Reimaging Traffic Control and Management for Network Sustainability.

Professor Margaret Bell CBE
Future Mobility Group,
School of Engineering,
Newcastle University.

ABSTRACT
This paper will look back at the beginnings of fixed-time area control of networks, plan change algorithms and benefits of co-ordination. The early attempts at developing demand responsive control systems at a time when detector technology was insufficiently robust and computers far too slow will be briefly explained. The basics of the fully demand responsive control system SCOOT, Split Cycle Offset Optimisation Technique Hunt et al (1981) will be explained and the need for research into the ageing of traffic signal plans being necessary to enable Local Authorities to justify expenditure on the state of art technology in the mid -1980s. However, despite increased sophistication in technology, within a decade increased car ownership, their use and for longer journeys, meant that traffic congestion remained a problem with the unintended consequence of poor air quality which remains a concern. Examples of traffic management measures to manage hotspots, and Air Quality Management Areas will be proposed and evidence that electric vehicles will not deliver the mandatory 67% reduction of carbon dioxide emissions target by 2050 over 2010 levels will be presented. The potential to use data available as by product of UTMC, Urban Traffic Management and Control to identify the level of traffic in a network which potentially will meet environmental objectives will be explored. Finally, ideas of how traffic control and management can help to reimagine and reengineer our networks in the future will be shared.

Introduction
In the late 1950s and early 1960s as cars became more affordable at peak times traffic in side roads began to suffer unacceptable delay. This prompted research into the design for isolated signal control the basic principles of which can be found in the seminal work of Webster and Cobbe (1966). These calculations were initially carried out manually. However, at a time when Government policies were creating a pro-car society by the mid-1960s as more and more junctions became signalised travelling through urban networks was frustrated by the need to continually stop at each junction. This led to the concept of signal co-ordination which initially was introduced predominantly along radials into a town or city. The starts of green at consecutive junctions were shifted – or offset - by the time taken of travel between the two junctions. The travel time was based on the desired/designed cruise speed and the stop-line to stop-line distance between consecutive junctions. This allowed green waves to be created for the dominant flows into or out of city. Early work (by Morgan and Little) (1964) considered methods which minimised band-width.

However, these early signal control strategies were often unable to provide sufficient bandwidth to allow green waves to be created for traffic flowing in opposing directions and often created long delays on side roads at junctions with high cross flows. Several methods of achieving linking were explored and are dealt with in the Webster and Cobb (1966), these include simultaneous or synchronised system, alternative or limited progressive system, flexible progressive system.

Signal design calculations were carried out manually and time distance diagrams used to create the linking. However, as computers became affordable software was written to facilitate these calculations and algorithms were developed to achieve the linking. Of note is LINSIG, Moore and Cheng (2004) developed in the 1980s by Brian Simmonite as a DOS based tool whilst working at Lincolnshire Council and later set up JCT to support others who found the valuable time saving tool. Whilst setting up green waves removed the stop – start issues traffic growth meant that delays increased on side roads as traffic queued to gain access to main roads.

At the time Dr Dennis Robertson working at Plessey (now Siemens) was developing the signal optimisation program, TRaffic Network StudY Tool (TRANSYT). He later moved to the Transport and Road Research Laboratory (TRRL), where UK government investment led to the software tool being adopted throughout the UK, Robertson (1969). TRANSYT has proved to be one of the most successful software tools developed, Holroyd and Hillier (1969), Timmermans et al (1979) and quickly TRANSYT was adopted by many authorities worldwide.

TRANSYT Traffic Model
TRANSYT manipulates flow profiles with NO representation of individual vehicles. The flow distribution during the cycle time refered to as the *flow profile* is assumed to be the same every cycle throughout the plan.

Traffic Flow Profiles
The pocessing of vehicle flows through a TRANSYT networkRobertson (1974) is based on manipulation of three patterns:

a) IN pattern which represents the arrivals at the stop line at the end of the link if the traffic were not impeded by the signal at the stop line,
b) OUT pattern which leaves the link and
c) GO pattern which would leave the stop-line if there was sufficient traffic to saturate the green.

The traffic flowing into the link is obtained by taking the correct proportion of the OUT pattern from the upstream link. The traffic entering the link is dispersed assuming exponential smoothing. The amount of smoothing depends on the journey time. Calculations are performed on an averaged picture but in practice the flow pattern varies because of the behaviour of the individual vehicles therefore, this random behaviour is accommodated with a correction factor.

Queue length, delay and stops
TRANSYT has a simplified model for vehicles travelling down a link. It assumes that all vehicles in the platoon travel at the same speed and arrive concurrently at the downstream stop-line in this way a **vertical queue** is formed at the stop-line. The average queue is estimated from the IN, GO + OUT patterns. When the saturation flow S< 100% average queue is equivalent to the rate which delay is incurred and when S>100% average arrivals > departures. Work by Bell (1978, 1981) studied 500 traffic queueing at signalised junctions and derived the unit of queue for a PCU, passenger car unit was 5.76±0.05 metres. Bell used this to develop an enhanced spatial queueing model and incorporated inot TRANSYT.

The **uniform delay** is defined by the cyclic flow profile which is the elapsed time from arrival at the stop-line to the departure in the green. The random delay is established by an empirically derived formula and is about half the random delay of traffic at an isolated junction as defined by Webster and Cobbe (1966). All traffic delayed contributes to stops even without stopping, given the assumption of vertical queues. The to the stop-line and accelartion away from the verticle queue is solved by fractional stops. Additional stops, caused by random variations and oversaturation are added to the "average picture".

The random plus oversaturation delay rate is equivalent to average pcu's in the queue at start of red. If it is assumed that all such pcus stop each time signals become red then:
Stops /pcu = $(N_{\text{start red}} - N_{\text{departures}})$
This is equivalent to the average number of red periods which each pcu must wait before crossing the stop line, which is equivalent to (random + oversaturation) stops/pcu. An arbitrary upper limit is set as 2 stops/pcu.

TRANSYT Performance Index, TPI
The TRANSYT derives signal times to benefit traffic across a whole netowrk and achieves this by minimising an Performance Index. The TRANSYT Perfomance Index, TPI, see Equation 1 minimises delay and stops and manages queues on short links.

TPI = U delay + R+O delay + U stops + R+O stops + queueing measure …….Equation 1

Where U is Uniform, R is random and O is oversaturation

The TPI can be translated into money cost and/fuel consumption using empirically derived relationships. TRANSYT minimises the TPI using a HILLCLIMBING PROCESS (which is a misnomer because the optimal solution is when the TPI is at a minimum) to either optimise signal offsets and/or splits. The green period of one junction is related to another via the **master cycle.** A **stage change time** at a junction is a time at which the green signal on one stage is terminated and the change to the next green period is initiated (next stage green commences following inter-green period). The **offset** is the stage change time when the change to green for stage I is initiated (ie start of cycle for node concerned). Subtracting the offset node (1) from adjacent node (2) gives the journey time. This difference in offset which gives start of the cycle of one node relative to another defines co-ordination. Over the intervening years TRANSYT has been extensively developed to improve its optimisation procedure and provide many facilities which:

a) catered for up to 7 signal stages at each of up to 50 junctions and 250 approaches
b) allowed for rigorous checking of data input and graphical display of flow profiles.
c) calculated initial signal settings by a method of equalising saturation.
d) modelled traffic sharing at a stop-line and in bottleneck situations.
e) gave priority to buses
f) accommodated signalised pedestrian crossings

Bell (1981) using the more realistic queuing model for TRANSYT Bell (1978) introduced the concept of a performance measure which included a component of spare capacity to enable offsets to be defined which prevented queue-back on traffic links.

Definition of signal plans

Some links in a network will experience little variation in flow throughout the day, whilst others will exhibit dramatic changes. It is the flow profiles of the latter type that should be used toidentify how many plans should be implemented, and when to change from one plan to the next. A technique often used to ascertain the time schedule for implementation of a set of plans is to overlay the daily flow profiles established for traffic at the crtical junctions in the network. Figure 1 is an example of a daily flow profile measured at a critical junction along a radial at the edge of an UTC system.

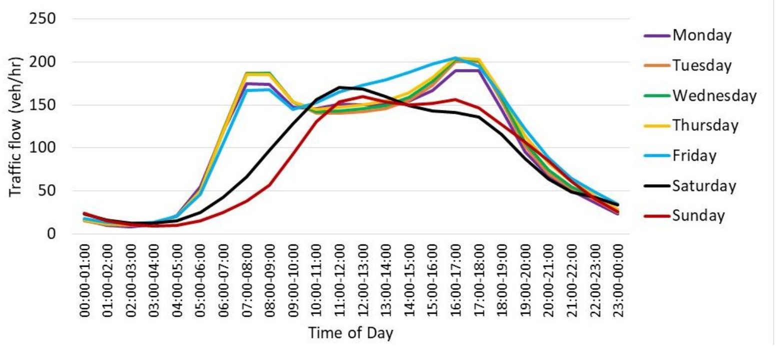

Figure 1. Average Daily Traffic flows

The different profiles shown here were based on twelve months data captured by automatic detectors but given the technology available in the early 1980s such profiles often would be based on one days measurement on a day of the week considered representative of all days often chosen as a Thursday. Traffic counts would be made, sometimes manually, on the one day of the week at approximately 6 monthly intervals over a period of typically two years. These daily flow profiles presented in Figure 1. for each week day suggest the need for a morning peak plan between about 07:30 and 09:30 hours, off peak 09:30 to 16:00 evening peak 16:00 to 19:00, after which vehicle actuation would be operated. Different plans and durations would be implemented on weekend days. When delays were found to be significant at other times spending resources to create special event plans to manage football matches, trooping of the colour in London and wet and dry weather plans in coastal towns to cope with tourists heading to the beach in fine weather can be justified.

When and how to change plan

Of course, due to random variations, the traffic flows prevailing at the specific time of the day chosen to change from one plan to the next often will be different on each days in the week. Therefore, congestion would occur at the transitions between plans. Several different algorithms to improve the network performance at the transition were developed. Some of these plan change algorithms involved an abrupt change and others introduced a series of short duration plans during the transition. These were referred respectively as FAST and SLOW plan change algorithms and there were several studies of the performance of different plan change algorithns during the 1970s and into the 1980s. These were carried out by Kay and Castle (1971), Bretherton (1979), Worrall et al (1973), Lieberman and Wicks (1974), Kittleson (1976), Ross (1977b), Basu (1980) and others. The research of Bell and Gault (1982) and Bell et al (1983) showed that:

a) The performance of a plan change algorithm did not appear to depend on the frequency of updating.
b) Irrespective of whether a plan change is from off-peak to peak or peak to off-peak, if the change is introduced at other than off-peak flow levels there was always a statistically significant increase in both vehicle stops and traffic delay. Typically 9% extra delay was found to occur if plans were not changed at off-peak flow levels.

Considering the infrequency of updating plans, the quality of data used to derive them, the large cyclic and daily flow variations likely at the plan change time, budget constraints, the reliability of the existing hardware and the computer power to process the algorithms to implement more sohpisticated algorithms, the research endorsed that the MODIFIED ABRUPT method (most commonly used in practice in cities in the UK and throughout the world at the time of the research) was the most effective.

Exactly how many plans should be implemented depends on the significance of the flow changes from hour to hour that are observed in a particular signal controlled region in a town or city. If the resources are available the TRANSYT model can be used to assess the benefits of operating the different signal plans. The research by Bell et al (1983) and Bell (19845) demonstrated that the TRANSYT model is tolerant to random flow variation of about 10% and ignoring special event plans, typically three or four plans were found to be adequate to successfully control traffic in most cities. The traffic engineer must weigh the benefits of operating a more appropriate plan against the extra delay caused by frequent switching between several different plans, and of course, the cost of their maintenance.
In fact, it is better to change infrequently to and from 3 or 4 good fixed-time plans which each operate for two or three hours, rather than change frequently to poorer quality plans which operate for periods of 15-30 minutes MacGowen (1980) and MacGowen and Fullerton (1980) and Bell (1983). Also it is believed that, rather than increase the number of plans, more benefit can be achieved by varying the time-table for switching plans to more appropriately to respond to shifts in the onset and decline of peak hour periods from day to day. As computers became more poweful this became the norm as is the case today.

Ageing of traffic signal plans
The benefits offered by the initial optimised signal plan depreciate in time, as traffic conditions change. The ageing process is related to the stability of flows across the network and the extent of modifications in the capacity of the network, new road building, land use changes and traffic management schemes. In the long term, ageing is often associated with a systematic uniform increase in the traffic over the whole network. This causes increased delay to traffic as the signal plan deteriorates more each year. In fact, the ageing process applies equally to the situations where flows decrease systematically or the overall network flow remains unchanged but the traffic is simply redistributed to alternative routes.

Another important phenomenon related to the ageing process occurs when a co-ordinated plan is first implemented. Because congestion is reduced, the vehicles experience less delay. Often in a very short time vehicles re-route to take advantage of the less congested routes. But by their own act of re-routeing they alter the distribution of flows within the network, and outdate the plan. Some may argue that the rate of ageing of traffic signal plans is large just after a co-ordinated plan is implemented. This principal has been discussed by Allsop (1974) and Allsop and Charlesworth (1977).

Updating traffic signal plans in practice
If minor changes to the traffic signal plans refered to as “tweeking”, are necessary, then a full network update cannot be justified and often TRANSYT is not used. In general, on-street observation of the changes in traffic patterns are made and manual adjustments follow. If these manual adjustments are significant the resulting plan is a second best to a full re-optimisation of the TRANSYT plan budgets are often limited and time elapses of up to ten years were found between full network updates. In essence fixed time plans perform well provided variations in the magnitude of flows remain less than about 10-15%.

By the mid 70's most large cities in the UK and throughout the world implemented area control referred to as Urban Traffic Control, UTC. This was achieved in two ways, either by centralised or distributed control. The cost of the two forms of control were about the same. The centralised form of control employs a large processor with a built-in allowance for expansion. The hierarchical control operates on a building block system. For both systems it was necessary to have two computers, one to back-up the other in the event of failure. In general the computer system requires trained staff to enable continuous surveillance of the network. Some UTC systems used close circuit Television, CCTV, most allowed operator intervention and all provided comprehensive checking facilities to ensure that the signals operated correctly.

The technological progress with traffic signalling equipment, the advent of microelectronics, Evans (1978), Davies (1984), and advanced computers with improved reliability have reduced both the capital and running costs of UTC systems. Network control in the form of Compact Urban Traffic Control (CUTC) has been a feasible proposition even for the smaller towns, since 1980. Guidelines of how to plan; prepare for and use CUTC have been proposed by Phillips (1982) and the system is described by Stannett and Sullivan (1981). It uses a dedicated computer with significant power and reliability to operate without a back-up computer and staff surveillance. The early CUTC systems were installed in Devon and Humberside, Redfern and Shapely (1981), in Hull and Torbay, Bernard and Hillen (1981), and elsewhere in Brighton and Hove, Chessell (1981). CUTC has much potential for influencing a basic system change in UTC from a central to a distributive processing strategy.

By the beginning of the 1980's there were about 250 UTC systems in operation around the world, Hunt et al (1981, 1982). Such UTC systems proved to be justly popular as urban traffic management tools because they benefit traffic without damaging the character of the town, and also tend to achieve reductions in accidents, vehicle noise and exhaust pollution, OECD (1977). UTC systems continued to be exploited to establish such things as priority routeing for buses and fire appliances, route guidance for vehicles towards free space car parking and away from congested areas. Hawkins (1979), Andrews and Hillen (I 980), Redfern and Shapley (1981), Stannett and Sullivan (1981), Bernard and Hillen (1981) and Phillips (1982).

However increase in car ownership caused networks to operate with less spare capacity and even short periods of high or low demand created recurrent congestion, fluctuations in flows increased during off peaks and consistency of time when plans changed changed. Methods to overcome these limitations led to research to develop concepts of demand responsive UTC. Early systems required frequent switching to different traffic signal plans in response to actual traffic flow changes detected in real time.

There are three levels of demand responsive systems. The first generation systems, often referred to as 'semi-responsive', use continuous monitoring of flows at key junctions to automatically trigger an appropriate fixed-time plan selected from a library of plans stored in the computer memory. There is little evidence to suggest that 'semi-responsive' systems consistently produced significant benefits over the simpler fixed-time systems, Ferguson and Jenkins (1973), Luk et al (1982).
Second generation control systems produced optimised signal plans in real time. These were derived using current traffic counts to update historical data at regular intervals. These systems required more powerful computers and tended to have the ability to implement the more complex plan-change algorithms.

Third generation control systems, researched in the 1970's that were fully responsive systems calculated the new signal settings continuously, KLD Associates Inc. (1974), Lieberman et al (1974). However, research by Holroyd and Robertson (1973), MacGowen and Fullerton (1980), Humphrey and Wong (1976), and Rach (1976), demonstrated that fully responsive UTC systems were difficult to develop. The main reasons why these early demand responsive systems showed insufficient merit was because the predicted flows, over small durations of typically 5 to 15 minutes, based on either or both historical and real-time data, were found to be poor, Kreer (1975, 1976), Eldor (1977), McShane et al (1976), Knapp (I 973), Nicholson and Swann (1974), Gazis and Szeto (1974), and others. The prediction was found to be less reliable the shorter the duration. However, the shorter the duration the higher response to changes in traffic demand and greater the benefits, Guberinic and Senbom (1978). The lowest practical limit for a co-ordinated system was found to be 5 minutes, Eldor (1976).

However frequent plan changing, even when supported by more sophisticated plan change algorithms, causes disruption; particularly at high demand, Bretherton (1979), Bell and Gault (1982), and Bell et al (1983). The early systems generally had slow response to traffic demand. Furthermore, the effects of making incorrect decisions as to when best to change, and to which plan, were fairly significant. It was for these reasons that the fixed-time systems were adopted as a national standard in the UK throughout the 1970's.

However, Holroyd and Robertson (1973) suggested a methodology which attempted to avoid these problems. This demand responsive control philosophy uses an on-line computer which continuously monitors flows entering all links in the network, predicts short term (every cycle) traffic arrival patterns at the stop-line, and makes small adjustments (typically 3-4 seconds) to the traffic signals in an optimal way. This control philosophy formed the basis of the SCOOT (Split Cycle Qffset Qptimisation Iechnique) system and its development was a co-operative venture between UK private industry and Government departments, This novel concept of demand responsive control system minimises transients and has a fast response because it is based on a short term prediction (typically every cycle). It requires no starting plans and performs its own detector monitoring and fault recording. The SCOOT strategy was successfully demonstrated in Glasgow and Coventry under a wide-range of conditions, Hunt et al (I 981, 1982), Robertson and Hunt (1982), Bretherton and Rai (I 982), and Clowes (1982), and the first commercial SCOOT system was installed in Maidstone in 1983, Boumer (1984). SCOOT is primarily a signal control strategy, and as such it does not replace conventional UTC systems, but rather works in co-operation with them. The 'kernel' SCOOT software, as produced by the joint development team starts with the analysis of raw detector data and ends with the recommendation of signal timings. All the standard UTC functions, such as transmission drivers and fault monitoring, are still required to make up a complete system. SCOOT can be thought of as a "black box" within or attached to, a conventional UTC system, Walmsley (1982). But fundamentally SCOOT is an on-line TRANSYT which substitutes the modelled cyclic flow profile at the top of the link with that measured in realtime cycle by cycle using traffic detectors.

Research by Bell (1984) showed in a study of TRANSYT networks that grid networks aged more than radial networks and on average a benefit of 3% per year was found over not updating signal. These metrics enabled LA to estimate the financial savings of implementing the SCOOT system which obviated the need to update signal plans. The research showed that typically the investment in SCOOT benefits was fully recovered 9 to 15 months in most networks.

Other demand responsive control systems have been developed and employ completely different control philosophy such as SCATS (Sydney Co-ordinated Adaptive Iraffic System), developed in Australia, Moore et al (1976), Luk (1981). SCATS derives traffic flow and occupancy from detectors placed in each lane immediately in front of the stop-line. The system assess degree of saturation to adjust splits and uses the information to assess the desirability of linking major intersections. If so, one of four predetermined linking plans is selected along with offsets. Moore et al (1976), claimed large benefits of the SCAT system over the conventional fixed-time systems and Luk et al (1882) suggests the SCAT system works effectively along dominant routes.

Expert Systems of Control

As the technology advanced and computers became more powerful further sophistication was introduced to manage short term, recurrent congestion events. Research funded by the EU in Leicester in collaboration with INRETS in France developed the CLAIRE expert system of control, Bell et al (1991). This was one of the first applications of artificial intelligence to traffic control which learned from the detector data the nature of the build-up and evolution of recurrent congestion events and selected an appropriate signal plan from a library of previously designed remedial strategies. Research of Withill (1992) under the supervision of Bell studied the re-routing of traffic in response to variable message signs indicating car parks were full. This showed that drivers did not chose the nearest empty car park but showed a tendency to divert to specific car parks at different times and days of the week. This led to sets of action plans to override the SCOOT decision making in response to specific triggers. With the introduction of new technologies traffic operators now have a set of tools that they can use to tailor UTMC to meet their specific traffic control policies. However, despite increased sophistication in technology, increased ownership of cars, their use and for longer journeys, has meant that traffic congestion remained a problem with the unintended consequence of poor air quality which initially was brought to the attention of LA back in 1995 but remains a concern today.

Traffic related Pollutant Emissions in Urban Areas
Research commenced in 1987 using the TRANSYT model to estimate the effect on emissions of fixed time signal co-ordination and recommendations were made to increase discharge of queues at specific stop-lines by splaying stop-lines to alleviate build-up of queues. But there were limitations due to the lack of good quality emissions data and without roadside monitoring it was not possible to explore the effect traffic flows were having on kerbside pollution or even to validate pollution models. Early studies that investigated the relationships between traffic flows, speed and roadside concentrations Reynolds (1991) used portable carbon monoxide systems. However, surveys were limited to dry weathers due to the sensitivity of the equipment to humidity and restricted to short duration (up to about two hours during morning and evening and off peaks periods) surveys because the equipment needed to be manned for security. Simultaneously with the concentration monitoring, traffic was counted, classified and speeds were measured. These studies revealed very weak relationships between pollutant concentration and traffic variables due to the huge variation in traffic flow, meteorological conditions (wind speed and direction) and the complexity of the relationships between traffic emission and concentration given the chemical and physical processes that govern the dispersal of pollution in the atmosphere. This work confirmed the need for continuous kerbside pollution monitoring.

It was 1997 before the first pollution monitors were developed by Siemens in collaboration with Nottingham University which enabled correlations between the traffic data available as a bye product of the from SCOOT control and the roadside concentrations to be explored. Research by Jalihal (1999), demonstrated that whilst congestion was clearly influencing the pollutant levels measured at the roadside there was no correlation with the SCOOT delay, stops or the congestion measures CONG or RAW. There was a stronger relationship found with the degree of saturation but for all traffic flow situations. Research carried out on the M42 which measured the real-world emissions simultaneously with speed knowing its position with respect to the MIDAS detectors it was possible to assign the aggregate emissions to the speed flow of the general traffic. This clearly demonstrated that the flow regime described by both the speed and the flow was a better indicator of pollution emission rather than any one specific variable. The results shown in Figure 2 showed that NOx emissions were measured to be 3 times compared to the other three flow regimes, Bell et al (2006). This led to further research which evaluated a combination of SCOOT modelled parameters to investigate correlations of composite measures of occupancy and flow to assess the effect of congestion.

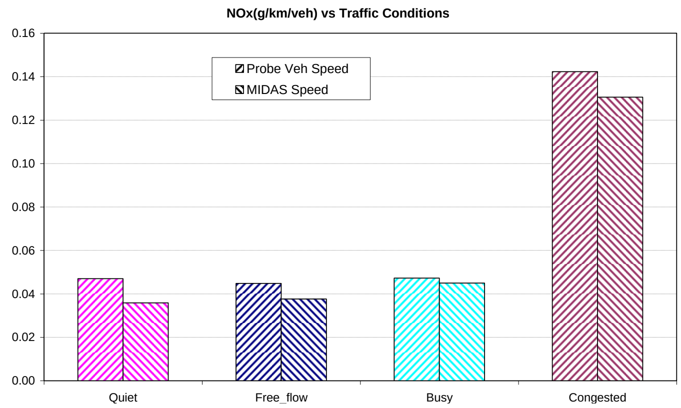

Figure 2 Tailpipe emissions depending on the flow regime measured simultaneously by MIDAS detectors on the M42, Bell et al (2006)

Enhanced Emissions model.
As well as flow regime, pollution emissions are a function of the vehicle type, age (Euro classification), fuel type, engine size. The UK Government gave Local Authorities the responsibility of assessing and delivering the air quality objectives. The emissions factors are available as a Toolkit from the defra, Department of Environment Food and Rural Affairs website, DEFRA(2019). Usually the recommended National Fleet is used to provide typical traffic characteristics of the vehicle fleet for different types of road is used. However, ideally, if the number plates of vehicles are available for traffic it is possible, at a cost, to use the dvla, Driver Vehicle Licencing Authority, to purchase vehicle licencing data to define the actual fleet characteristics for a more accurate estimate of emissions. The SCOOT traffic flow and occupancy, available cycle by cycle, is used to assign the traffic flow with a

regime either free-flow, smooth-flow, unstable or congested. Using the data in the Emissions Factor Tool Kit the total emission for the traffic travelling in the assigned flow regime is estimated for each five minutes. These algorithms have been coded in the product AQATANE by Amey Consulting which allows the data to be presented on a 2-D map with links between junctions changing colour red, amber, and blue, green depending on the magnitude of the pollutant emission. The latter can be either nitrogen dioxide, NO_2, carbon monoxide, CO, carbon dioxide, CO_2 or particulate matter, PM10. Knowledge where excessive levels of pollution are being emitted is necessary to be enable traffic intervention measures to be taken.

Pollution Concentrations

However, whilst these estimates of pollution emissions advise engineers where the pollution is emitted, it does not necessarily inform where the pollution problems are occurring in the network. This is because the meteorological conditions, influenced by the built environment, along with the chemical interactions between pollutants actually govern which pollutant and where pollution builds-up. Therefore, there is a need to use the emissions in a dispersion model, to estimate the pollutant level at specific locations in a cross section of a street. The dispersion model used in AQATANE is the canyon model OSPM, Operational Street Pollution Model KAKOSIMOS (2010) which requires both the meteorological conditions (magnitude and direction of the wind) along with the heights of the buildings and the façade to façade spacing. Typical levels of pollution predicted in a cross section of a Canyon depending on the direction of the wind is shown in Figure 3.

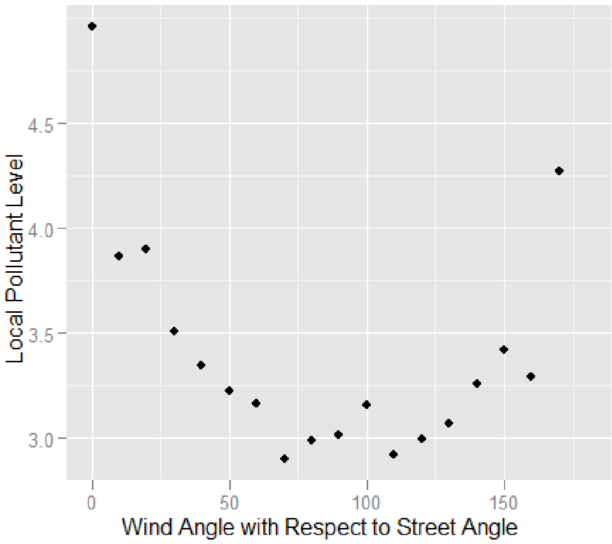

Figure 3. The effect on pollutant concentration depending on wind direction estimated using the OSPM model. Note 90° represents the wind when it is blowing in the direction aligned with the street. Hill (2015)

Figure 3 clearly shows that local pollutant levels are highest when the wind is oriented perpendicular to the alignment of the road and pollutant concentrations build up on the lee sides of the road (0° and 180 °in the figure). Pollutant levels reach a minimum as the wind shifts to a direction parallel with (blowing along) the road (90°in the figure). This is consistent with increased dispersion from the induced vortices ventilating the street. The heights and width of the street as well as the strength of the wind also affect the rate of dispersion. Pollution builds up when wind speeds are low and in steep continuous canyons.

At junctions, depending on both the levels of traffic, prevelence of congestion and the general openness of the built environment governs whether a hotspot occurs. Of course open spaces such as fields, parks are places where there is natural ventilation of traffic related air pollution, locations that experience lower levels of pollution concentrations even though emisions may be high. Also, emissions are higher for vehicles travelling uphill, especially if queues build up when stopped at traffic lights, therefore it is advisable to create green waves to avoid stopping vehciles travelling uphill.

The effect of the wind on pollution across a network is illustrated in Figure 4, Hill (2015). The use of data available as a by-product of UTMC and Intelligent Transport Systems per se enables concentration maps across a city area to be created in real-time based on emissions data calculated every five minutes. The emissions are summed to estimate pollution concentrations every hour using OSPM. By archiving data over several years it is possible to use the models off-line to hypothetically explore the effect on hotspots of implementing policies to introduce clean vehicles (eg. investment in low emission buses, penetration of electric vehicles).

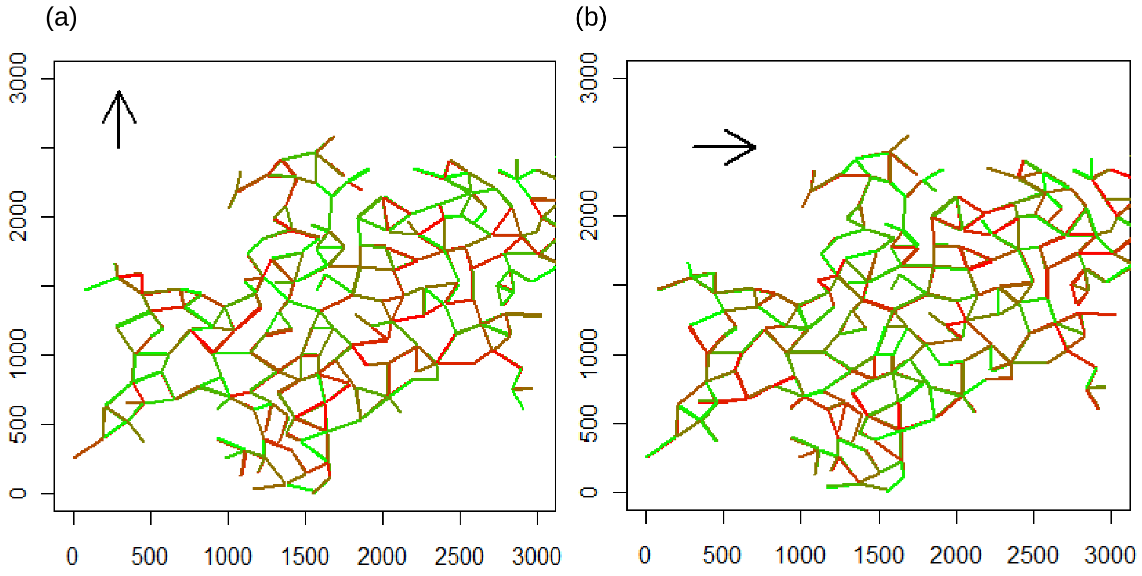

Figure 4. The effect on pollution concentrations calculated using the OSPM model on links in a network depending on (a) northerly or (b) westerly wind.Hill (2015).

Managing Air Quality using UTMC

The OSPM, is the model commonly employed in grid dispersion models including ADMS Urban CERC (2020) and Airviro, Apertum (2020). These use average flow, average speed pollution emissions factors which provide reasonable pollution estimates usually on an hour by hour basis and over grid squares of typically 250mx250m. Furthermore, these air quality models tend to use modelled traffic rather than measured data often available for peak periods only. This means assumptions are made about the hourly daily traffic flow profiles. Whilst the emissions factors to some extent accommodate congestion effects, these are averaged over distance. Therefore, as such these models are not useful for identifying which link(s) in a network are causing elevated pollution specifically due to congested related emissions.

The potential to use actual traffic data available as by product of UTMC, Urban Traffic Management and Control to estimate the hourly canyon pollutant concentration level based on 5 minute emissions estimates using actual traffic flow regimes, offered real opportunity to better understand where those links in a network that are prone to the build-up of pollution are located. Coupled with the ability to predict emissions on a five minute by five minute basis to understand the traffic source characteristics (unstable or congested flow) responsible for creating the pollution, remedial measures can be designed to deliver the environmental objectives. Several studies have explored intervention methods to alleviate recurrent congestion related pollution. Tate (2000) demonstrated how queues can be relocated from closed to open space by simply changing the offset and cycle time between consecutive junctions. Important lessons emerged from this study. The first was the importance of modelling the changes made to the splits, offsets and/or cycle time and using traffic assignment (in this study SATURN) to predict their effect on route choice. TRANSYT subsequently was used to optimise signal timings on the alternative routes. The reassigned traffic flows and speeds were then fed into an air quality model which confirmed that the rerouted traffic did not result in the displacement of the pollution problem. This provided confidence that strategy was be beneficial. The second was the fact that the public were rather unsympathetic towards the scheme with many complaints concerning the build-up of queues in a part of the network where traffic normally travelled freely and yet journey times remained unchanged and traffic at the downstream hotspot junction ran freely. This demonstration attracted some very bad press which was rather unfortunate given the trial was a complete success. An important message emerging from this demonstration was the flexibility of traffic signal control which allows engineers to easily change signal control parameters by a few seconds, to subtly achieve the desired change in signal plan by gradually relocating the queue a vehicle at a time.

The TRL carried out a trial of cascading of queues along a radial into the city of Leicester to alleviate the build-up of pollution in the vicinity of the Central Railway Station by spreading the emissions systematically onto upstream links. This study showed that with a combination of adjustments to offsets and splits delivered significant reductions in emissions on the polluting links. However, this study did not carry out the more strategic modelling to assess any displacement of queues on re-routeing to evaluate any consequential pollution displacement. Interestingly, this research did highlight a different political issue. The scheme caused queue build-up in the neighbouring local district of Groby at the periphery of the city. This confirms the need for a collaborative approach across regions when resolving environmental problems. Another study of pollution hotspots in Leicester City demonstrated that the only way to have significant impact on city centre pollution was to facilitate a mode shift to public transport. Consequently six park and ride sites were planned. Iterative modelling between SATURN and TRANSYT followed by air quality modelling using Airviro showed that whilst the total pollution emission across the Leicester conurbation only reduced by 14μg^{-3} the air quality hotspots were remedied.

Re-engineering networks.
Traditionally the two main principles controlling traffic in networks are (a) to respond to the times of travel and routes chosen by vehicles and (b) to minimise delay and stops, manage queues and alleviate congestion. However, given that signal control is designed to manage traffic which choses routes to meet the desired destination it is well known that signal control can influence drivers' route choices Allsop (1974), Allsop and Charlesworth (1977). Therefore, instead it is proposed that the signal timings for junctions in a network are "engineered" to deliver the environmental objectives, both in terms of carbon emissions and air quality. In this respect it is necessary to change the fundamental design principles and use UTMC and intelligent transport systems.

Control and Management of Air Quality in Networks
The basic concept of an *environmental capacity* to optimise control and manage traffic in a network was presented in Bell (2011). For urban areas there are two approaches. The first is to control traffic to manage the more pressing issue of poor air quality and secondly to optimise traffic to reduce total eCO_2 emissions across a network.

At today's traffic flows AQMA, Air Quality Management Areas, are declared where a particular pollutant exceeds certain limit values, in most areas in UK this is due to elevated NO_2 rather PM10. Larger areas are declared as AQMA because it is necessary to manage traffic over an area despite the fact that the pollution 'hotspot' is constrained to particular junctions or links. Tactical signal control adjusts splits reduce the volume of traffic entering a link where pollution builds up (due to orientation of road with respect to the prevailing wind and ratio of height of buildings to the façade-façade distance) and/or by changing offsets between consecutive junctions to hold traffic in streets with natural ventilation (open spaces, for example parks and fields, and streets parallel to the prevailing wind). Even short links with low flow but persistent queueing can become polluted depending on the built environment. Such constraints on signal timings manifests an area signal plan sub-optimal creating more delay to side road traffic, these remedial actions aim to *spread the emissions around* . There is a need to be mindful of the build-up of pollution on side roads due to displacement of traffic, in which cases steps need to be taken to incentivise the use of park and ride and sustainable modes to reduce demand. Given that pre-COVID areas of urban networks were consistently failing to meet environmental objectives, CAZ, Clean Air Zones were being considered seriously in cities across the UK, to limit access to only low emitting vehicles. However research by Cairns (2012) in Leicester which modelled the impact of introducing electric cars into our fleets showed that even with 100% penetration PM10 levels would reduce by only 20%. Given there is no safe limit of particles, this suggests that there is need to reduce vehicle kilometres travelled and a radical behaviour change with a shift to sustainable travel particularly in vulnerable areas of the city.

Optimising networks to reduce carbon emissions
Notwithstanding tactical control, Local Authorities should give serious consideration to adopting a policy which optimises networks to minimise total air pollution which is synonymous with optimising fuel consumption and carbon dioxide emissions. However, this would achieve about a 3% reduction in

emission across the network. However, at today's traffic levels this is insufficient to prevent air quality exceedances at specific junctions and roads. By implementing tactical the area traffic plan is shifted away from the optimal solution and increases carbon as traffic spends time idling for longer at stop-lines and rat-runs making journeys longer. Developing win-win strategies for carbon and air quality with tactical control is difficult to achieve. Whilst many people believe that new vehicle technology will *save the day* research by Cairns (2012) modelling traffic in Leicester at 2005 flow levels showed that for private cars 96% penetration of electric vehicles would needed to deliver the mandatory eCO_2 limit, but of course levels of traffic have increased since then. Cairns concluded that realistically, given that a similar of penetration electric buses and heavy goods vehicles would be unlikely, the only way to deliver on targets was to reduce the VKT, vehicle kilometres travelled.

Delivering the mandatory UK Government target of 67% reduction of eCO_2 by 2050 over 2010 levels as well as meeting air quality targets poses interesting questions. "Just how much traffic, with future low emission engine technologies, can be allowed to use the network?" and "Can the impact of lockdown on traffic levels, the environment and travel choices inform network control and management to assist in re-imaging our future networks?"

Post-COVID social distancing has reduced the capacity of buses to 15%-20% and people are using their cars more to avoid contact with others, the future is uncertain. Whilst many more people have purchased cycles and levels of cycling have increased dramatically, as we approach the winter months it is anticipated that people will move towards alternative, likely private transport. Of course economic recovery requires movement of goods, delivery of services and people travelling to shop, to work, for personal business and leisure. The question arises: "Can network management and control be re-imagined to support economic growth by putting environmental objectives first?"

Re-imagining networks.
Rather than accept the inevitable consequences of lockdown, decline in the use of public transport, reduction in cycle use in inclement weather and increase in private car use, it is suggested that the situation we find ourselves in is turned into an opportunity. By working collaboratively with the bus operators, Schools, Local Authorities and Businesses, UTMC and ITS can play an important role reimagine our future networks. A future that reduces the need to travel, influences mode shift to sustainable modes and manages traffic in networks to deliver environmental objectives. This requires pedestrian and cycle focussed policies in controlling networks with emphasis on the provision of door to door seamless travel by a combination of sustainable modes. This will require a fully integrated approach and cannot be delivered over night. However, co-creating an evidence based re-imagined future urban area, incremental steps can be designed to re-engineer our networks and produce a road map. Engagement with the public is essential because by sharing the ambition and giving ownership of solutions maximises the success of uptake. This can only be achieved by understanding the public's barriers to change whilst simultaneously presenting evidence of the need to act and how sustainable travel choices can make a difference. Given every town, city, urban area is unique how a re-imagined future will be designed and delivered will be different, some ideas and approaches are now presented.

Reducing demand to travel
Given the success in working from home, WFH, companies are considering accepting this as the norm in the future for staff if not all the time but on few days each week. Whilst to be encouraged a study of the CO_2 emissions from the energy use (gas, electricity and for travel) over a period of one year in 575 households in Leicester, Allison et al (2016), suggested that the 50% of gross emitters of CO_2 were annually responsible for 96% of transport emissions and 60% of gas and electricity. The same research suggested that on average if people work at home and use gas, electricity to heat (or cool) the home they on average emit 75% more CO_2 than saved on average by not using the car to travel into the place of work. This has implications if people continue to choose to work from home post-COVID during the winter months.

A positive aspect of WFH is reduced vehicle demand for parking spaces in city networks and reduced congestion and pollutant emissions however it does have implications for well-being and mental health of the working population. It is suggested that efforts to create facilities for hot-desking with printing and scanning services, secure wifi and video conferencing facilities within walking and cycling distances from homes. This would mean that several people can interact on a regular basis saving energy (and carbon emissions) and overcoming the effects of isolation. Such facilities could develop dynamically at coffee shops in local villages, at bicycle shops or in the future integrated within new housing schemes or public transport hubs acting as catalysts for existing and new businesses.

Evidence is emerging that in-town and city business is falling causing large department stores and take-away food shops to close. This is due to the growth in on-line shopping coupled with reduced footfall during the day due to employees continuing to WFH due to social distancing requirements in offices and places of work.

As city centre and out of town retail businesses begin to close down and potentially also future office blocks, real estate will become available. Therefore to avoid areas becoming blighted grants should be awarded to repurpose buildings for housing targeting the younger population and essential workers as residents. Businesses should become more proactive in encouraging staff to use sustainable travel options, perhaps offering incentives (for example interest free loans for purchasing homes instead of a company car) to live locally with an undertaking to walk or cycle daily to work. Such housing may also be repurposed for the elderly population to be close to amenities. Shared mobility services to encourage city dwellers not own cars but to use electric vehicles when needed can be integrated with such city centre developments.

Businesses should be proactive and use postcode data of their staff to arrange out of phase WFH practices to more effectively use workplace carparks from day to day, and provision of secure convenient cycle storage and showering facilities which will be needed if well-known barriers to cycling are overcome.

Creating mode shift to public transport

The first step to creating a shift to sustainable modes is, through targeted campaigns, to re-instate the publics' confidence in using public transport. Incentives can be put into place to incentivise public transport use. These include purchase of travel cards (through company schemes for example) which allow seats to be booked for regular journeys but on fewer days in the week, carriers for transporting cycles, secure parking for bicycles at public transport hubs. An integrated approach to facilitate door to door services with seamless transfer between modes including with private vehicles requires investment in shared mobility facilities to provide first mile last mile services.

As companies, restaurants, shops and schools respond to meeting social distancing inside their premises, they should also give thought transport needs of their staff customers and clients. In the interest of maintaining public transport services financially viable into the future there is scope to begin to explore a change of policy for timetabling of bus services suggesting that operators consider tailoring bus services to meet the public's need.

Acknowledging that public transport is at the heart of a sustainable future, operators should consider working with:

- Education Authorities teachers and parents to tailor services to meet the school run, with an undertaking by parents to accept public transport as the main access mode across all ages.
- Companies and businesses to understand how bus services can be tailored to meet changing business practices (WFH, social distancing etc) influencing work patterns with shifts starting earlier and later to accommodate the use of buses for the school run and spread the demand for seats on public vehicles across the day.
- Retail outlets and city business community groups to again tailor opening times to compliment the demands for school and commuter travel.
- Consider dual purpose of use of buses with compartments for delivery of packages and shopping to out of town hubs, with racks on the rear to facilitate cycle carriage perhaps engaging with shared cycle schemes to transport cycles to places where they are needed.

Implications for traffic signal control and management

The ITS community can boast decades of research and a legacy of skills and expertise upon which they can build to support re-imagined futures. What they also have is the wealth of data available as a by-product of the application of UTMC systems and ITS technologies. Presented here are some suggestions moving forward.

Given there will be traffic, air pollution and meteorological conditions data available historically an analysis of such data along with the data captured during and since lockdown will help to identify how traffic influences the levels of pollution with the ability to establish the threshold level of traffic flow and congestion at which the air quality objectives will be delivered.

Canyon modelling assuming a dirty and clean year will help to establish a range for the threshold value for each link and hypothetical intervention measures (low emission buses, penetration of electric vehicles etc) can be evaluated. This understanding combined with an evaluation of carbon and pollution emissions will help to inform the size of the challenge facing the traffic manager in delivering a re-imagined future and what effort is needed to re-engineer travel appropriately.

Set up routine data capture from existing UTMC and ITS on an integrated data platform and use the data on a five minute sampling time to estimate traffic emissions to understand sources of traffic related air pollution and use a canyon model to predict where and when pollution hotspots occur in the network. There are potentially many reasons for elevated emissions including, ageing public transport fleets, excessive queues, the built environment, pedestrians and bus stops interrupting traffic flows, etc but this understanding will inform the design of intervention measures.

Use an emissions sensitive Performance Measure to penalise traffic on sensitive routes according to the offending pollutant. Networks optimised to reduce NO_2 will have be different signal timings if PM10 or CO_2 is minimised. Traffic engineers can explore tactical control combined with reductions in cycle time over areas to slowly reduce the capacity of networks for private cars whilst reducing delay to travel by sustainable modes as initiatives to promote mode shift to public transport and cycling.

Over time as the focus of the Performance Measure moves towards the delivery of environmental benefits more capacity is shifted to public transport, cyclists and the pedestrian. At this point traffic engineers need to address whether there is a need to revisit the basics of signal junction design and optimise timings to provide green waves for buses, cycles as well as pedestrians. How do we effectively manage the interaction of these three modes at junctions as the bus, cycle and pedestrian flows increase? Are our geometric design principles adequate and what changes are needed to the design calculations?

Knowing passenger occupancies will become more and more important; the use of mobile phones for checking services and bus arrivals means that public travel patterns can be tracked also. However, issues of data protection and sensitivity in competitive markets need to be addressed to successfully manage seamless travel across the modes.

More emphasis will be placed on delivering safe areas for people to move and enforcement of bus and cycle lanes will be needed. Access and egress to shared mobility facilities and managing secure parking for ever increasing bicycles will be needed. The physical layouts of roads and networks to accommodate changes use of modes (wider pavements for passengers' queueing at bus stops), cycle and pedestrian congestion.

Final Comment

This paper in setting the scene for the need to re-engineer and re-imagine future networks and to offer some ideas for the future is by no means complete. Instead, the purpose was to present food for thought and to sow seeds as basis for debate. Sustainable transport delivers win-win for carbon and air quality but active travel also has positive benefits for health, tackling obesity, heart disease to name a few. Reducing the amount of traffic in networks means less local pollution emissions resulting in cleaner healthier urban areas. This win-win-win sets out the basic principles for future policy and traffic signal control and management which aim to put people first.

Acknowledgement

My colleagues, too many to name, with whom I have carried out research over the decades that this paper has covered. The UKRI councils, the EU and DfT for funding the research which underpins much of what is presented.

References

ALLISON D. IRVINE K N., EDMONDSON J. L., TIWARY A., HILL G., MORRIS J., BELL M.C., Davies Z., DAVIES G., FIRTH S. K. FISHER J., GASTON K. J., LEAKE, J. R., Mc

HUGH N., NAMDEO A.K. RYLATT M., LOMAS K (2016) Measurement and analysis of household carbon: The case of a UK city. Applied Energy 164, 871-881
ALLSOP, R.E. (1974) Some possibilities of using traffic control to influence trip distribution. Transportation and Traffic Theory, (Proceedings of 6th International Symposium on Transportation and Traffic Theory). Elsevier, Amsterdam. 1974 pp 345-374.
ALLSOP, R.E. and CHARLESWORTH, J.A. (1977) Traffic in a signal-controlled road network: an example of different signal timings inducing different routeings. Traffic Engineering and Control. May 1977, pp 262-263.
ANDREWS, D. and HILLEN, S.M. (1980) Compact UTC Car Park Information Service. PTRC Summer Annual Meeting, University of Warwick. July 1980.
APERTUM (2020) Airviro on the Web Accessed 7th September 2020 Air Quality management System.
http://www.smhi.se/polopoly_fs/1.9234!Waved_v.1.11_UsersGuide.pdf
BELL Margaret C. (1978) Queues at junctions controlled by traffic signals TORG Research Report 26 Newcastle upon Tyne University, England
BELL. M.C., (1981) A queueing model and performance indicator for TRANSYT 7, Traffic Engineering & Control 22 (6)
BELL, Margaret C. (1983) A survey of the methods used to define and change signal plans in the UK. Transport Operation Research Group, Research Report 50, University of Newcastle upon Tyne. 1983.
BELL, Margaret C. (1984) Ageing of fixed-time signal plans. Paper presented at the Universities Transport Studies Group, Sixteenth Conference, University of Loughborough. January, 1984.
BELL M.C. 2006 Environmental factors in intelligent transport systems IEE Proceedings-Intelligent Transport Systems 153 (2), 113-128
BELL Margaret C. and GAULT, Helen E. (1982) An empirical study of plan change algorithms for area traffic control systems. IEE Conference proceedings on Road Traffic Signalling, London. 30 March 1982 - 1 April 1983.
BELL, Margaret C., GAULT, Helen E. and TAYLOR, LG. (1983) Transport Operation Research Group, Research Report 51, University of Newcastle-Upon-Tyne. April 1983.
BELL M. C., SCEMAMA G. IBBETSON L.J. CLAIRE An expert system for Congestion Management. Proceedings of the DRIVE Conference, Brussels, February 4th – 6th 1991
BELL M.C., CHEN H., HACKMAN M., Mc CABE K., PRICE S., (2006) Using ITS to reduce environmental impacts Published by 13th world congress on Intelligent Transport systems, London, 9-12
BELL Margaret. C (1996) An introductory guide to the instrumented city facility Traffic engineering & control. Vol. 37, no. 12
BELL M., (2011) How Can Traffic Engineers Help Manage Our Environment? Traffic Engineering & Control 52 (2)
BERNARD, N.W. and HILLEN, S.M. (1981) Compact UTC, (4) Evaluation of the Hull and Torbay Systems. Traffic Engineering and Control. May 1981 pp 281-288.
BRETHERTON, R.D. (1979) Five methods of changing fixed-time traffic signal plans. (Department of the Environment and Department of Transport.) Transport and Road Research Laboratory Report LR 879, Crowthome. 1979.
BRETHERTON, R.D. and RAI, G.I. (1982) The use of SCOOT in low flow conditions. Traffic Engineering and Control. December 1982, pp 574-576.
BOURNER, M. (1984) SCOOT Experience in Kent. IEE Colloquium Digest No. 1984/58. May 1984.
CAIRNS J., (2012) Technology, Alternative Fuels and Low Emission Vehicles: win-win for air quality and climate change? Paper presented at the Universities Transport Studies Group, 44th Conference, University of Aberdeen. January, 2012
CERC (2020) ADMS –Urban, Air Quality modelling Software, Accessed 7th September 2020 https://www.cerc.co.uk/environmental-software/ADMS-Urban-model.html
CHESS ELL, B.A.C. (1981) Compact UTC in East Sussex. Traffic Engineering and Control. June 1981, pp 366-369.

CLOWES, D.J. (1982) Real-time wide area traffic control -the users ,·iewpoint. Traffic Engineering and ControL April 1982, pp 194-196.
DAVIES. D.M. (1984) The use of microprocessors in traffic controllers. IEE colloquium on Road Traffic Signalling, Digest No. 1984/58. 1984. .
DEFRA (2019) Emissions Factor Tool Kit, Department for Environment Food and Rural Affairs https://laqm.defra.gov.uk/documents/EFTv9-user-guide-v1.0.pdf
ELDOR. M., (1976) Integrated real-time freeway on Ramp Control Strategies. PhD Dissertation, University of California, Berkeley. September 1976, p 625.
ELDOR. M., (1977) Demand Predictors for computerised Freeway Control Systems. Proceedings of 7th International Symposium on Transportation on Traffic Theory. Edited by I.Saska and T. Vamoaka. 1977, pp341-370.
EVANS. J.B. (l 978) Microprocessors: A discussion in the context of traffic control. Traffic Engineering and Control 19(3). March 1978 p 112.
FERGUSON, J.A. and JENKINS, LA. (1973) Performance comparison of frequent and infrequent plan changing in Area Traffic Control. Transport Operations Research Group, Research Report 4, University of Newcastle-Upon-Tyne. November 1973.
GAZIS, D.C. and SZETO, M. W. (1974) Design of Density Measuring Systems for Roadways. Transportation Research Record 495. 1974, pp 44-52.
GUBERINIC, S. and SENBORN, G. (1978) Optimal Sequences of Fixed-Time Signal Plans. Transportation Science, Volume 12, No.I. February 1978.
HAWKINS, M.R. (1979) The development of UTC for medium sized towns. Proceedings of Traffic Engineering and Control, Traffex. 1979.
HILL G. (2015) Internal TORG Report Newcastle University
HUMPHREY, T.L. and WONG, P.J. (1976) Improved control logic for use with computer-controlled traffic. NCHRP Report 3-18 (1)/1 Stanford Research Institute. March 1976.
HUNT, P.B., ROBERTSON, D.I., BRETHERTON, R.D. and WINTON, R.I. (1981) SCOOT - a traffic responsive method of co-ordinating signals. Transport and Road Research Laboratory Report, LR 1014, Crowthorne. I 981.
HUNT, P.B., ROBERTSON, D.I, BRETHERTON, R.D. and ROYLE, M.C. (1982) The SCOOT on-line traffic signal optimisation technique. Traffic Engineering and Control. April 1982, pp 190-192.
HOLROYD, Joyce and HILLIER, J.A. (1969) Area Traffic Control in Glasgow: A summary of results from four control schemes. Traffic Engineering and Control. 1969, 2(5) pp 220-223.
HOLROYD, Joyce and ROBERTSON, D.I. (1973) Strategies for area traffic control systems: present and future. Transport and Road Research Laboratory Report LR 569, Crowthome. 1973.
JALIHAL S., (1999) Estimation and prediction of roadside pollution using SCOOT and ADMS (urban) model 31st Annual Universities Transport Studies Group Conference, University of York, January 1991.
KAKOSIMOS, K.E. HERTEL O., KETZEL M., BERKOWICZ R., (2010) Operational Street Pollution Model (OSPM) - A review of performed application and validation studies, and future prospects Environmental Chemistry 7(6):485-503 November 2010
DOI: 10.1071/EN10070
KAY, P.C.M. CASTLE, D.E. (1971) Plan changing with TRANS YT. A paper presented at the "Symposium on Road Traffic Simulation" at the University of Birmingham. September 1971.
KITTLESON, W.K. (1976) Application of existing strategies to arterial signal control, Volume 1 -Functional description of signal control techniques. Draft First Interim Report, Alan M. Vorhees and Associates, McClean, Virginia. 1976, pp 31-49.
KLD ASSOCIATES Inc. (1974) Variable Signal Timings Program, Volume 1 -Development of third generation control policies for the UTCS, Springfield, Virginia. National Technical Information Services, (PB 241 717/AS). May 1974.
KNAPP, C. (1973) Traffic Density Estimation for Single and Multi-lane Traffic Transportation Science 7(1). 1973, pp 75-84.
KREER, J.B. (1975) A comparison of Predictor Algorithms for Computerised Traffic Control Systems. Traffic Engineering Journal. April 1975, pp 51-56.

KREER, J.B. (1976) Factors affecting the relative performance of traffic responsive and time of day traffic signal control. Transportation Research 10. 1976, 75-81.
LIEBERMAN, E.B. and WICKS, D. (1974) Arapid signal transition algorithm. Transportation Research Record 509, Transportation Research Board, Washington DC. 1974, pp 1-15.
LIEBERMAN, E.B. et al (1974) Variable cycle signal timing program Volume III -CYRANO cycle free responsive algorithms for network optimisation, moderate, congested and light flow regimes, Springfield, Virginia. National Technical Information Service, (PB 241 719/ AS). May 1974.
LUK, J.Y.K. (1981) Australian Road Research Board, Internal Report, AIR 331-332. 1981.
LUK, J.Y.K., SIMS, A.G. and LOWRIE, P.R. (1982) SCATS -Application and Field Comparison with a TRANSYT optimised fixed-time system. Proceedings of The Institution of Electrical Engineers International Conference of Road Traffic Signalling. 30 March -I April 1982, pp 71-74.
MACGOWAN, J. (1980) Private communication.
MACGOWAN, J and FULLERTON, Iris J. (I 980) Development and testing if advanced control strategies in the Urban Traffic Control System. Public Roads, Volume 40, No.4, Washington DC 20590, US Department of Transport. March 1980.
McSHANE, W.R. et al (1976) Developing a predictor for Highly Responsive System-based Traffic Signal Control. Presented at the 55th TRB Meeting. January 1976.
MOORE et al (1976) Three traffic signal control philosophies applied to an arterial traffic system. Proceedings of 8th ARRB Conference 8(5) session 22. 1976, pp 1-9.
MOORE, P and CHENG P. (2004) New Developments in LINSIG for Windows Ninth JCT Traffic Signals Symposium 8th September 2004
MORGAN, J.T. and LITTLE, J.D.C. (1964) Synchronising traffic signals for maximal bandwidth. Ops. Res. 12(6). 1964, pp 896-912.
NICHOLSON, H. and SWANN, C.D. (1974) The prediction of traffic flow volumes based on Spectral Analysis. Transportation Research 8. 1974, pp 533-538.
OECD (1977) Integrated Urban Traffic Management. OECD Report TS 13, Paris. 1977.
PHILLIPS, J. (1982) Compact UTC (l) The 'chips' come to town: preparing for compact UTC and using it. Traffic Engineering and Control. January 1982, pp 4-9.
RACH, L. (I 976) The development and evaluation of Metropolitan Toronto's real time program for computerised traffic control devices. Paper to the 3rd IF AC International Symposium on Control in Transportation Systems, Columbus, Ohio. August 1976.
REDFERN, P.C. and SHAPELY, G.A.P. (1981) Compact UTC (3) Its application in Devon and Humberside. Traffic Engineering and Control. March 1981, pp 127-132.
REYNOLDS S., and BELL M.C: (1991) Carbon monoxide monitoring in urban areas: 23rd Annual Universities Transport Studies Group Conference, University of Newcastle-Upon-Tyne. January 1991.
ROBERTSON, D.I. (1969) TRANS YT: A TRAffic Network StudY Iool. Transport and Road Research Laboratory Report LR 253, Crowthorne. 1969.
ROBERTSON, D.I. (1974) Cyclic flow profiles. Traffic Engineering and Control. June 1974.
ROBERTSON, D.I. and VINCENT, R.A. (1975) Bus priority in a network of fixed time signals. Transport and Road Research Laboratory Report LR 666, Crowthorne. 1975.
ROBERTSON, D.I., LUCAS, C.F. and BAKER, R.T. (1980) Co-ordinating traffic signals to reduce fuel consumption. Transport and Road Research Laboratory Report LR 934. 1980.
ROBERTSON, D.I. and HUNT, P.B. (1982) A method of estimating the benefits of co-ordinating signals by TRANSYT and SCOOT. Traffic Engineering and Control. November 1982, pp 527-531.
ROSS, Paul (1977) An Evaluation of Network Signal Timing Transition Algorithms. Traffic Engineering and Control. September 1977.
STANNETT, A. and SULLIVAN, T. (1981) Compact UTC (2) The System. Traffic Engineering and Control. February 1981, pp 72-78.
TATE J.E. BELL M.C., Evaluation of a traffic demand management strategy to improve air quality in urban areas, IET Digital Library

TIMMERMANS, W.F., VAN DEN BOSCH, P.P.J. and KLIJNHORT, J.J. (1979) Improved network control by using TRANSYT. Traffic Engineering and Control. July 1979, pp 353-356.
WALMSLEY, J. (1982) The Practical Implementation of SCOOT Traffic Control Systems. Traffic Engineering and Control. April 1982 pp 196-199.
WEBSTER, F.V. and COBBE, B.M. (1966) Traffic signals. Ministry of Transport Road Research Technical Paper No. 56, HMSO, London. 1966.
WITHILL A., (1992) Expert system for demand responsive control PhD Thesis Nottingham University.
WORRALL, R.D., LIEBERMAN, E. and FERLISS, R.A. (1973) Network flow simulation for Urban Traffic Control System, Phase II Volume L Report No. FHWA-RD-73-83. Federal Highway Administration, Washington