The 'Queensway' Mersey Tunnel entrance control project

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In 1968, a computer-controlled system was installed by the City of Liverpool to schedule vehicles on the approaches to the 'Queensway' Mersey tunnel. In 1972, the scheme was extended by their own Engineering Division, to provide direct control of the traffic entering the tunnel itself. This paper discusses the project, together with some of the problems encountered in the design of the scheme.

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1. Introduction

In September 1971 the toll-booths at the Liverpool entrance to the 'Queensway' tunnel, linking the City of Liverpool to the Wirral peninsula beneath the River Mersey (**Fig. 1**) were closed and transferred to the Birkenhead entrance, where a redesigned approach and toll-booth system had been implemented. Prior to this transfer it had been hoped, from a traffic-management point of view, to have installed a control system employing traffic signals at the Liverpool entrance. Unfortunately, due to practical considerations in the siting and installation of this equipment, the booth-transfer had to take place first.

The decision to control the traffic entering the tunnel by means of traffic signals had been prompted by a number of factors:

1. The presence of the booths ahead of the 'Plaza' merging area regulated the speed at which the vehicles could enter the tunnel, and hence the speed at which vehicles could merge from opposing approaches (**Fig. 2**) remained fairly low. Absence of any speed constraints would permit undesirable speed-conflicts and unsafe conditions in the merging area. Releasing only one approach at a time would be more satisfactory, and would have an inherent safety factor.
2. The Tunnel Authorities required manual override facilities to control traffic to reduce the flow or prevent entrance into the tunnel in the event of emergency conditions, such as a breakdown within the tunnel.
3. Experiments conducted by the Port of New York Authorities on the 'Lincoln' and 'Holland' road tunnels (Strickland, 1954; Greenberg, K. W., and Crowley, 1965), had suggested that an entrance control could improve the throughput of the tunnel, by reducing conditions which induce 'shockwaves', and which in turn rapidly encourage queue-formation.
4. The requirement for a manual control console to define the mode of control to the signal installation, to isolate the signals, and to apply an 'all-red' state at any time by a suitable key-setting. This control console was to supplement the existing consoles in the main Traffic Control Centre (**Fig. 3**) established in 1968 in the Liverpool Congestion Control Scheme (Davison and Honey, 1970).
5. Because of differences in the geometry and capacity of the two approaches, the origins of the vehicles, and the personal preferences shown by the motorist to use one approach rather than another, the provision of suitable biasing in the favour of one approach over the other was required. Additionally, under congested traffic conditions, diversion signs were to be illuminated to encourage the motorist to take an alternative approach, to which a manually-set bias had been applied. These were to be originated at the control panel (above) and reinforced by the computer.
6. An extension to the existing computer-control scheme (Davison and Honey, 1970) was required to interface the approaches to the new signalised section leading into the tunnel Plaza.

2. System analysis

The major problem encountered in the initial analysis was the definition of the switching of the two groups of proposed traffic signals (one group for each main approach to the tunnel) in such a way as to ensure smooth traffic-flows into the tunnel itself. The interface between each approach and the tunnel entrance is a variable, comprising a 3-lane approach feeding 2 lanes of the tunnel under normal control conditions, such as 10.00 hours to 16.30 hours. During the commuter peak-hour, the 'lane-mode' is changed, so as to permit 3 approach-lanes to feed 3 lanes of the tunnel in the evening, and 3 lanes to feed one tunnel-lane during the morning peak-hour (16.30-18.30 hours, and 08.00-09.30 hours respectively), since the tunnel lanes are allocated by the Tunnel Authorities according to traffic demands. Additionally, these control modes (hereafter identified as a 'lane-mode') must be modified according to the flow-conditions experienced within the tunnel, as a platoon containing too many vehicles, or travelling too quickly can quickly induce congestion at the tunnel mouth, and queueing conditions created within the tunnel itself (and remote from the

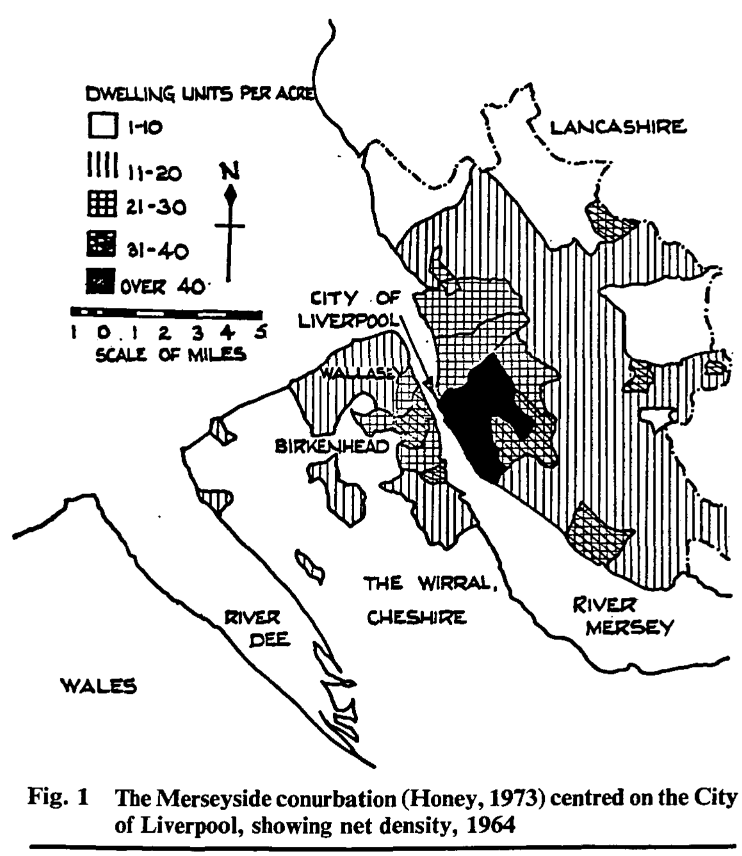

Fig. 1 The Merseyside conurbation (Honey, 1973) centred on the City of Liverpool, showing net density, 1964

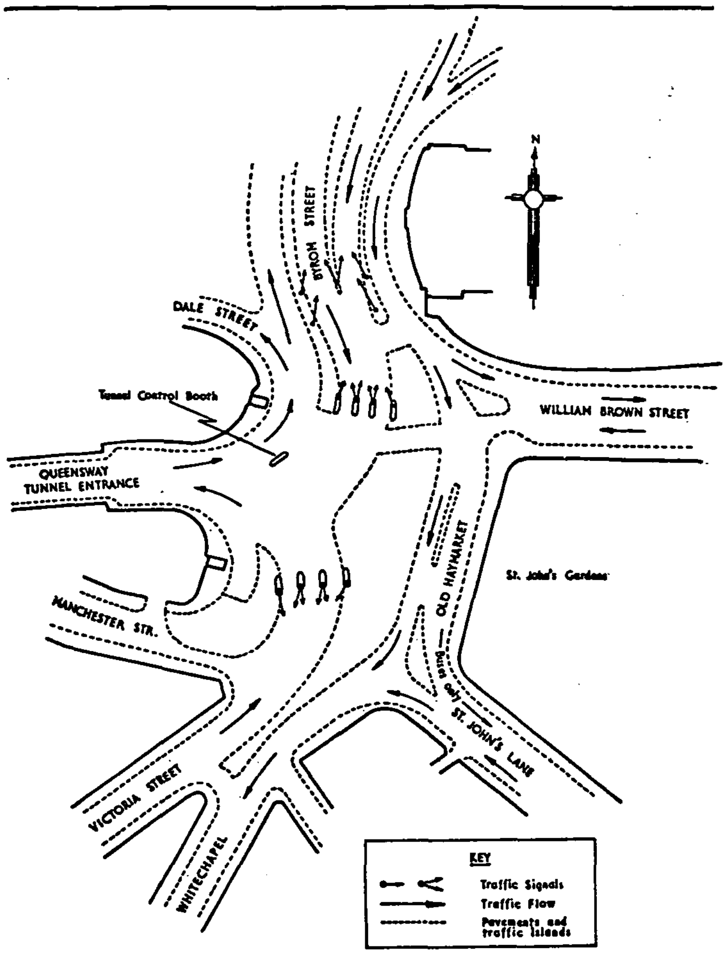

Fig. 2 Approach layout to the Liverpool entrance of the Queensway Mersey Tunnel, 1971

entrance) can upset the balance of control. With the lane-mode of '1' (one lane Liverpool to Birkenhead), the problem is intensified, as only one lane of the current approach can be released at a time, to eliminate 'overcrowding' in the Plaza area.

Additional complexities have been introduced by the requirement to give a bias of one approach over the other, either by manual insertion from the control panel or by automatic detection of conditions along the approaches upstream of the control point. Finally, the accommodation of partial or total human intervention which may be applied at any time either from the Central Control room, or from a remote control point at the tunnel entrance and operated by the Tunnel Authorities, must be borne in mind.

Recognisance has to be taken of the fact that a traffic signal controller was a hard-wired computer in its own right, with built-in algorithms, for example, to ensure that once a phase-sequence had been initiated (red-amber), that the green follows, and remains 'green' for a legal minimum of 7 seconds. Hence, once the phase had been started, no commands can prevent it running (short of switching off the power supplies). Sampling of phase-state of all the signals was therefore employed at all times, to ensure a smooth transition between one control mode and another.

The street furniture employed differs slightly from that used at a conventional signal-controlled intersection, in that six separate 2-phase controllers are used, one for each individual lane. When computer-control is not being used, a seventh (principal) controller defines which of two phases is to operate, and commands three of the 'slave' controllers to operate accordingly. The principal controller has a third 'phantom' phase which is selected and held when manual- or computer-control is demanded, and selection of this phase relinquishes control of the principal controller over the slave-controllers, causing the latter to revert to a 'red' state. Commands from the computer system may now be extended to the 'slaves' in any combination and time-length (each slave controller separately defines its own red-amber, minimum-green, and amber periods), and the control algorithm must take these factors into account. Once the minimum-green period has expired, the phase may be terminated by removing the 'green-demand' control signal. Synchronism between each group of three signals must also be maintained by the computer.

3. Traffic management and design

The traffic signals in the Plaza have been positioned as close to the tunnel entrance as practicable. The lantern-posts have been erected between massive reinforced-concrete 'book-ends', in an effort to preserve the posts from lateral encounters with long lorries negotiating the curve from the approaches into the tunnel. Channelling islands on the two approaches (**Fig. 4**) guide the traffic through the change of direction, and portable bollards are used by the Tunnel Police in the Plaza area (beyond the lights) to delay any remaining merging conflict until the vehicles are travelling almost parallel to one another.

Each approach utilises a set of primary signals arranged so that the three lanes of each approach have two signal-heads each. As a secondary lantern cannot be provided due to the geometry of the merging area, 'continental repeater' lanterns (aptly referred to as 'dog-lights') are sited on each lantern pedestal below the main signal-heads, and about a metre above the road level.

Upstream of the Plaza lights another set of signals are sited on each approach. On the Victoria Street approach, the lights control a pedestrian crossing. On the Byrom Street approach, a signal-controlled merge occurs between two three-lane approaches. Three phases are provided at this intersection, the third 'phantom' phase being selected to give a controlled 'all-red' facility on the merge area.

4. The computer equipment

A digital computer system had been implemented in 1968 to control the traffic on the approaches to the 'Queensway' tunnel, and required little extension for the current project. A detailed description of the system is given in Davison and Honey (1970) and may be briefly summarised as follows:

1. *Inputs*

Inductive-loop, sub-surface vehicle-detectors sited at convenient points in the road-system provide digital indications of vehicle presence or absence. The information is transmitted via twisted-pair cables as DC-signals to operate buffering relays in the Control Centre. The buffering relays provide 'clean' signals to the 'single-bit input' units, where the information is scanned by software every 1/4 second, and staticised into tables of 'just-on', 'just-off', 'this-time', 'last-time' combinations. A presence- or absence-count is also generated (by software) for each loop, and used to indicate loop-failure when certain time-count thresholds are exceeded.

Most of the loop-installations are grouped in pairs about 2 metres apart, and in line with the traffic flow, so that traffic parameters such as speed (for traffic-control only), vehicle spacing, and vehicle lengths may be derived. When speed indications are required, the loop-states are sampled at 50-millisecond intervals to give a reasonable accuracy (about 4% at 30 mph).

2. *Central system*

The heart of the system is a Plessey 'XL9', a 24-bit digital computer, currently with a 32K store. There are no encumbrances, such as mag-tape, -disc, -drum, etc. apart from the bare

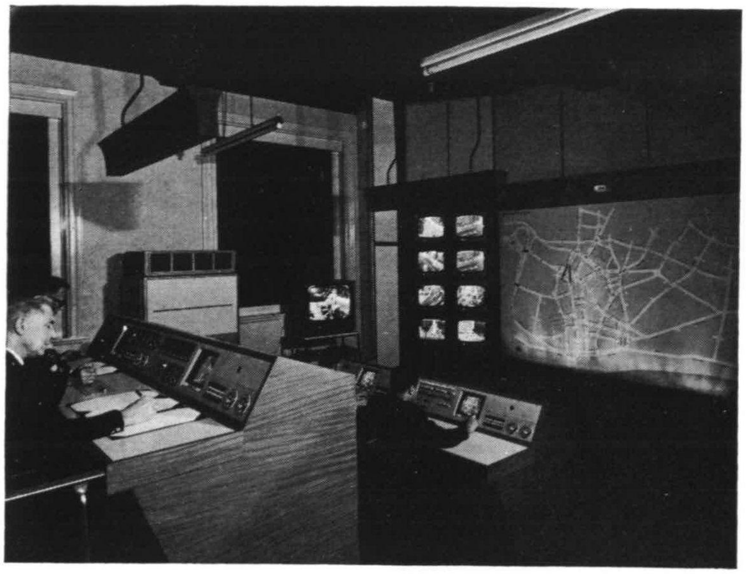

Fig. 3 The Traffic Control Centre, showing the control desks, CCTV-monitors, and mimic display. The marks on the road are 'green' indicators, reflecting the phase-state at each intersection.

necessities of a 500 cps paper-tape reader, 100 cps paper-tape punch, and a now-veteran Flexowriter for use as a control typewriter. All three peripherals are served by a 10-msec polling service routine. An engineering control console, originally provided for fault-diagnosis and off-line work, now entertains the visitors with its 'blinking lights', and reassures the staff that the system is still running.

The system cycles at a basic 1-second rate, 24-hours per day, 7 days each week. There are no scheduled maintenance periods—indeed, to date none have been necessary, as no computer failures have been recorded since installation in July 1968. Currently, there is 68% spare time available, each second.

3. *Outputs*

Outgoing control signals are staticised on mercury-wetted- or dry-reed relays, and the control state is transmitted at the beginning of each 1-second period. These control signals operate traffic signals on the approach routes, together with certain other traffic lights on routes established for the Fire Service (Honey, 1972a; 1972b). Outgoing signals also operate advisory signs on the street, and indicate queueing conditions on a large mimic street-map in the Control room (Fig. 3). Traffic signal states (green phase only) are also displayed on the map.

5. Program development

The entire system program is written in a low-level pseudocode 'EXEC 9', which is basically a one-for-one code. Its simplicity of use has proved invaluable in the debugging of programs on-line, in real time, especially where alterations have to be loaded into specific store-areas. Additionally, efficiency in core-occupancy (the new control program only occupies about 2500 words) and real-time demand this low-level language useage.

Each new program developed (by the Systems department) is initially defined in high-level language (ALGOL) not only to obtain a clear understanding between the traffic engineers and the software engineers of the intended operation, and to provide a rigorous definition of the software logic, but also to provide a basis for the final documentation. The program is then 'hand-compiled' into the pseudocode, and the high-level statements incorporated in the pseudocode as comments. This has proved invaluable at later stages in system development, and provides good program documentation at the point of development rather than as an afterthought some weeks (or months) later. Further, it eliminates the need for detailed and verbose plain-language documentation at the conclusion of the project. The ALGOL statements—which programmers are trained to provide—describe the logic in crisp and accurate descriptions; programmers are (alas) not trained as technical writers, and experience has shown that plain-language descriptions of programs are often incomplete, vague, and misleading.

The procedures are written modularly, and tested off-line with suitable test procedures. Most debugging is effected off-line, for once the procedures are in system (online, in real time), the data is only available for one or two seconds, before being replaced by fresh data, and re-capturing or reproducing that elusive bug is impossible.

Once in system, cause and effect are noted, and any corrections required may be quickly injected as direct overwrites via the control typewriter (for small quantities), or via the tape-reader (for longer ones). Where re-compilations are required, the machine-code (developed offline on another free-standing computer) may be bootstrapped into the system online, and then linked-in by a suitable overwrite. New system tapes are then dumped from the core-store on to paper tape, its predecessors becoming 'father', and 'grandfather', and so on in the conventional manner. 'Great-grandfather' is laid to rest.

As a point of interest, the system tape also contains its own 'system dump', 'verification' (after dumping), 'bootstrap' etc. procedures. The computer does have its own hardware bootstrap, but is restricted to about 20K-programs, due to register limitations. These facilities are called via the engineering console when the system is offline, although 'load' and 'dump' can be initiated online.

6. Experimental control operation

During the quiet hours, and during the off-peak hours of normal working days, the Plaza signals are manipulated in the Control Centre to give a permanent green-aspect on the Byrom Street approach. The lanterns on the Victoria Street approach are switched off, and a 'part-time' sign 'GIVE WAY' (positioned above these lanterns) is illuminated. As the tunnel traffic-flows increase with the onset of the peak-hour, the Duty Controller, monitoring the traffic by means of closed-circuit television (CCTV) equipment, decides when to cancel the 'GIVE WAY' sign, and select manual- or computer-controlled operation, to permit the normal cycling of a right-of-way.

Initially, to obtain the control information required, and to gain experience in the new system, the rotation of the right-of-way was determined by the manual selection of the appropriate keys on the control panel, and the phase-timings were derived by conventional means. Assessments were then made of these phase-timings, and the parameters introduced into the computer control-algorithm as 'plans' of green and intergreen timings. The computer output parameters were used to drive a set of indicators on the control desk, representing the signal lanterns at the Plaza.

As the computer control program changed the aspect of these indicator lights, the Duty Controller, currently assessing the state of the traffic by means of the CCTV system, either manually changed the state of the Plaza lights to that suggested by the computer, or ignored them (when obviously incorrect) and implemented his own decisions. When sufficient experience and reliance had been gained in the system, and the correct parameters had been set into the plans, the main signal-controller and sub-controllers were connected electrically to the computer outputs, and although carefully monitored by the Duty Controller, the computer was allowed to make the necessary changes directly.

One basic facility remains intact throughout the complete system, whether it be under manual control, computer control, or 'GIVE WAY', namely that, at any time, a Duty Controller, either at the Control Centre or at the Tunnel Entrance Control booth, can set any or all of the Plaza lights to red. As each lane is individually controlled, any one lane may be stopped to prevent or delay access to the tunnel. This is particularly useful to the Tunnel Police who, on being warned of a 'high load' by a sensing device, can stop the vehicle before it enters the merging area, and then manually control it into an adjacent marshalling area. The inhibited lane can then be released, the light-operations automatically being re-synchronised with the main phase.

7. System operation

Control of the lights is effected by extending green-demand signals directly to the controllers required. Application of an inhibit (a red-demand) isolates the green-demand from the appropriate controllers, once the minimum-green periods have been satisfied, and allows the controller to return to the red state. Release of an inhibit re-establishes the green-demand—assuming that it is still present—and once the phase has been initiated, a minimum-green aspect of 7 seconds will be displayed regardless of further inhibit application or by the removal of the green-demand.

Isolated lane-control is invaluable when 'tidal flow' operation from Birkenhead to Liverpool is required, which constrains the Liverpool to Birkenhead traffic to single-lane usage in the tunnel. In this mode, each approach-phase is sub-divided into three individual lane phases, and each lane is released independently of the other two. Once each cycle, the computer runs a simple pseudo-random number generator to establish a sequence in which the three individual lanes are to be selected, each cycle differing from the previous sequence. This selection prevents the approaching motorist from observing and predicting the next lane to be selected, and discourages 'queue-jumping' and unnecessary lane-changing, thereby encouraging lane-discipline.

During each lane-phase, samples of vehicle-presence and passage are made via inductive-loop detectors sited in each approach lane; absence of a vehicle causes the phase to be shortened or skipped as appropriate to reduce unnecessary delays to other waiting vehicles, but after one lane has been omitted for three successive cycles, a minimum-green is allocated to that lane to encourage full lane-usage.

Finally, to ensure that one lane is not over-used by continuous flows from the upstream road-section, the traffic signals upstream of the Plaza signals (namely, the pedestrian lights in Victoria Street and the merge lights in Byrom Street) are used to 'gate' vehicles into the final section. Hence, when the Victoria approach is released, the traffic aspect of the pedestrian lights is forced to red, and similarly for the Byrom Street approach. Additionally, to control random pedestrian demands during normal 2-lane and 3-lane operation, the traffic aspect of the pedestrian lights is forced to 'green' about 12 seconds before the start of the anticipated Plaza green, thereby inhibiting another pedestrian demand until the end of the current phase.

Inductive-loop detectors have also been sited in pairs in each lane about 25 metres inside the tunnel proper, to enable traffic flows, vehicle counts, speeds, etc. to be monitored at all times.

Fig. 4 The 'Queensway' Mersey tunnel entrance in Liverpool

8. Traffic-computer-control philosophy

The anticipated flows for the 9ft tunnel-lanes were calculated from the Highway Capacity Manual (1965), which suggests that a stable flow of only 1000 vph per lane is practicable. Under actual conditions (not peak-hour), measured flows showed that about 1200 vph was feasible. Theoretical saturation flows (Webster, 1958; Webster and Cobbe, 1966) from the stoplines at the Plaza lights imply a value of 1950 vph per 14ft lane, but a figure of only 1750 vph or less was observed. (Computer measurements made at a later date indicated saturation flows ranging from 1526-1786 vph, depending upon the lane (Honey, Turner and Hayes, 1974). These discrepancies are due to the rapid change of direction required on leaving the stopline, and the subsequent minor interference between vehicles in the Plaza area as lane-discipline is enforced on entering the tunnel.

The control philosophy therefore had to restrict the input flows to about 67 per cent. of the free flows, and the author postulated that a 20 second green phase in which a (saturation) flow of 1800 vph could be attained, followed by a 10 second intergreen, would give an overall flow of 1200 vph. However, as the tunnel can only maintain a maximum stable flow of 1200 vph (per lane), it was argued that a platoon of vehicles concentrated at 1800 vph would become unstable, and induce 'shockwaves' (interference patterns) during the propagation of this platoon through the tunnel, due to the platoon catching up with the preceeding platoon. The dispersal of a highly-concentrated platoon is a lengthy process—especially in the confines of a tunnel—and it is unlikely that the dispersion would be complete before the next platoon would have been released, and caught up with the first platoon. Unheeded shockwaves usually propagate against the traffic flows, towards the tunnel mouth, and ultimately would impede vehicles waiting for their release from the stopline. Control at this point would then break down, as platoon-release would be controlled basically by the availability of space in the tunnel plaza.

Clearly, a policy was required to allow the platoons to disperse freely. Ideally, each platoon would contain a single vehicle travelling at its free speed, with sufficient headway to permit the following platoon (one vehicle) to travel at its free speed. This is impracticable, and compromise has been reached by setting the green-time to a fixed value, and adjusting intergreens to produce the desired tunnel-flow.

Accordingly, the control mechanism has been made traffic-sensitive, so that when the flow within the tunnel reaches a predetermined level, overall control is applied by the computer for a fixed minimum time. Any tendency for the traffic flow to change from the desired flow is then countered by the computer, by selecting a 'plan' of green and intergreen times most suited to the prevailing conditions. Evidence of increasing flows (based upon past histories and a prediction routine) calls for a plan having a higher intergreen value to reduce the average flow, and vice versa. Detection of queues in any lane is interpreted as a requirement to constrain the flows further, and total congestion (indicated by stationary or slow-moving queues) induces an all-red state, until at least one lane-queue moves at a speed which exceeds a preset minimum.

As congestion is eased, shorter intergreens are introduced, quickly at first, and then more slowly, asymptotically approaching the plan with the highest green/intergreen ratio in its library, and finally relinquishing computer control after three complete cycles during which the actual flow remains less than a preset 'threshold' flow.

The decision to use a convergent 'iterative' procedure was taken to ensure that when initially installed, it would work reasonably well, even with incorrect plan-parameters, whereas a more subtle program (involving considerably more work) may well have required substantial amendment before it was considered satisfactory. Also, by its very design, this iterative system is inherently stable, which is a most important asset.

Finally, it is desirable that the final control gives results which appear reasonable to the motorist. From the onset of the project, the author (himself a motorist) has realised that individual drivers will always retain some control over their vehicles, that they will use this control to achieve their own purposes, and may evade or disobey the rules so carefully formulated for them. It is an unrealistic solution to any traffic problem to schedule drivers by forcing them to adopt undesirable origins, destinations, or intolerable delays.

9. Recording of results, and system evaluation

So that this system could be evaluated and assessed against previous and subsequent control systems, vehicle-counts were taken during the morning and evening peak-hours via the loop detectors sited in the tunnel lanes, and by means of a logging program in the computer. Counts are accumulated for six minutes, and then punched out (on paper tape) for later analysis. This process had been employed for some time prior to the introduction of the new 'Boothless Control', and direct comparison of the flow-values for 'before' and 'after' was considered viable.

Flow measurements have shown an overall increase of about 5 per cent. in hourly flows, which is the order of increase anticipated from the results published for the 'Lincoln' and 'Holland' tunnels (Strickland, 1954; Greenberg and Crowley, 1965).

The success of the scheme is reflected by its smooth operation, even at the peak of commuter flow. A considerable reduction in vehicle breakdowns within the tunnel has been experienced; these were often caused by the overheating of engines and by 'tunnel-clutch', both induced by extended stop-start-stop queueing conditions. Vehicle breakdowns such as these are less likely under fluid traffic-conditions, both because there are fewer vehicles present (a lower density) in the tunnel at any time, and because those vehicles are able to move continuously, and avoid the conditions which promote and precipitate breakdowns—especially in hot weather.

And for much the same reasons, air pollution inside the tunnel caused by vehicle exhausts is much less when fluid conditions are maintained, and the fact that traffic is delayed less on the approaches infers that external pollution is also reduced.

10. Further developments

As stated earlier, the saturation flows from the stoplines adjacent to the tunnel entrance were initially estimated, and then measured via the computer (Honey, Turner and Hayes, 1974). A wide range of saturation flows were obtained, and it was noted that drivers had a marked preference for the lane nearer the tunnel entrance. Further, the measured flows were found to be even less than the 'observed' flows initially used. By using the measured saturation flows, a series of cycle-times were calculated to define a set of new 'plans', and adjusted to give the desired tunnel-flows under different conditions. Additional plans were calculated for manually-applied bias conditions, in which one approach is given a modified green-time to give some preference to it over the other.

The new plans contain reduced green-times, thus ensuring that a saturation-flow can be maintained throughout the phase. This means that a concentrated platoon can be released more regularly, thus increasing the efficiency of the intersection.

Additional traffic-sensitivity has since been introduced into the computer program to enable the system to react more rapidly to changing conditions, and in the near future, it is hoped to predict approach delays by sampling the flows throughout the tunnel.

11. Conclusions

Critics of the control system have commented at the large gaps separating the platoons released into the tunnel entrance. Additional criticism is made at the ever-present queues on the tunnel approaches during the peak-hours. These criticisms have been offset by the evidence of the smooth flows experienced within the tunnel, by the accommodation of a noticeable increase in the volume of tunnel traffic which has been recorded (in toll fees) during the past year without a similar increase in approach delays, and the measured increase of physical throughput in vehicles per hour. Additionally, a marked reduction of the overall peak-hour—even under adverse conditions—has been observed, and hence the control system is deemed to be a success.

Valuable experience has been gained in the ever-widening field of computer control of road traffic, and it is hoped that this new-found knowledge will be reflected in Liverpool's latest 'wacker', the 'Wide Area Control' project (Honey, 1973).

12. Acknowledgements

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References

DAVISON, A. and HONEY, D. W. (1970). The Liverpool Congestion Control Scheme, *The Computer Bulletin*, Vol. 14, No. 12, pp. 407-411.

GREENBERG, K. W., and CROWLEY, I. (1965). Holland Tunnel study aids efficient increase of tube's use. *Traffic Engineering*, pp. 20-44.

The Highway Capacity Manual, Highway Research Board, Special Report No. 87, 1965, U.S. National Research Council.

HONEY, D. W. (1972*a*). Priority Routes for Fire Appliances, *Traffic Engineering and Control*, Vol. 14, No. 4, pp. 166-167, August.

HONEY, D. W. (1972*b*). Extensions to the Liverpool 'Green Wave' System, *The Journal of the British Fire Services*, Vol. 65, No. 804, pp. vi-viii, June.

HONEY, D. W. (1973). Computer Control of road traffic at a tunnel entrance, *Traffic Engineering and Control*, Vol. 14, No. 12, pp. 568-574, 589, April.

HONEY, D. W. (1973). Liverpool's Wide Area Traffic Control Scheme, *Traffic Engineering and Control*, Vol. 15, No. 6, pp. 302-304, October.

HONEY, D. W., TURNER, J., and HAYES, D. L. (1974). Signal Settings for a downstream bottleneck, *The Surveyor*, Vol. 143, No. 4261, pp. 22-25, February.

STRICKLAND, R. I. (1954). Traffic Operation at Vehicular Tunnels, *Highway Research Board Proceedings*, Vol. 33, pp. 395-404, 1954. U.S. National Research Council.

WEBSTER, F. V. (1958). Traffic Signal Settings, *Road Research Laboratory (R.R.L.) Technical Paper No.* 39, HMSO, London, 1958.

WEBSTER, F. V., and COBBE, B. M. (1966). Traffic Signals, *Road Research Technical Paper No.* 56, HMSO, 1966.