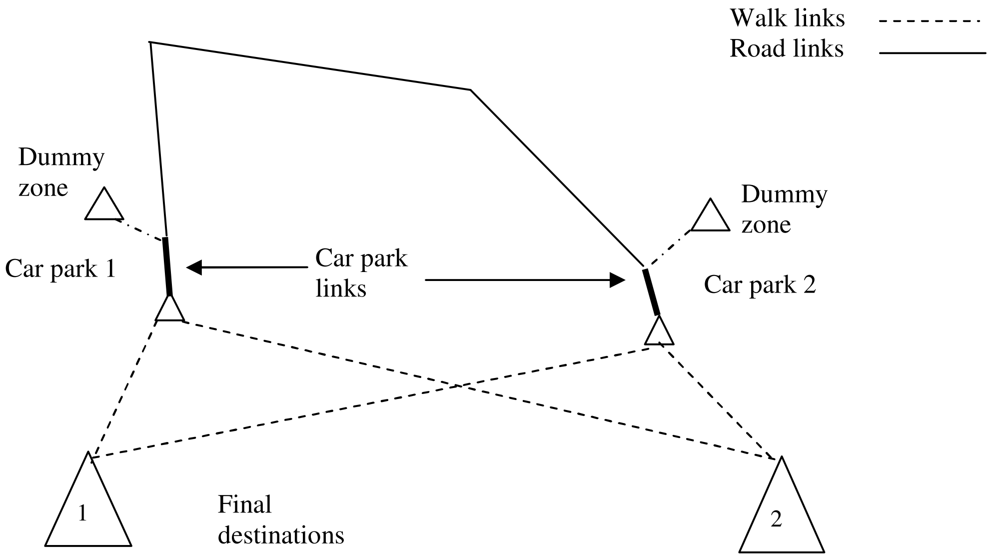


Figure 1(b) Modified Network Model with Additional Elements

Each dummy zone is used to pre-load the car park link with the number of cars which are already present in the car park at the beginning of any time period. As part of this step it is also necessary to expand the Origin Destination matrix to make it consistent with the number of dummy zones in the network. The steps involved can be summarised as below:

2.4 Algorithm for modelling car park search time

Time period $t = 1$:

i. Set the parking link characteristics e.g., minimum search time, capacity, λ and μ (from calibrated values –see later).
ii. Add a dummy origin zone to the tail node of each parking link
iii. Adjust the size of OD matrix to be consistent with the number of zones in the network
iv. Assign updated OD matrix for the time period
v. Obtain the demand for parking from the assignment results
vi. Update the flows in the *dummy parking zones* to represent the parked cars

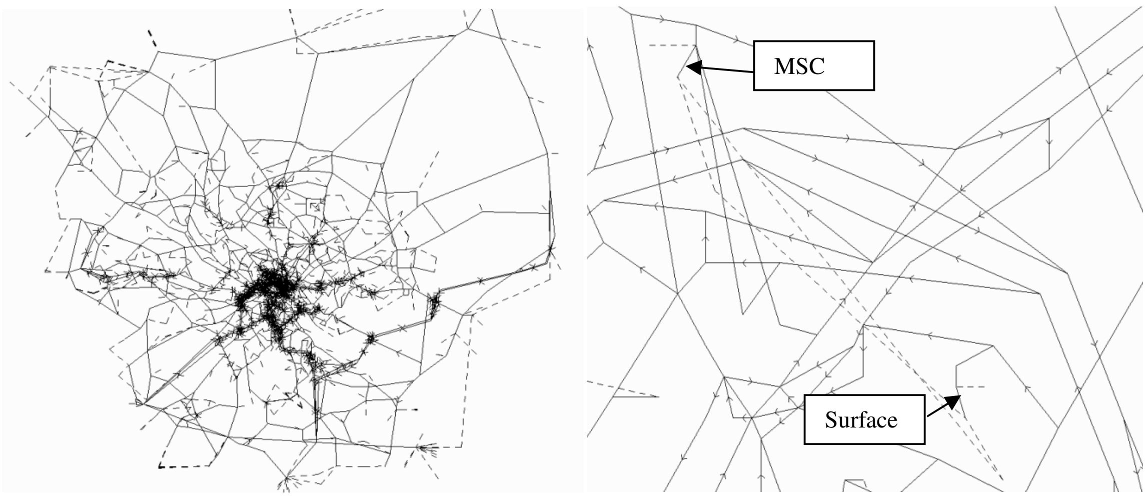
vii. Set $t = t + 1$, and go back to step (iv) until all time periods are simulated.

3. NUMERICAL STUDIES

In this section we illustrate the Cumulative Occupancy Method with the data commonly available to practitioners. In particular, an OD matrix and a coded network for the city of Leeds implemented in SATURN (Van Vliet, 1982) have been used. Search time functions described in the previous section and walk links have been incorporated into SATURN data files. Although we have used SATURN for illustrating the method, it is noted that any other similar network assignment model can equally be used.

3.1 Leeds city network

Leeds is one of the major cities in England which has transformed into the largest financial centre outside London over a period of time. Leeds is located in the county of Yorkshire and has an extensive road transport network. This research work adopted the latest version of the available coded road network, which is continually being updated. Travel demand is represented in the form of an OD matrix with 478 traffic zones including the external zones outside the Leeds district. Figure 2(a) shows the full network and Figure 2(b) locates the two selected car parks viz., Woodhouse Lane car park (which is a multi-storey car park – referred to as MSC) and Clay Pit Lane car park which is a surface car park (referred to as Surface car park). While the network links are shown as continuous lines, connections to zonal centroids are denoted by dotted lines.



(a) Full Network (b) Network Around Selected Car Parks

Figure 2 Leeds Modelled Network

3.2 Calibration of search time functions

For any model to be used in practice, it is very important to calibrate the model first and then validate the outcome of the model against some observed real situation. It is important to note that the parameters, s_p^t, λ and μ in car park search time in (2) will need to be calibrated to reflect the observed situation at a car park.

3.2.1 Search time and car park occupancy

As part of this study, two closely located car parks (offering alternative choice to park), near the town centre of Leeds were selected. Clay Pit Lane (Surface Car Park) is a car park with a capacity for 275 cars and follows a ‘pay and display’ type charging system. Woodhouse Lane Car Park is a multi-storey facility (MSC) and uses a ‘pay at the exit’ system. It has a capacity for 900 cars. Both car parks are managed by the city council, with charges of £3.80 ($5.95

US) at Surface Car Park and £4.00 ($6.26 US) at MSC for up to 5 hours. At each of these car parks, the search time was observed on a typical working day during the AM period for six hours starting from 7am. Simultaneously, the parking accumulation was also noted and Figures 3 and 4 show the accumulation and search time profiles observed at Surface Car Park and MSC, respectively, between 7am-1pm. See the Appendix for comments on the data collection method.

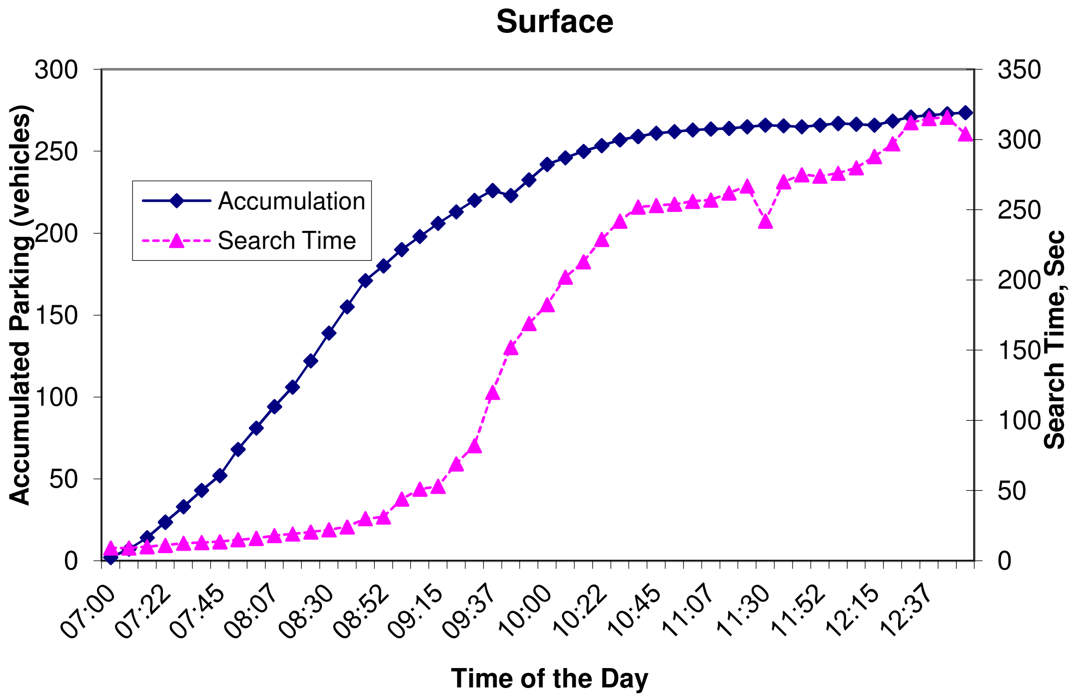


Figure 3 Surface Car Park – Observed Parking Accumulation and Search Time

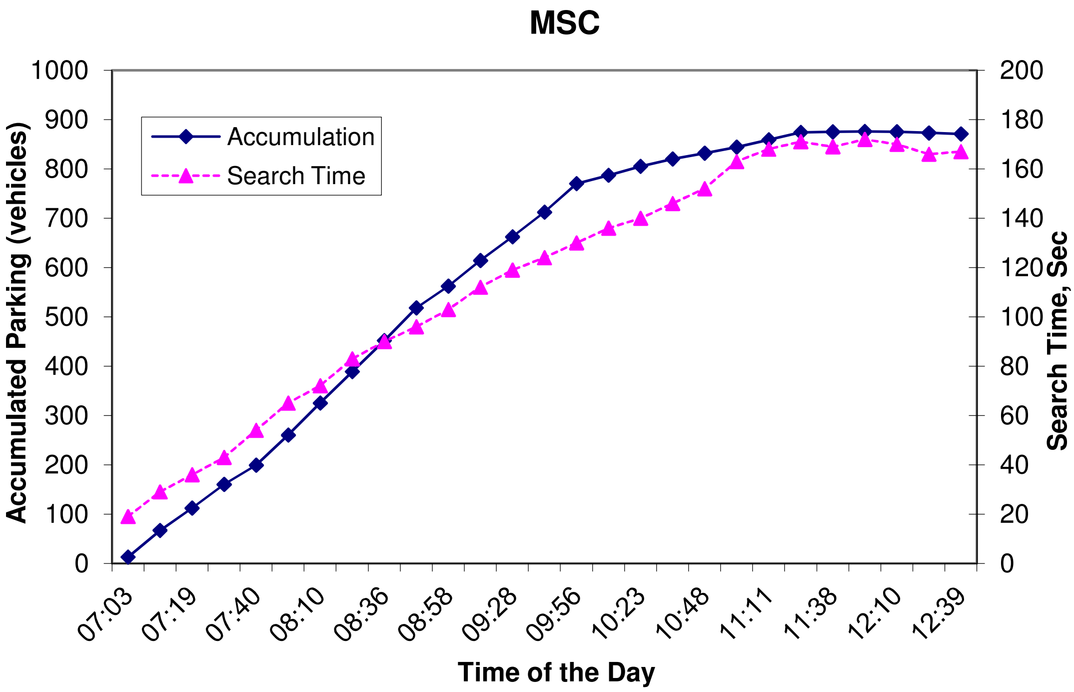


Figure 4 MSC – Observed Parking Accumulation and Search Time

The accumulation profiles at both the car parks are similar which increase steadily starting from no occupancy at 7am to near capacity by mid-day. However, the search time profiles are quite different. At the Surface Car Park, once the occupancy reaches around 200 vehicles, the search time increases steeply from 50 seconds and it then levels off to a final value of 320 seconds at capacity. However, the search time at MSC increases uniformly with an increasing level of accumulation, and reaches a final search time of 175 seconds at capacity. This observation reflects the physical nature of the facility with multi-storey car park requiring steadily higher traverse times as they get filled gradually from the lower levels to upper ones – but with relatively less searching act needed. The next and the subsequent paragraphs discuss the calibration and validation of the search time function at Surface Car Park and MSC.

3.2.2 Calibration of search time function at Surface car park

Figure 5 plots the observed number of cars in the car park against the search time (shown by scattered diamonds). It also shows a calibrated BPR-style search time function (shown as a continuous line). When the car park was empty, the minimum search time was observed at 9 seconds, and when full, a maximum of 320 seconds were needed to find a vacant place to park. Finally, the best fit values of the parameters λ and μ were worked out to be 311 and 5 respectively, using a standard minimisation of least squares approach.

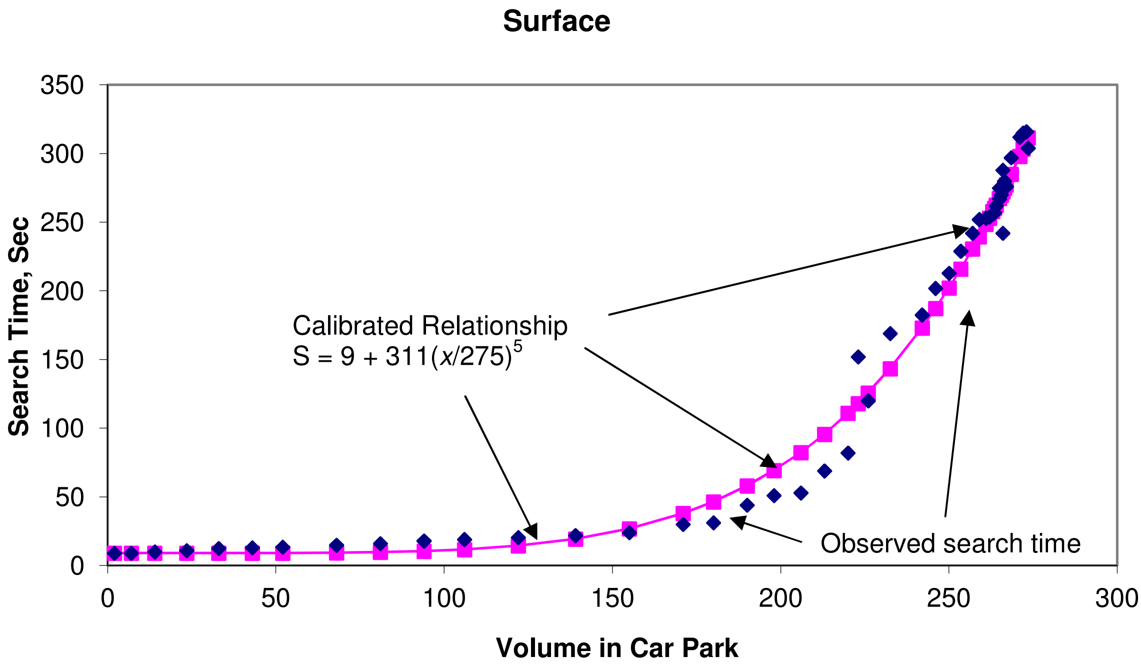


Figure 5 Calibration of Search Time at Surface Car Park

3.2.3 Calibration of search time function at MSC

At the beginning of the day when the car park is empty, 19 seconds were needed to find a place to park, however, it required 175 seconds to search when the car park is nearly full. Calibration parameters were worked out at λ = 156 and μ = 1.2 (See Figure 6). In MSC car park, the search time increases steadily with an increase in the number of parked cars compared to a steep increase at the Surface car park. This is mainly attributed to the movement of cars to higher levels, however, drivers appear to require a much longer search time at the Surface car park when it is nearly full.

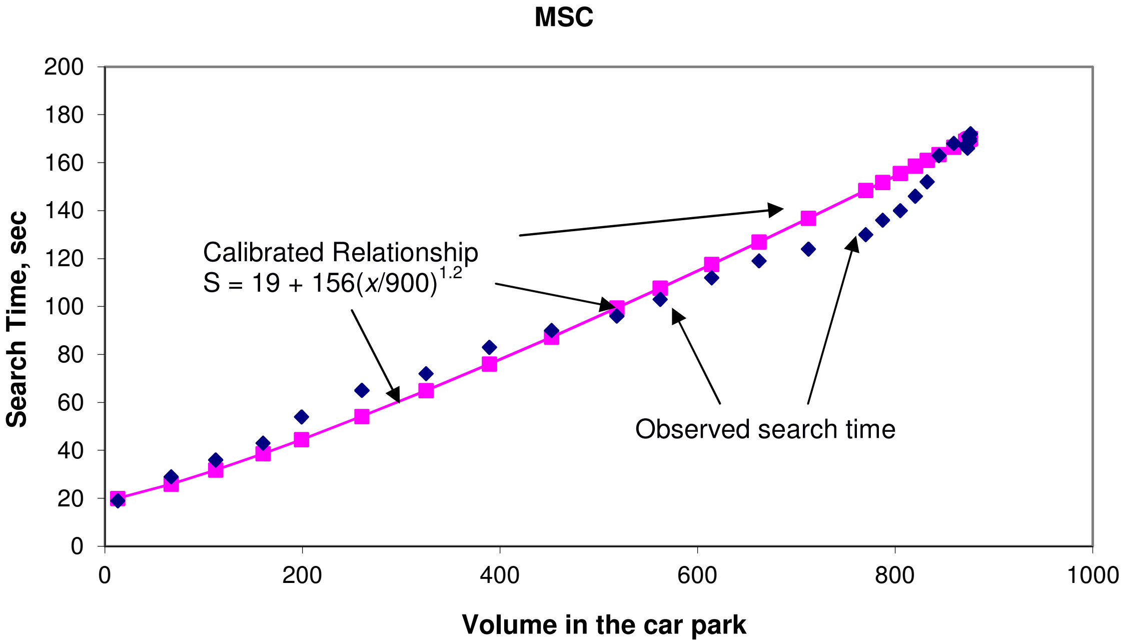


Figure 6 Calibration of Search Time at MSC

3.3 Validation of the model

The validation process checks and ensures that the calibrated model produces outputs with a reasonable level of accuracy. As part of this process we have incorporated the calibrated car park links into the network model and assigned the traffic to the network to estimate the demand on each of the car park *links*. While defining the characteristics of car park links, published parking charges (Leeds City Council 2009) at both the selected parking locations were incorporated into the network model. In particular, parking charges applicable for long stays have been applied as we have observed that the demand accumulates (See Figures 3 and 4) during the AM period with few leavers and peaks by mid-day. The model can also deal with the parking duration similar to that in Lam et al (2006). Secondly, it is noted that the search time within the car parks varies significantly over this period. In order to reflect such changes in search times, the model is run over multiple time periods rather than using one peak period of a few hours duration which is typical in practice. For this reason, we set up a series of hourly assignments starting from 7:00 and ending at 13:00. Modelled and observed flows are compared and their agreement is assessed by the GEH[1] statistic which is commonly used in traffic modelling. In general, GEH values ≤ 5 are taken to be satisfactory.

3.3.1 Base and test cases

In order to test our approach it was first of all necessary to expand the matrices used in the current Leeds model to cover the full period of interest. As the current network also treats the car parks as separate destinations then some thought was given to what should be a reasonable base case. With isolated car parks as destinations and the demand based on a previous matrix, we found that the results were poor in terms of demand for each car park. So much so that the total demand for Surface Car Park exceeded the capacity of the car park

[1] GEH statistic, similar to the chi-squared test, is commonly used in traffic modelling and is recognised by the UK Highways Agency's *Design Manual of Roads and Bridges* (DMRB Volume 12, Section 2, pp 4/28). GEH measure of any two sets of traffic flows (usually modelled and observed flows) x and y is given as $GEH = \sqrt{2(x-y)^2/(x+y)}$. GEH avoids the shortcomings associated with using simple percentages, and values of GEH ≤ 5 are considered satisfactory.

by a factor of four. We therefore decided to adjust the base case around the modified network with choice between car parks. The total demand for both car parks over the period was factored into a revised matrix so that it was in line with the observed data. In other words we have artificially adjusted the demand matrix to be consistent with the total demand for both car parks in each time period. Whilst this may not be in line with practice it allows us to investigate the impact of moving from a fixed time to a variable search time approach when dealing with car park choice without worrying about the total demand issue.

Test cases then involve variable search time as modelled by the calibrated functions which can then be compared against the base case. We also introduce the effect of a Car Park Specific Constant (CPSC) to explain unobserved preferences between the car parks. Thus the general approach in validating the models is to assign the flows to car parks by a simple fixed search time method with and without a CPSC, which are then compared with the proposed variable search time results with a CPSC.

Thus, we have set up the cases for analysis as defined below:

Base Case S0: Car parks are interconnected with walk links and the observed *fixed (average) search time* is applied at each car park

Test Case S1: S0 plus an optimal CPSC applied to Surface Car Park (η_p from (1)) (Note that we only need to apply one specific constant to optimise the split in demand in the first period.)

Test Case S2: Car parks are interconnected and *variable search time* applied plus a CPSC applied to Surface Car Park.

3.3.2 Validation of assigned flows under test scenarios

Scenario S0 connects alternative parking locations by means of walk links thus offers a choice to park at one or the other location, and reach the final destination on foot. S0 incorporates a fixed search time at each of the car parks which does not vary with the car park occupancy. The fixed search time has been set equal to the average observed search time applicable at each car park, though we considered other possible alternatives such as minimum search time instead of the average. With a minimum search time, our preliminary results showed that all of the demand is assigned only to one car park and the other receives nothing. For this reason, we have retained the average search times which are equal to 153 sec for Surface Car Park and 115 sec at the MSC. Table 1 shows the assigned flows at each car park and the associated GEH statistics. It is noted that under S0, Surface Car Park still receives most of the cars in time period 1 while MSC receives only 90. These results are poor compared with the observed values.

Table 1 Assigned Cars to Parking Locations under S0 (Fixed Average Search Time)

Time period	Surface Car Park			MSC		
	Observed	Modelled	GEH	Observed	Modelled	GEH
7:00-8:00	81	280	14.81	288	90	14.40
8:00-9:00	109	286	12.59	280	103	12.79
9:00-10:00	52	259	16.60	206	3	19.86
10:00-11:00	21	90	9.26	70	1	11.58
11:00-12:00	4	36	7.16	32	0	8.00
12:00-13:00	7	11	1.33	4	0	2.83
Total	274	962	27.68	880	197	29.43

The results in Table 1 revealed that, in general, there is a greater propensity of drivers being attracted towards Surface Car Park compared to MSC at all time periods. There may be two reasons causing this kind of attraction towards Surface Car Park. Firstly, the base level long stay parking charge at Surface Car Park is slightly lower at £3.80 compared to £4.00 at MSC. Secondly, while Clay Pit Lane is a surface car park, Woodhouse Lane is a multi-storeyed facility, and the latter may be preferred conversely by some drivers. For these reasons, we propose to add a CPSC to Surface Car Park to represent any unobserved preference towards MSC which is aimed at improving the calibration of the model. As such, a new scenario S1 was developed by optimising the value of CPSC using a simple linear interpolation of trial and error results to fit to the flows in the first time period (which is unaffected by variable search time in later approaches). The optimal CPSC was found to be equivalent to 21pence ($0.39 US) which was then added to the base level charge at Surface Car Park.

Table 2 shows the resulting assignment under S1. It is noted that introducing a simple CPSC works well in this case and the modelled flows in all the time periods are very close to the observed flows and hence GEH values too are within the acceptable range.

Table 2 Assigned Cars to Parking Locations by S1: (Fixed Average Search Time + 21p CPSC)

Time period	Surface Car Park			MSC		
	Observed	Modelled	GEH	Observed	Modelled	GEH
7:00-8:00	81	82	0.11	288	288	0.00
8:00-9:00	109	87	2.22	280	302	1.29
9:00-10:00	52	54	0.27	206	208	0.14
10:00-11:00	21	16	1.16	70	75	0.59
11:00-12:00	4	7	1.28	32	29	0.54
12:00-13:00	7	2	2.36	4	9	1.96
Total	274	248	1.61	880	911	1.04

In contrast with the previous scenarios, Scenario S2, introduces a variable search time incorporated via the previously calibrated search time functions. Under S2, the second and subsequent time periods inherit the allocated demand from the previous time period(s) which can be carried forward by cumulating the flows as described earlier. A test scenario (results not shown here) indicated that the variable search time method works well from the second and subsequent time periods but not in the first time period. This result indicates that some value of CPSC needs to be added even when the variable search time is applied, essentially to correct for unobserved preferences as in the fixed case S1. In this case an optimal value of CPSC worked out to be 30pence ($0.47 US) which was applied to Surface Car Park as before. Note that the value of CPSC is different from the earlier as the search times in period 1 are now lower than the average search times used in S1. Table 3 shows the results of S2. It is noted that once again the variable search time method performs very well with most of the modelled flows being very similar to the observed ones. Note in particular that the model now gets the flows in period 2 closer to the observed flows with increases in Surface car park and decreases in MSC. This is due to the differential in car park search times which now varies with occupancies of the car parks. Given that the flows are higher in the first two periods we therefore conclude that the variable search time approach with CPSC is marginally better than the fixed time approach with CPSC. However this small improvement has come at a cost in both data collection and modelling complexity required.

Table 3 Assigned Cars to Parking Locations by S2 (Variable Search Time + 30p CPSC)

Time period	Surface Car Park			MSC		
	Observed	Modelled	GEH	Observed	Modelled	GEH
7:00-8:00	81	82	0.11	288	288	0.00
8:00-9:00	109	105	0.39	280	284	0.24
9:00-10:00	52	45	1.01	206	217	0.76
10:00-11:00	21	11	2.50	70	80	1.15
11:00-12:00	4	7	1.28	32	29	0.54
12:00-13:00	7	3	1.79	4	8	1.63
Total	274	253	1.29	880	906	0.87

3.3.3 Significance of search time in route travel time

While integrating the parking search time into the network assignment model, implicitly it was assumed that the search time is an important variable in ones decision making while selecting a route. This section analyses the relative significance of parking search time in the overall generalised time/cost.

For any given OD pair, the total generalised time (cost) comprises of elements -

- Travel time by road (including delay at junctions en-route);
- Parking search time within a car park;
- Parking fee;
- CPSC (if any)
- Walk time to the destination

From the results of the assignment, we have identified pairs of OD's using both car parks. Components of generalised time for a typical OD pair for period 2 are listed in the Table 4.

Table 4 Components of Generalised Time (seconds)

Component	Route 1 (MSC)	Route 2 (Surface)
Travel Time	559	483
Parking Search Time	110	54
Parking Fee	3145	2988
CPSC	0	236
Walk Time	200	250
Total	4014	4011

From the table, it is noted that although the equilibrium assignment has converged, there is still a slight difference in the costs experienced by the drivers on each route. This is due to convergence errors and is typical in the application of all network models. For this reason, recently more advanced assignment techniques such as Origin Based Assignment (Bar-Gera, 2002) are increasingly being used in existing computer codes for traffic assignment. In our case, as the difference between the equilibrium costs is much smaller than the search time itself, we can carry on with the rest of the analysis.

From the total travel time, if we subtract the fixed components such as the parking fee, CPSC and walk time, then we are left with the "variable" part of travel time. In case of Route 1, the variable part is 669 seconds of which the search time is about 16.5% and similarly for Route

2 the variable part stands at 537 seconds of which the search time is over 10%. From this analysis we note that the parking search time is significant relative to the travel time. Furthermore, if we assume that the travel times to reach the car parks are constant for a given level of network congestion, then as long as the search time at Surface Car Park is less than half that of MSC, then the drivers would continue to choose Route 2 leading to the surface car park, otherwise they will start using Route 1 involving parking at MSC. The illustration presented here so far is based on a typical OD pair and it is obvious that the relative position of the Origin from the car park will influence the analysis. In general, for Origins further away from the car parks, search time may only be a small proportion of the travel time, but for nearer Origins it may be much more significant. For these reasons, and in order to explain the pull-, push- of drivers between the car parks over a number of time periods, it is useful to analyse the search times at an aggregate level for all OD pairs using the car parks.

Table 5 shows parking search times at each of the car parks during various time periods. Firstly, note that the absolute difference in search times between the two car parks increases in period 2 which helps explain how this approach can fit better to the observed data with Surface Car Park becoming relatively more attractive in period 2. For subsequent periods the differential is diminishing until eventually the search time in the Surface Car Park exceeds that in MSC and so more of the demand is pushed towards MSC.

Table 5 Parking Search Time (sec) by S2

Time period	Surface Car Park		MSC		
	Cumulative occupancy	Parking Search Time	Cumulative occupancy	Parking Search Time	Difference in Search Times (MSC-surface)
7:00-8:00	82	10	288	59	49
8:00-9:00	187	54	572	110	55
9:00-10:00	232	142	789	152	10
10:00-11:00	243	177	869	169	-8
11:00-12:00	250	202	898	175	-28
12:00-13:00	253	214	906	176	-38

3.3.4 Discussion

From the analysis carried out as part of this research, we have made a number of observations. Firstly, the results have clearly shown that connecting the competing car parks by suitable walk links will help improve the assigned flows to the car parks. This observation may sound fairly trivial, but it has a large impact on the demand assigned to car parks as illustrated in Tables 1-5. Standard network modelling practice does not allow direct connections between any two traffic zones except via "proper" road links. The introduction of parking links allows for the choice of car parks to be modelled and for the effect of search time or occupancy of car parks to be accounted for in the choice process. In Tables 1-5 we have found the evidence that the drivers' route choices are sensitive to the search time within the car parks – be it a fixed average value, or dependent on occupancy within the car park (relative to the car park capacity). Between the fixed average search time (plus CPSC) and the variable occupancy dependent search time (plus CPSC), the former is a sensible choice when the car parks are under-occupied as in the early hours of the day, but a variable search time may be more appropriate when the car parks become very busy. Finally, drivers may prefer certain car parks for some unobservable reasons which are best treated as car park specific constants added to the search time. Calibrating such car park specific constants may be onerous if there are more than two competing car parks, which is clearly not the focus of this research paper. In conclusion, it is believed that connecting the competing car parks to ultimate destinations with walk links offers choice of car parks, which together with introducing the search time within car parks, improves the validation of the flows assigned to car parks in network models.

4. SUMMARY AND CONCLUSIONS

Standard network models commonly treat large off-street car parks as origins/destinations, which precludes drivers the choice of parking location. Such an approach can lead to a poor model validation of flows especially those assigned to the car parks as shown above. Moreover, such an approach implicitly assumes that the drivers are insensitive to the search time spent within car parks. This research hypothesised that drivers are sensitive to the search time within car parks and explored an approach which has been based on representing car parks as *links* of a road network. The search time within car parks can be modelled as a fixed value based on average search time or it can also be considered as dependent on relative occupancy of car parks at any given time. While the fixed search time is straightforward to implement, the variable search time requires some network amendments and additional processes within the model. This research followed the work by Lam et al (2006) and a method was implemented with a variable search time based on cumulative flows into a car park. It also discussed the calibration of search time functions for car park links based on observations of parking search time and occupancy at two city centre car parks in Leeds, England. Test scenarios were set up to assess the efficacy of the new search time approach illustrated by validating the assigned flows to the car parks. This work has developed a practically implementable approach for a real life application which could enhance the quality and scope of policy tests available in network assignment models when used in practice.

The main conclusions drawn from this work are as below:

- Firstly, traditional approaches which treat car parks as traffic zones will lead to problems with model validation as evidenced by poor agreement between the modelled and observed flows into car parks. The new approach involving connecting the competing car parks with appropriate walk links allows choice between car parks within the usual equilibrium approach and facilitates improved validation.
- Search time within the car parks can be modelled as a fixed average value or as dependent on relative occupancy of car parks at a given time. While the fixed average search time is more sensible to adopt especially during the earlier parts of the day, the variable search time may be more appropriate when the car parks get busier during the day and where capacity comes into play. The approach can be used to restrain the demand for car parks which have reached capacity.
- Certain car parks, for example multi-storeyed car parks, may be preferred more than other car parks, and hence the competing car park may need to be associated with a CPSC. Such a CPSC may be added to the generalised cost of a car park and thus incorporated into the equilibrium approach.

Finally, this work has extended the approach by Lam et al (2006) by applying it within a real case study. Whilst the approach was shown to improve validation of car park flows in our case, it should also be noted that a simple fixed time approach with unobserved preferences accounted for via inclusion of a CPSC can also achieve good results in terms of validated flows. Thus it might suffice in practice to consider the preference for car parks over the effect of search times as the data needs are expensive compared to the benefits over the fixed approach. The greatest benefits are derived from connecting the car parks by walk links, and introducing the CPSC further improves the validation of flows into car parks and allows a wider set of policies to be modelled and assessed. We believe that as demand for parking exceeds supply in most cities, then this is a step which can be implemented in practice within a reasonable budget and which should provide a better assessment of strategies designed to deal with the parking problem.

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APPENDIX – COMMENTS ON METHODOLOGY FOR DATA COLLECTION

This appendix outlines the potential ways to observe the two data items viz., parking accumulation and parking search time within a car park. Firstly, the parking accumulation is relatively easy to observe. In the case of car parks having controlled entry/exit (e.g. pay at the barrier system) the barrier data directly may be used to obtain the accumulation in the car park at any given time. The accumulation can be easily derived by subtracting the cumulative outflows from the cumulative inflows at any given instance. Alternatively, the number of free spaces available is routinely updated and displayed on real time information systems or over the internet for some car parks in most cities. By subtracting the available free spaces from the total capacity of the car park, we can obtain the accumulation over time. This method should be preferred where possible as it is convenient/cheaper and efficient. Finally, in the case of open car parks (e.g. pay and display), one may have to adopt manual methods – e.g. involving noting down the number of vehicles that had entered/left the car park within a time window, - which are well known and need not be discussed here.

Parking search time observations ideally involve recording time stamped registration number of the vehicle at the entry to the car park and again at the location where they park. By subtracting the entry time from the latter, we can obtain the parking search time. In our case study we were able to make use of closed circuit television cameras within the multi-storey car park, which required an observer within the control room tracking the time spent parking for each vehicle. For the open surface car park manual observation was employed using a natural vantage point. Whilst this is not ideal it may be that in the future other technologies related to mobile devices could prove useful.

REFERENCES

Abrahamsson, T. and Lundqvist, L. (1999) Formulation and estimation of combined network equilibrium models with application to Stockholm, *Transportation Science*, **33**, 80-100

Arnott, R. and Inci, E. (2006) An integrated model of downtown parking and traffic congestion, *Journal of Urban Economics*, **60**, 418-442.

Bar-Gera, H. (2002) Origin-Based Algorithm for the Traffic Assignment Problem, *Transportation Science,* **36(4)**, 398-417

Beckman, M.J., Mcguire, C.B. and Winsten, C.B. (1956) *Studies in the Economics of Transportation,* Yale University Press, New Haven.

Belles, B.B., Carrese, S. and Negrenti, E. (2007) Parking search model, *TRISTAN VI: Sixth Triennial Symposium on Transportation Analysis*, Phuket Island, Thailand.

Benbow, N., Kidd, P., Woolley, A., Skinner, A. and Palmer, I. (2008) The Continued Innovation of Aggregate Transport Demand Models, In the *Proceedings of the European Transport Conference*, Leeuwenhorst Conference Centre, The Netherlands

Benenson, I., Marten, K. and Birfir, S. (2008) PARKAGENT: An agent-based model of parking in the city, *Computer, Environment and Urban Systems*, **32**, 431-439.

Bifulco, G.N. (1993) A stochastic user equilibrium assignment model for the evaluation of parking policies, *European Journal of Operational Research*, **71**, 269-287

Bonsall, P. and Palmer, I. (2004) Modelling drivers' parking behaviour using data from a choice simulator, *Transportation Research* C, **12**, 321-347

Feng, S. and Duangao, L. (2009) Multi-user and multi-mode mixed traffic assignment model under the influence of parking charge, *Journal of Transportation Systems Engineering and Information Technology*, **9(3)**, 71-77

Gur, Y.J. and Beimbourn, B.A. (1984) Analysis of parking in urban centres: equilibrium approach, *Transportation Research Record,* **957,** 55-62.

Hensher, D.A. and King, J. (2001) Parking demand and responsiveness to supply, pricing and location in Sydney central business district, *Transportation Research* A, **35**, 177-196

Hess, S. and Polak, J. (2004) Mixed logit estimation of parking type choice, presented at the 83rd Annual Meeting of the Transportation Research Board, Washington D.C.

Hunt, J.D. and Teply, S. (1993) A nested logit model of parking location choice, *Transportation Research B*, **27(4)**, 1993, 253-265.

IHT (2005) Parking Strategies and Management. *Institution of Highways and Transportation*, HQ Media Services Ltd, Essex.

Lam, W.H.K, Li, Z.C., Huang, H.J. and Wong, S.C. (2006) Modelling time dependent travel choice problems in road networks with multiple user classes and multiple parking facilities, *Transportation Research* B, **40(5)**, 368-395

Lau, W.W.T, Poon, P.S.T., Tong, C.O. and Wong, S.C. (2005) The Hong Kong second parking demand study, *Proceedings of the Institution of Civil Engineers, Transport*, **158**, 53-59

Leeds City Council (2009) http://www.leeds.gov.uk/Transport_and_streets/Parking/City_centre_parking_charges.aspx web site accessed on 27 Aug 2009.

Marsden, G.R. (2006) The evidence base for parking policies – a review, *Transport Policy,* **13,** 447-457.

Nour Eldin, M.S., El-Reedy, T.Y. and Ismail, H.K. (1981) A combined parking and traffic assignment model, *Traffic Engineering and Control,* **22(10)**, 524-530

Petiot, R. (2004) Parking enforcement and travel demand management, *Transport Policy*, **11,** 399-411.

Shoup, D.C. (2006) Cruising for parking, *Transport Policy*, **13**, 479-486

Tong, C.O., Wong, S.C. and Leung, B.S.Y. (2004) Estimation of parking accumulation profiles from survey data, *Transportation*, **31**, 183-202

Thompson, R.G. and Richardson, A.J. (1998) A parking search model, *Transportation Research Part A*, **32(3)**, 159-170

Van Vliet, D. (1982) SATURN - a modern assignment model, *Traffic Engineering and Control* **23**, 578-581

Wardrop, J.G. (1952) Some Theoretical Aspects of Road Traffic Research, *Proceedings, Institution of Civil Engineers*, **II(1)**, 325-378

Wong, S.C., Tong, C.O., Lam, W.C.H. and Fung, R.Y.C. (2000) The development of parking demand models in Hong Kong, *ASCE Journal of Urban Planning and Development*, **126**, 55-74

Young, W., Thompson, R.G., and Taylor, M.A.P. (1991) A review of urban parking models, *Transport Reviews*, **11**, 63-84