Airflow Problems Related to Surface Transport Systems

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I. SOCIAL SIGNIFICANCE OF AIRFLOW PROBLEMS

Airflow problems related to surface transport systems

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Until comparatively recently surface transport engineering managed to get along reasonably well while paying only slight attention to aerodynamic problems. Speeds were low, and on the whole designs were determined by other considerations. But recent increases in the power, speed and size of vehicles, and the increasing dependence of modern society on transport systems that are completely reliable, have begun to focus attention on the need to devote more effort to understanding the movement of the atmosphere past moving vehicles, and over or through stationary portions of transport systems such as roads, bridges and tunnels.

This paper aims to illustrate the problems that can arise in the field of surface transport. They tend to be in some ways more awkward than those encountered in the design of aircraft. The proximity of the ground plane, the frequent inability to introduce symmetry or two-dimensional geometry as simplifying factors and the emphasis on transient effects all make the analysis difficult to handle theoretically, or in some cases to explore experimentally. This being so, it is hardly a matter for surprise that the surface transport field is still relatively neglected, particularly in comparison with the more obviously glamorous field of aircraft design. Nevertheless, the sums involved in making an existing railway system perform satisfactorily at high speeds from an aerodynamic viewpoint may well be substantial. Tunnel ventilation will certainly become of increasing significance as tunnelling technology improves and as the falling cost of tunnelling opens up new applications for city transport and for road crossings of water and mountain barriers. And motorways in exposed places must be made as safe and weather-proof as knowledge permits. A case can certainly be made out for reconsidering our priorities in aerodynamic research.

Roads

The geography and climate of the United Kingdom are particularly suitable for the intensive exploitation of motor transport; and as the motorway system develops the amount of freight traffic moving by road is steadily mounting. Already over 60 % of the country's freight—as measured in ton-miles—travels in this way, and the volume handled is going up by 5 % each year. Over the past 20 years the general picture has been of a steady process of capture of traffic from the railways. This transfer of allegiance is, however, accompanied by an increasing dependence on climatic conditions. The railways are intrinsically well-equipped to maintain schedules in all but the most severe conditions; but this is far less true of the roads, so that by this switch we are to some extent making our economy a hostage to climatic misfortune, unless by design we can eliminate the worst of the hazards.

One recurring problem in the north of these islands is snow-drifting. The complexity of the physical processes involved in any attempt to control or limit the extent of drifts by man-made barriers can be appreciated from a paper by W. I. J. Price (1961), from which the examples given here are taken. A prolonged series of experiments carried out under winter conditions in Inverness-shire established the general behaviour of snow drifts over periods of several weeks at a time, when the wind was disturbed by snow-fences of various heights and 'densities' (using this term to denote the proportion of fence area offering a barrier to wind penetration). The experiments showed the importance of the local wind eddies artificially induced by the snow fence. For instance, it was found desirable to leave a gap of around 20 cm between the bottom of the fence and the ground, so that a powerful leeward rising eddy could be formed; the effect of this eddy is evident from the way in which the average profile of the drift grows with time (figure 1). Presumably the purpose of the fence is to secure the deposition of the maximum amount of snow in advance of reaching the actual road; and a gap of about this size appeared to optimize the performance of the fence, as measured in this way. It also proved to be more efficient to use fences which were not completely opaque to the wind, but had open space for slightly more than half of their total area.

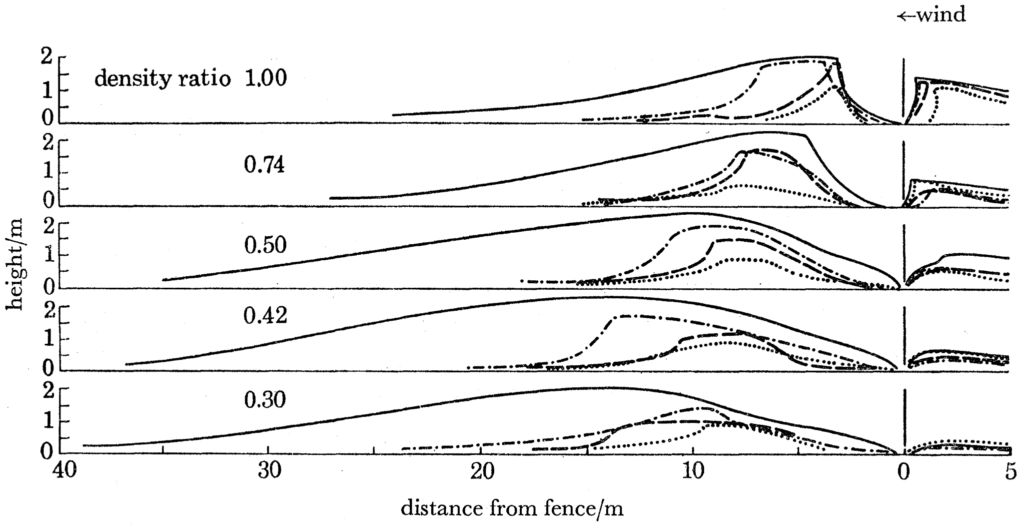

Figure 1. Effect of snow-fences of various densities and of duration on accumulation of snow drifts (Price 1961). All fences 1.87 m high; gap below fence 20 cm ± 5 cm. · · ·, 26 January; – – –, 27 January; –·–, 28 January; ——, 12 February (1954).

Snow drifting is likely to be a special problem where motorways in the north of the country pass through cuttings. One site which was given particular attention from this point of view was the approach cutting to the Scammonden dam, about 11 km (7 miles) west of Huddersfield. As a result of work carried out by the National Physical Laboratory the profile of the cutting was altered at the design stage, in order to alter the behaviour of snow drifts and to reduce the risk of avalanches from the high walls of the cutting.

The direct effect of winds on the directional and lateral stability of motor vehicles also needs attention, now that large freight vehicles regularly travel at motorway speeds in areas where the terrain offers little protection from high cross winds. In Yorkshire, for instance, during the period 1966–8, 37 vehicles are known to have been overturned by wind forces; while 20 were driven sufficiently off course to cause them to strike safety fences, and 70 two-wheeled vehicles were involved in accidents where wind forces were believed to have played a contributory role. In terms of the total number of movements during the same period these statistics can hardly be regarded as alarming; but neither are they wholly negligible, and an attempt to see how far the use of man-made windbreaks can improve the situation is clearly worth undertaking.

Such an attempt has been made in connexion with the building of the new M 62 motorway across the Pennines. It was recognized from an early stage in the design of this road that weather hazards would be very pronounced, and a great deal of work was carried out to reduce them to the minimum consistent with engineering feasibility. A place of particular interest is the point where the new motorway emerges from the cutting already referred to and crosses the Scammonden dam itself. The motorway at this point is about 15 m (50 ft) above the reservoir surface, across which strong southwest winds can blow without obstruction for about 1 km before striking the dam. Since the wind speed experienced over an embankment is strongly affected by its height it was obviously necessary to ensure that large vehicles like furniture lorries were not exposed to any abnormal risk. The need to take this point seriously was made all the greater by the existence of the approach cutting, so that drivers would receive relatively little advance warning of abnormal conditions.

During the past 3 years a considerable volume of work on the wind problems associated with this dam has been carried out at a number of centres, including Nottingham University, the Road Research Laboratory, the Royal Aircraft Establishment, and the National Physical Laboratory (see, for example, Brown & Coates 1967; Hay & Williamson 1969). Wind-tunnel tests established that without any special windbreaks the wind speed in the most critical motorway lane—the windward hard-shoulder—could be as much as 60 % greater than over the unobstructed surface of the reservoir. Further tests suggested that a substantial reduction in wind-speed would be provided by a windbreak about 1.4 m (4.5 ft) high of density (as defined above) of about 40 %. Moreover, the extent of this reduction was not expected to depend sensitively on the exact location of the windbreak, which made it possible to site it a little way down the embankment on the edge of a specially provided step, which was made a feature of the design of the dam for this particular purpose. This had the advantage of minimizing the visual intrusion which the windbreak would otherwise have created, and which have been particularly undesirable in a site with such dramatic visual quality.

A companion paper (Kerensky, this volume, p. 343) deals with the design problems of bridges. But it is worth making the point here that modern designs of large suspension bridges, which are intended to minimize the wind force on the structure, do not necessarily at the same time also reduce the forces on the vehicles using the bridge.

In spite of the technical interest of problems of this kind the total costs of such hazards to road traffic are not, in national terms, on a large scale. They have been estimated by the Road Research Laboratory at about £300 000 per year, or three orders of magnitude less than for the totality of road accidents. It seems likely therefore that any special precautions will tend to be limited to a few really exposed locations, and that elsewhere, apart from warning signs at potentially hazardous cuttings and bridges, drivers will be expected to adopt the obvious precaution of reducing speed substantially in bad weather.

RAILWAYS

At the present time there is remarkably little real knowledge of train aerodynamics. The difficult geometry of most train designs, and the proximity of the ground plane, are obvious complicating factors, and even such basic data as the way in which the boundary layer depends on the speed are only imperfectly established. However, the problems posed by current developments of very high-speed trains extend beyond the estimation of the power required to overcome drag resistance, and include a variety of other effects which could collectively give rise to additional capital expenditure, and which could thus set an economic rather than a technical limit on the speeds with which existing railway networks can be operated.

Unlike aircraft, trains do not head directly into the wind; and the overturning effect of side winds—already mentioned in connexion with road traffic—exerts a design constraint at very high speeds. This arises from the fact that in order to minimize track wear the axle load needs to be kept to a minimum by reducing the weight of the train; but before the limit of possible weight reductions is reached these overturning forces become significant, and in practice can themselves set the lower limit to the weight. At speeds of up to 240 km/h (150 mi/h) this is not a serious limitation, and the lightweight British Advanced Passenger Train (A.P.T.), due to make its first experimental runs in the autumn of 1971, represents a reasonable compromise in this regard. But if railway speeds are to be pushed still higher—and there is no intrinsic reason why the steel-wheel-on-steel-rail principle should not be capable of a good deal of further extension—then these overturning problems will need to be given close attention; and if speeds continue to mount they could eventually make it necessary to adopt a broader gauge for high-speed traffic.

In the short run such quasi-steady-state effects are likely to have a less dramatic influence on railway practice than the transient effects associated with the passage of a train past nearby objects. In several countries train windows have been sucked out when high-speed trains have passed each other, and the phenomenon was observed for the first time in Britain in 1969, on the 160 km/h (100 mi/h) electrified Manchester line.

These awkward side effects are associated with a pressure pulse immediately ahead of the moving train which changes, as soon as the head of the train has passed, to a rarefaction of about the same magnitude. Such pulses, if large and of short duration, can exceed the comfortable limit for human beings. Japanese practice on their high-speed line is to limit internal pressure changes to 0.85 kN m^{-2} (0.12 lbf in^{-2}) and rate of change to 0.4 kN m^{-2} s^{-1} though the external values are much greater. Values of many times these figures have been observed in a stationary conventional train, when passed by another at high speed. When both trains are moving the rate of change can be still larger, roughly in proportion to the closing speeds. In terms of the pressure change itself, entry into double-bore tunnels can give 3.5 kN m^{-2}, while entry into a single-bore tunnel at 240 km/h (150 mi/h) can increase this to 11 kN m^{-2}.

The size of the transients depends fairly critically on the train's cross-sectional area, and also to some extent on the smoothness of its side and nose shape. Because of its superiority in both these respects the British A.P.T., when running at 200 km/h (125 mi/h), is expected to produce transients no worse than those made by existing conventional trains at 160 km/h. But at its maximum design speed of 250 km/h (155 mi/h) even the A.P.T. is likely to create transient pressure changes which would be above the limits now thought desirable. The A.P.T. passengers and crew would not themselves be inconvenienced, on account of the totally sealed nature of the window system; but a possible limitation concerns the concurrent operation on adjacent lines of conventional coaching stock, with no sealed windows, poor entry lines, and major discontinuities every 20 m or so down the length of the train. Large transients could arise when the A.P.T. passes such trains, whether stationary or moving; the same could be true if the speeds of such conventional trains were themselves still further increased—say to 200 km/h—without introducing modifications designed to limit the peak-to-peak pressure changes experienced by the passengers.

The capital locked up in conventional railway rolling stock is enormous, and it will clearly have to remain in use for many years to come. Its continued existence, side by side with more specialized high-speed vehicles, implies the need for a careful survey of the possible costs—for instance, as regards the strengthening of windows—incidental to a policy of gradually increasing speeds. The alternative method of reducing the size of these transient effects, through opening out the track, also needs to be studied. In either case the consequential sums could well be large enough to impose something of a brake on the progress which would otherwise be possible. A hint of what might be involved can be found in the decision of German railways to adopt—for such aerodynamic reasons—a standard spacing of about 1 m between passing coaches, at the cost of opening out the lines used for high-speed running. The standard clearance in this country is rather less, and can be a minimum of 0.66 m.

The influence of these transient forces on railway engineering will not necessarily be limited to the avoidance of passenger discomfort or of damage to windows. For instance, the sideways forces experienced by railway coaches will be large, and will tend to increase the volume swept out by a coach as it proceeds along the track. It will therefore be necessary to ensure that the loading gauge is not exceeded, and that at the same time the coach is not brought up against its yaw limit stops too frequently. A second example concerns the possible influence of these forces on the tilting mechanism with which some modern fast trains like the A.P.T. are to be fitted, in order to give their passengers the illusion of sitting in a properly banked vehicle on curves. While it should not be difficult to avoid coupling between the tilting mechanism and very short transients, the design must be made proof against any longer transients of duration comparable with the time constants built into the banking mechanism. Thirdly, it will be necessary to keep a watchful eye on the derailment statistics of freight vehicles. At the moment there is no evidence to suggest that aerodynamic forces have made any appreciable contribution to the gradually increasing number of derailments which British Railways have unfortunately been experiencing in recent years; but as the relative speeds of passing trains become generally higher it will be necessary to verify that this remains true.

Sufficient has been said to underline the case for devoting much more theoretical and practical effort to train aerodynamics. An improved theoretical understanding is needed for model work since, in view of the practical impossibility of modelling to scale, the most fruitful approach is to use models to check the theory, and then to use the same theory to predict the effects that will be experienced at full scale. An approach using slender body theory, in ground proximity, is now thought likely to be fruitful—there is some American work on these lines—and similar work is soon to be undertaken by the British Railways Research Centre at Derby. In parallel with these theoretical developments it is self-evident that a considerable effort will also be needed to broaden the experimental data base; and some additional physiological work on the discomfort from transients of that duration is also desirable.

The importance of all this to the railways could be considerable. Engineering developments in recent years have opened the way to a new generation of very high-speed trains, which seem likely to be able to compete in economic terms with any other mode of transport at distances of up to 450 and possibly 600 km (300 and 400 miles). Since inter-city services are one part of their operations where British Railways are confident of making a profit, it is clearly of importance to be able to settle as soon as possible how far any hidden costs, arising from the problems discussed above, might adversely modify what would otherwise be a very encouraging economic picture.

Tunnels

Reference has already been made to the transient aerodynamic effects experienced when a fast train enters or leaves a tunnel, or when two trains pass each other; but this by no means exhausts the problems which have to be considered. For very long railway tunnels, such as the Channel Tunnel, aerodynamic effects have a major influence on the detailed layout of the running and service tunnels and of the adit shafts connecting them. A study carried out at the Royal Aircraft Establishment (Earnshaw & Owen 1969) shows that in the most critical case—the car-carrier trains, which will be of great length (800 m) and large cross-section—the estimated increase in power required to propel the train at the projected speed of 140 km/h would rise from about 3.8 MW (5100 hp) in open country to about 11 MW (15 000 hp) in the tunnel, on the simplifying assumption that the tunnel was one single bore 52 km long, with no side adit shafts or cross-overs to the other running line (figure 2). Since such an increase is quite unacceptable, it is essential to adopt instead a design which permits recirculation of the air via adit shafts connected to a parallel service tunnel. With adits at 250 m intervals the power for the car-carrier falls to 4.8 MW (6400 hp) which is sufficiently close to the open air figure to make more frequent adits unnecessary. There are, however, some points of detail which need closer examination. The number of adits that are simultaneously almost closed off during the passage of a train will have an influence on the size of the transients experienced at each adit, so that the spacing needs to take into account the design length of the trains. The detailing of the adit contours can also have

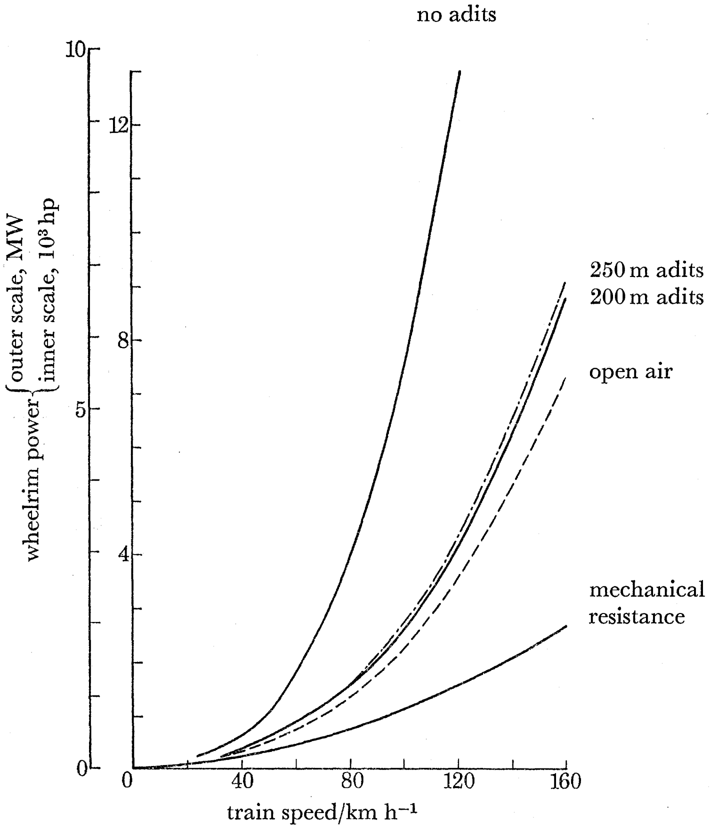

Figure 2. Estimated power requirements for car-carrier train of 31 coaches in Channel Tunnel (Earnshaw & Owen 1969).

a marked influence on the air-flow and hence on the transients. A further point is that the very marked reduction in locomotive power is only obtained at the cost of high wind speeds in the adit shafts and service tunnels—wind speeds of from 30 to 80 % of the train speed have been estimated—and the effect of these on maintenance staff has to be weighed when deciding upon a final design. Detailed study of the connecting door and ventilation arrangements inside each type of train is also needed, to ensure that the very large pressure differences that can occur along its length do not result in gale-force winds along corridors.

The sums of money involved in a project such as the Channel Tunnel would normally be regarded as justifying a very detailed attempt at optimization, aimed at minimizing both construction and operating costs. In this case the basic data on which to base our estimates are only known roughly: and assumptions have to be made about such factors as the equivalent roughnesses of the tunnel lining or of the trains themselves. Here again a certain amount of infilling of the subject seems to be desirable.

Aerodynamic problems in road tunnels have a quite different emphasis, being almost entirely associated with the problem of keeping the concentration of pollutants in the atmosphere—principally carbon monoxide and smoke—down to acceptable levels. A review of the available literature (Hogbin 1968) draws attention to the somewhat empirical approach normally adopted, and to the scarcity of data on which to base a full optimization. This is not to say that inadequate ventilation is the normal state of affairs in road tunnels (the contrary is very often the case) but rather that—when the provision of ventilation ducts and machinery can sometimes account for as much as 30 % of the capital cost of a tunnel—there are clearly economic returns to be gained from a more comprehensive understanding of the subject.

This list of examples is not intended to be exhaustive, and in any case new points where aerodynamics impinge on surface transport problems are continually coming to light: it has recently been realized, for instance, that in modern port operations the stacking of containers—some empty, some full, in various geometrical arrangements which could conceivably augment natural wind effects—could lead to a new form of industrial accident in which a stack was unexpectedly toppled over by a high wind. But what has been said is sufficient to make the point: that since surface transport speeds are increasing, and since all-weather operation in exposed places is nowadays regarded as essential, a new range of transport aerodynamics deserves to be given closer study. The impact of problems in this kind of work on the transport pattern may not be as dramatic as in the case of aircraft; but the scale of surface transport activity is so large—depending on how the count is made it can amount to as much as one-sixth of the gross national product—that almost any research effort that is likely to be available can reasonably be regarded as justified.

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