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ZIG ZAG TUNNEL No 10

COMPUTER SIMULATION OF FIELD TEST RESULTS

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1. INTRODUCTION

This report compares the results of several field tests carried out by SRA and computer simulation results of the test conditions. The field tests and simulations have been carried out to check the reliability of the SES simulation program in predicting conditions and providing a basis for the design of the ventilation system for the Avon Tunnel.

2. SUMMARY AND CONCLUSIONS

The prime criteria for the ventilation system of the Avon Tunnel is the temperature limitation for the diesel-electric locomotives hauling coal trains and environmental effects on train crews and maintenance personnel.

In making comparisons between field test results and computer simulations, it must be recognised that the SES program (in common with all other such programs, we believe) cannot forecast local air temperatures resulting from complex air flow patterns and non-uniform heat emission and distribution around the train, particularly around the locomotives. Also the instrumentation used in the field tests does not yield an average temperature in the tunnel. The comparison cannot therefore be precise.

The comparison between field test results and simulations is covered in detail in the body of the report. It is to be noted that for the Uphill Restart Test, that is the critical condition for locomotive temperature limits, the simulation produces comparable results (actually somewhat higher and therefore conservative for ventilation design) to those measured at the radiator air inlet, the reference location established in the Scarborough Tunnel Tests.

It is concluded that:-

a. The time/average temperature trace at the tunnel cross-section in line with the engine radiator air inlet of the second locomotive produced by the SES program is conservatively placed in the spread of measured temperatures at radiator inlets (Ref Fig 5). This is consistent with the conclusions reached from the earlier Scarborough Tunnel tests. Thus for the temperature limitation on locomotive performance, the SES program results can be used without qualification in the Avon Tunnel design.

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b. Where particularly high temperatures are recorded in both field and simulation results involving stopping and starting in the tunnel, these persist for very short periods only and can be disregarded for all practical purposes. This conclusion is significant in regard to the environmental considerations of personnel for the case of a train stopping and restarting in the tunnel.

3. THEORY

The actual fluid motion in a railway tunnel is a three-dimensional, unsteady, compressible flow with regions of varying temperatures. However, co-ordinated analytical solutions capable of modelling such phenomena have not yet been fully developed. Therefore the principal features of tunnel flows are usually described by single dimensional flow models for which the theory is well established.

This is the theory on which SES and other tunnel ventilation programs are based. These programs utilise analytical solutions such as the finite difference method of characteristics. Usually these programs are not capable of accurate evaluations of vehicle heat release and their evaluation of vehicle aerodynamic drag is usually based on semi-empirical relationships of velocity and blockage ratio. The SES program, which comprises four interdependent sequences dealing with train performance, aerodynamics, temperature/humidity and heat sink is designed specifically to accommodate accurate, continuous computations of the total heat released from trains and to permit the direct computation of the aerodynamic drag acting on the trains using continuously computed aerodynamic parameters. We believe the SES program is capable of an accuracy equal to that of any other available theoretical analysis.

4. LIMITATIONS OF A ONE DIMENSIONAL APPROXIMATION

The inherent assumption with a single dimensional model is that the properties of the air are taken as being constant throughout any one tunnel cross section.

As a result each temperature predicted by the program represents a hypothetical average air temperature which in practice would only occur if the heat from all the sources in the section at any instant were emitted evenly throughout the section.

In the real situation the tunnel sections immediately adjacent to a heat source (eg locomotives) can contain areas of extreme temperature variations depending on:

- location of heat sources on the train
- position of the train in the tunnel cross sections
- shape of tunnel cross section
- actual train shape

Note that none of the above information is used in a one dimensional simulation.

Since field temperature recordings at tunnel walls only indicate local temperatures, similarity between these and the computed average results will not necessarily occur. Also it is not possible to accurately predict an average temperature from field measurements without taking into consideration the three dimensional flow pattern.

4. Limitations of a one dimensional approximation

The justification for using a single dimensional model comes from the fact that in the absence of further unsteady heat loads the air rapidly achieves a more uniform temperature as it is drawn along the tunnel, and under these conditions a one dimensional approximation will give accurate results. Therefore we conclude that the computed temperatures can only be expected to accurately model measured field temperatures recorded at tunnel wall thermocouples at positions sufficiently removed (with respect to time or distance) from major heat resources.

Despite these limitations useful conclusions can be made by comparing the field test and simulated temperature profiles.

5. SCARBOROUGH TUNNEL FIELD TESTS

The limiting criterion adopted in the Avon ventilation studies was temperature limitation affecting diesel electric locomotive performance. A temperature relationship between SES computer predicted results and field test results was established for the Scarborough Tunnel tests conducted in 1983. A brief description of these tests follows.

With an upper limit of 50°C as the ambient temperature in which locomotives were permitted to operate it became necessary to be able to predict the temperatures at the radiator intakes of the trailing locomotive when travelling uphill through the proposed Avon Tunnel. Field tests carried out by the SRA in Scarborough Tunnel were modelled using the SES program to determine to what extent the computed temperatures (figure based on one dimensional theory) matched the measured results in the region in which theone dimensional approximation is not directly applicable.

Results:

a. Thermocouples down the side of the trailing locomotive recorded a temperature variation of approximately 40°C.

b. At the higher thermocouple location the temperatures fluctuated significantly, probably as a result of transient pressure pulses and general three dimensional (3D) turbulence affecting the flow of the hot exhaust gases. The computed temperatures were compared with the apparent average of the two temperatures representing the mean air temperatures at the two radiator intakes. The assumption here was that the fluctuation was such that the locomotive would only experience this mean temperature value.

The comparison showed that computed hypothetical average temperatures were slightly higher than the measured figures representing the radiator inlet temperature. However the following factors are relevant:

i. During the Scarborough tests the trailing locomotive was running backwards. However we were advised that the temperature which would have occurred at the radiators had the train been operating in its forwards configuration would be the same as the temperature measured at the dynovane inlet.

ii. The data on which the computer runs were based assumed full power at maximum efficiency from the lead locomotive and lower efficiency/reduced power from the trailing locomotive as a result of air starvation at the engine air intake.

iii. Although the amplitudes of the temperature distributions varied the profiles were similar, indicating that the program as used was accurately modelling the flow. Also the variation between the temperatures was approximately constant percentagewise.

As a result of the above it was decided as a conservative basis to assume that the computed figure could be used to directly indicate the temperature at the radiators for a train moving up through the Avon Tunnel at constant velocity.

Note that this result is relevant for uphill journeys only. On downhill journeys the heat distribution is different as most of the heat is emitted from the brakes. For this reason temperatures around the locomotives although not known, would be significantly less than the maximums computed.

6. ZIG ZAG No 10 UPHILL SIMULATION TEST

An initial report covering the computer simulation of the uphill start condition was forwarded on 5 September 1984. At that time it was pointed out that because of the variable air temperature profiles established throughout the tunnel as a result of the trains entrance to the tunnel and the subsequent stop before restarting, correlation of the one dimensional computer simulation with the field results would be difficult.

The simulation had to proceed solely on the basis of calculated heat output values based on a speed/time relationship. Since four separate sets of field performance data were provided with time variations of up to 80 seconds and speed variations of 8 km/h, it was concluded that the oscillograph chart performance details were most likely to be correct. Accordingly this data was used in the simulation study. Such data is a compromise only. It does not reproduce the variable acceleration/deceleration rates nor the major fluctuations in trailing engine power output indicated by field test results.

Following issue of the first report SMEC was advised that some data used in the simulation study was incorrect, (location of stationery train in tunnel, speed at exit from tunnel) and consequently a rerun using revised data was requested. The revised data in the form of a speed/distance trace with marked up time stations as recorded by dynamometer car instrumentation was used as the basis for the second simulation run. The following comments relate to the second simulation run.

Fig 1 - Basic Data

Figure 1 is a graphical representation of simulation data. Numerical values are tabulated under Form 8E heading in computer print-out. This data is the best possible compromise between revised data provided, achievement of specified time/distance values and variable acceleration/deceleration rates occurring at field test.

Fig 2 - Temperature/Time Comparison at 550 m Mark from Uphill Tunnel Portal

The 550 m mark is the thermocouple location 30 m behind the front of the train at the point where it stopped in the tunnel.

The following is noted:

a. In the computer simulation heat is emitted along the entire length of the locomotives therefore temperature changes register earlier and continue later than the field test results.

b. Train starts at approximate time 22.24.50. Field tests shown a reduction in the rate of temperature change at this point as expected.

   Computed rate of temperature change is constant at this point. This is probably because the rear of the trailing loco is still opposite the thermocouple and the increasing heat output of the loco's under acceleration is countering the fact that the loco's are pulling away.

c. Field measured temperatures decrease significantly as the train accelerates. This is most likely due to the forward motion of the train dragging cold air in from the bottom tunnel portal.

6. Zig Zag no 10 uphill simulation test

The computed results show a more gradual temperature decline due in part to heat output being uniformly distributed along both locomotives.

Fig 3 - Temperature/Time Comparison at 500 m Mark from Uphill Tunnel Portal

a. At 500 m mark the train has stopped 20 m further down the tunnel and while stationery the measured temperatures increase slightly and then decrease. The increase could be explained by a resultant air flow up the tunnel. The subsequent decrease could be due to:

   i. Air flow reversing to the downward direction once the train has stopped

   ii. The heat is dissipated once the train has stopped irrespective of which way the air is flowing.

   Once the train starts the temperature rises to a peak after the loco exhausts have passed the thermocouple.

b. Two computer simulations are shown.

   - Plot 1 - no initial air flow assumed

   - Plot 2 - minus 2 m/s air flow assumed (flow down tunnel)

   Plot 1 case shows the temperature increasing while the train is stationary due to the 'piston effect' induced air flow causing hot air to flow up the tunnel.

Plot 2 shows the temperature initially similar to that measured. This correlation can be expected since the measuring point is approximately 20 m away from the front of the loco giving the air time to mix to a more uniform temperature. Once the train starts the temperature increases by a similar amount in all cases. However we would expect the computed result to be less than the field result since the heat output in the simulation is taken to be uniformly distributed along the length of the two locomotives. This distribution results in a more gradual decline of the maximum simulation temperatures as is to be expected.

c. Unlike the downhill run where an oscillograph chart was provided, we did not obtain the anemometer traces of tunnel airflow for the uphill test but we were informed that flows could be taken as zero while the train was in the tunnel. Traces require checking as simulation results indicate that a small airflow down the tunnel would significantly reduce the maximum predicted simulation temperature over that computed for zero airflow.

Fig 4 - Temperature/Time Comparison at 250 m Mark from Uphill Tunnel Portal

This position corresponds to the upper tunnel thermocouple location where the accelerating train is approaching maximum speed. The following is noted:

a. Temperature profiles of the simulation results and field test readings are similar but there is a very marked simulation temperature rise to a maximum of approximately 50°C. This peak simulation temperature occurs earlier than that recorded by field instruments due not only to the simulation data distributing heat output from the engines evenly over their total length but also due to the apparent lag in field instruments recording relative tunnel temperatures while the train is travelling at speed.

b. It is apparent that the accelerating train carries the hot engine exhaust gases along in the airspace between train roof and tunnel ceiling such that field instruments do not provide an accurate picture of the average tunnel temperatures at specified locations.

Fig 5 - Temperature/Time Comparison at Trailing Locomotive Radiator Air Inlet

This graph is relevant to the comparison basis used in the Scarborough Tunnel Tests where field test results were modelled using the SES program to determine the temperature relationships at radiator air inlet on a train travelling at constant speed up the tunnel.

The following is noted:

a. Field temperature results of the radiator air inlets closest to the tunnel wall (points of 03, 04, 05) follow a predicted path of overall highest recorded temperatures with temperature increasing from front radiator air inlet through centre inlet to rear inlet. Radiator inlets on the opposite side of the locomotive (points 06, 07, 08) appear to follow a reverse trend contrary to anticipated values. Possibly points 06 and 08 were reversed in actual tests although complex 3D airflow patterns around the locomotive may be the cause of this variation.

b. Temperature profiles of simulated and field recorded temperatures show good co-relation. The simulation temperatures were based on calculated position of the front of the trailing locomotive whereas the radiator air inlets are to the rear of the locomotive. This would justify shifting the plotted simulation peak temperature shown at approximately 22.26.20 hours to the right which would more closely correspond with field test peak temperature values.

c. Comparison of the average air inlet temperatures recorded at locations 03, 04, 05 and the simulation predictions at the two highest field values are:

Time	Average Temperature (03, 04, 05)	Average Temperature (04, 05)	Corresponding Maximum Simulated Temperature
	^oC	^oC	^oC
22.23.00	39.2	49.6	44
22.27.50	54.4	67.0	64.5

Note that temperature readings at station 03 are consistently low compared to all other temperature values.

7. ZIG ZAG No 10 DOWNHILL SIMULATION-TESTS

To date interim reports dated 21 and 27 September and a telex dated 23 October 1984 have been forwarded covering downhill simulation results. The computer printout of the last run is attached to this report complementing the two printouts previously forwarded.

As covered in earlier reports the proportion of heat instantaneously released to the air and that retained in the axle assemblies during emergency braking was taken to be in the ratio 80% to 20%. Similarly a value of 500 kW constant heat output from axle assemblies after the train had stopped was adopted for simulation studies.

Field tests results indicated fluctuating tunnel airflows both in magnitude and direction before and after tests. Based on tunnel anemometers, an initial upward tunnel airflow of 3.5 m/s was taken and assumed to remain constant subject to the 'piston' effect of the moving train. As shown in the uphill simulation study errors in tunnel airflow data may have a significant effect on predicted simulation temperatures.

Initial studies indicated a continuous braking effort of 3 362 kW was necessary to maintain a constant speed of 54 km/h based on an allowance for windage and friction of 40 N/ton.

As a result of discrepancies between field recorded temperatures and the first simulation predictions using constant braking effort of 3 362 kW, SRA advised that braking once train entered the tunnel could be considered as negligible until application of emergency braking. Train speed increase in this period was also advised as negligible. Both these field observations were contrary to theoretical predictions but were adopted for all subsequent simulation studies. The following discussion relates to the final computer results as attached.

Fig 6 - Temperature/Time Comparison at 400 m Mark where Guards Van Stationery

Temperature plots are similar in profile but the maximum value of the simulation result is higher than the field test values. Possible reasons for this are:

a. Field test results do not show any temperature increase until application of emergency brakes whereas the simulation correctly records heat output from the engine at idle setting prior to initiation of emergency braking. This is similar to uphill test results with the engine travelling at speed where field instruments could not accurately predict 'average' tunnel temperatures.

b. Simulation temperatures are based on a 2 second cycle analysis with results plotted graphically every 10 seconds. Maximum simulation temperature occurs at time 15.26.43 and there is no comparable field test reading at this time. Extension of plotted field test results at this time could reasonably be taken to show higher maximum temperatures for all four thermocouple locations.

Fig 7 - Temperature/Time Comparison at 650 m Mark

Field test results gave two different times at which the train stopped under emergency braking viz 15.27.07 hours and 15.27.23 hours. Graphical comparison is based on train becoming stationery at 15.27.23 hours.

From graph the following is noted:

a. Based on field data the train took 52 seconds to stop indicating initial application of emergency brakes at time 15.26.31. Assuming uniform retardation the front of the leading locomotive would be opposite the 650 m mark thermocouple location at time 15.26.35 hours. The simulation temperatures based on a constant heat output of 6 441 kW equally distributed along train length in proportion to mass shows a rapid increase from this point to a maximum of 18.7°C in line with thermodynamic theory. The field results do not show any significant increase until time 15.27.20 hours well after loco's have passed. Possible explanations of the variations are:

- Heat generated by braking is carried along with airflow around train and does not register immediately on remote static wall station thermocouples influenced by boundary layer.

- Proportional braking known to be used on long, heavily laden goods trains with maximum braking from rear of train and minimal at leading loco's and wagons. This possibility was raised in our telex of 23 October 1984 but no comment has been forthcoming to date.

6. Temperature increases shown by field test results occurring at times 15.28.20 to 15.28.50 cannot be readily explained. This discrepancy may be due to turbulence at a 3D airflow pocket.