Final Report

of the OECD Seminar on

Road Tunnel Management

Lugano (Switzerland), from 26 to 29 November 1990

Organisation for Economic Co-operation and Development (OECD), Paris
Permanent International Association of Road Congresses (PIARC), Paris
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1. Foreword

The OECD Road Transport Research Programme, in association with the Swiss Federal Highways Office, and in conjunction with the Tunnels Committee of PIARC, organized a seminar on the management, safety, and environmental aspects of road tunnels in Lugano, Switzerland, from 26 to 29 November, 1990.

Opening the seminar, Mr A. Ogi, Federal Councillor and Head of the Federal Department of Transport, Communications, and Energy, expressed his desire to see contributions to the seminar help provide a better approach to future problems associated with the management of large road tunnels.

This Final Report does not set out to reproduce the followings and detailed contents of the seminar - which is amply documented in the form of reports and other publications which appeared subsequently (refer to § 3) -, but to present some aspects through a certain number of themes, and to add more detailed comments. Bearing this in mind, it was also attempted to introduce the opinions and statements of fact which appeared out of discussion.

That is why the report is broken down into two sections:

- the general part, with a report on the seminar and a list of publications dealing with it, and,
- the special part, the purpose of which was to develop and comment a certain number of special topics.
2. Objectives of the 1990 seminar

The seminar enabled participants to exchange information on new and current problems associated with tunnel management. Special stress was put on economic aspects, including the involvement of the public and private sectors, optimization of operations, environmental demands, and general problems of safety, as well as some important special aspects e.g. the transport of hazardous loads.

The seminar did not set out to deal with aspects of tunnel construction.

The seminar was aimed at:

- those in charge of national road transport and infrastructure policies and management,
- tunnel owners, operators, and designers,
- financial backers and insures,
- engineers, researchers, and scientists with government authorities or industry who specialize in the topics dealt with by the seminar,
- representatives of associations active in the sectors covered by the papers presented at the seminar.

As Sir Alan Muir Wood (GB) so strikingly pointed out in his paper to the closing session, the conference achieved the following objective:

"Renovation of the "continuous thread" that pervades all stages of a project from planning to operation. We are looking towards the future and endeavouring to distill experiences from other people and other occasions, recognizing that no two tunnels or their users or operators are precisely the same. This conference has been particularly successful in the way that people have discussed what goes wrong as well as right."
3. Publications and abstracts

The documents dealing with the seminar break down into the following three groups of reports and publications:

- The official volume of the entire text of papers presented, which can be ordered from the Swiss Federal Publications Office (Elggenössische Drucksachen- und Materialzentrale) in Berne, or from the Swiss Federal Highways Office, under reference number 308.045 e/f 10.90 700 53291, costing 80 Swiss francs, together with the following offprints which were not received in time to be included in the main volume:
  - "Rénovation de l'éclairage du Dullin", R. Naud (F)
  - "Comportement de la ventilation du tunnel du S' Gothard", A. Henke (CH)
  - "Accidentalité in Malmasin Tunnels", M. Romana (E)
  - "Le transport de matières dangereuses dans les tunnels routiers", W. de Lathauwer, J. de Groof (B)
  - "The Stockholm Ring - Dangerous goods transports", O. Sahlström (S)
  - "Memorial tunnel fire ventilation test program", A. Bendelius (US)
  - "Transit des matières dangereuses", M. Bailly (F)
  - "Développements futurs, besoins de recherche", J. Pera (F).

- The texts of speakers to the closing session, including the paper of Federal Councillor Mr A. Ogi, and the summaries of rapporteurs to the various sessions, particularly:
  - Environment, A. Haerter (CH)
  - Safety, J. Izarzugaza (E)
  - Dangerous goods, O. Sahlström (S)
  - Traffic, signalization, and geometry, W. de Lathauwer (B)
  - Policy/development, research needs, E. Scotto (I) and J. Pera (F)
  - Contribution to the closing session, Sir A.M. Wood (GB)
  - Concluding remarks, B. Horn (OECD).

To this group also belongs the paper entitled "Quelques aspects de l'économie des grands tunnels routiers" presented by G. Lombardi (CH) to the meeting of the OECD Road Transport Research Programme Steering Committee which took place on 23rd November, 1990.

- In addition to the summary in the following chapter, three further abstracts and publications have been published separately, i.e.:
  - Brief report by W. Knobel (CH, Swiss Federal Highways Office), in French and English
  - Report by P. Boskovitz (CH), published in the April 1991 issue of the French-language "SIA" magazine (8/91),
4. Summary of papers presented

4.1 Introduction

The principal purpose of the seminar was to present the experience acquired in the management of tunnels currently in service and their influence on future tunnels. In addition, some results of interesting research were presented, together with new developments in the construction of tunnels.

In all, a total of 70 papers were presented to some 270 participants from 18 countries, and in particular the USA, Canada, Australia, and Japan. The different topics were examined in 5 sessions:

- Management and operation
- Environment
- Safety
- Traffic, signalization, geometry
- Policy/development.

In the opening session, after being welcomed by K. Suter (CH), A. Muir Wood (GB), and C. Mariotta (CH), B. Horn (OECD) drew attention to a particular point which was resumed subsequently by one or another of the speakers, i.e. when designing tunnels, in addition to applying theoretical methods conforming to standards, one should exercise practical reasoning, which he appropriately defined as "imagineering", to produce better and safer tunnels.

4.2 Management and Operation

Under the guidance of R.L. Jones (GB) and O. Anelli-Monti (A), this session demonstrated that in road tunnel construction too, operation, maintenance, and repair were becoming increasingly important.

Some papers dealing with repair works in different Alpine tunnels gave an indication of the scale of the task. F. Cuaz (I) spoke of the lining of the walls of the Mont-Blanc tunnel; R. Naud (F) spoke of renovating the lighting and refurbishing jet fans in the Dullin tunnel in the foothills to the French Alps; and H. Maillant (F) described the rehabilitation of the walls of a tunnel between Nice and the Italian border. Using concrete examples and cost data, H. Maillant demonstrated the enormous difference between the most recently built tunnels and those of the first generation - which require expensive remedial treatment because of serious construction and corrosion damage. In France too, modern tunnels are practically all fitted with complete insulation and painted "user-friendly" sidewalks.

In discussing the damage analysis and repair strategy applied to Denmark's 950 m-long Limfjord tunnel which has been in operation for 20 years, P. Christensen (DK) clearly demonstrated the gravity of problems caused by corrosion in immersed tube tunnels, where salt-water attacks concrete reinforcement.

It is a well-known fact that extreme climatic variations and the effect of de-icing salts reduce the lifetime of road facilities, and especially high-altitude tunnel equipment. On this topic, A. Arnold (CH) presented the remedial measures planned for the San Bernardino tunnel which has been in operation for 23 years and urgently requires repair work on the precast concrete side panels and roaddeck. Since the works will be performed maintaining the tunnel in operation, they require not only detailed studies and careful choice of materials, but also careful scheduling.

The increased importance of organizational aspects and obligations in tunnel maintenance was also clearly evidenced in the experience recounted by G. Piazzini (CH), dealing with 10 years of operation of the Saint Gotthard road tunnel (figure 1). He expressed the concern of tunnel operators who are expected to manage increasing quantities of maintenance and repair work without hindering traffic, which is also increasing.
The tendency of recent years for maintenance costs to make quantum leaps is confirmed by the information given by U. Schlup (CH) on tunnels on Swiss national highways. From 1986 to 1990, maintenance costs per kilometre of tube increased almost five-fold, the average cost per km now being Sfr. 230'000.-- more than half of this concerns electro-mechanical equipment.

![Figure 1: Maintenance on ventilation system](image)

Other papers (H. Heidinger (A), B. Monclus (E), J.-C. Roussel (F), G.W. Davies (GB), P. Seidelin (DK), and W. Gobiet (A)) also showed the need for early replacement of technical installations, and referred to general and particular experiences acquired in Europe in the operation of various tunnels.

Although announcing himself as an engineer and not a psychologist, M. Romana (E) spoke of two typical human behaviours - claustrophobia (abnormal fear of confined spaces) and agoraphobia (abnormal fear of open places), the latter being the lesser known of the two - and of the consequences he sees on the design of road tunnels. This paper, which dealt with the subject at hand but also with things beyond the normally technical nature of the topic, recommended that design be more a function of the road user, and that fuller information be communicated to drivers taking the tunnel. More generally speaking, M. Romana requested that people work in this field not just as engineers but also as creators-cum-architects.

4.3 Environment

The papers presented to the second session dealt chiefly with the environmental impact of vitiated air discharged from tunnels. In this series of communications of general and theoretical relevance, A. Haarter (CH) - who lead the session in conjunction with H.-J. Kayser (D) - gave an indication of the current situation with respect to the standard methods for assessing the diffusion of pollutants in the vicinity of tunnel portals, as well as of ventilation systems and portal layouts which help reduce ground-level peak concentrations of pollutants to acceptable levels. The example of Valerenga tunnel in Oslo, presented by S. Larsen (N), showed that the results of in situ measurements corresponded quite well to extrapolations from a model designed by the Norwegian Institute for Air Research. The two papers by M. Berner (CH) and H. Noguchi (J) dealt with air stacks. At the moment, there is a trend - and this is particularly so in Switzerland - to build short, supposedly inconspicuous air stacks whose shortness is made up for by high discharge speeds, which in turn engenders high power consumption. In Japan, on the other hand, some air stacks are up to 40 m high in urban zones (figure 2), and some are even incorporated into office blocks. R.T. Balz (CH) explained the positive impact road tunnels have on the environment: readings taken near
the southern portal of the Milchbuck tunnel in Zurich have shown that the operation of the tunnel has significantly reduced excess pollutant levels (average NO2 per half-hour reduced to less than 50%, CO to less than 25%). He then developed the results of analysis which show that the tunnels planned for Zurich’s southern bypass (N4) would reduce the surface area exposed to pollution from surface traffic and tunnel portals to a mere fifth of the annual average of 30 μg/m³ NO2 if the air, instead of being discharged directly from the portals, is drawn to the portals and discharged vertically.

![Figure 2: Air discharge stack in urban environment, Tokyo](image)

Although regularly studied, air cleansing does not yet appear to be marketable commodity in Europe. The excellent presentations by K. Pucher (A) and F. Schröder (D) were an opportunity to examine experience with tests currently under way in the Plabutsch tunnel (A) and the Elbe river tunnel (D). Engines with catalysts have helped reduce gas emissions, thereby making it possible to modify both types and dimensioning parameters for ventilation systems in new tunnels and operating parameters for existing tunnels. W. Meyeroltmans (D) analyzed the potential savings on construction and operation costs, and A Henke (CH) stressed some interesting experience concerning operation of the Saint Gotthard tunnel, and in particular the constant reduction of power consumption by fans (Figure 3). J. Santner (A) gave similar results for the Tauern and Katschberg tunnels which have been in operation since 1975.
Figure 3: Average power consumption for ventilation of St Gotthard tunnel

To conclude, E. Keller (CH) listed the advantages of frequency conversion techniques in operating fans, comparing this technique to conventional operations with two speeds and adjustable blade angle. He showed that the technique is especially advantageous in financial and power consumption terms, for installations which are used at low air flow during the most part of the time.

4.4 Safety

K. Iwai (J) and J Izarzugaza (E), who steered proceedings for the first part of the session, also took a general look at the accident situation for road tunnels. J. Izarzugaza pointed out that radical measures for eliminating accidents such as building separate tubes for traffic in each direction instead of a two-way tunnel resulted in additional costs which had to be assessed for each individual case. On the other hand, it is undeniable that there are far fewer accidents in tunnels than in surface sections. Most of the 10 papers stressed that although there is little chance of there being an accident in a tunnel, its consequences are potentially extremely serious for the persons concerned. Several communications from Switzerland (F. Ruckstuhl), Austria (E. Mikura), Japan (M. Kotari), Norway (E. Lundebrakke), Great Britain (M.P. O'Reilly), Spain (M. Romana), and Germany (H.-J. Kaiser) gave statistics devolved from different parameters (number of lanes and tubes, urban road or major corridor, traffic type and density, alignment, level of development, etc.). A quick comparison of all this data shows that the coefficient of the accident rate in surface sections of road to that for tunnels tends to be higher for inter-urban corridors (> 2) than in built-up areas (< 2). Several speakers stated that the alignment and layout of portal areas have a great effect on the occurrence of accidents, curves on inclines being the worst combination.
4.5 Dangerous Goods

The second part of the session took place under the guidance of P. Dörflicher (CH) and P.O. Sahlström (S), and was devoted to hazardous loads. Some of the papers presented dealt with technical facilities aimed at avoiding catastrophes or at the very least limiting their detrimental effects on man and the environment. With respect to this, A. Inokuma (J) outlined the tunnel classification system applied in Japan, which takes account of the length of the tunnel, traffic and the level of safety equipment required.

Several contributions stressed the importance of practical and organizational aspects of the transport of hazardous loads through tunnels. Restrictions and steps taken are applied differently from country to country, or even within a country. As J. de Groof (B) mentioned, several studies have already been devoted to this subject by PIARC, but today the various partners involved are seeking co-ordination so as to obtain mutual understanding and fuller information, given the fast-increasing numbers of toxic or flammable products being transported and their potential hazards. This situation, which is criticized above all by operators of heavily-used road tunnels in urban areas, requires additional effort. In summing up, the organizers of the session stressed that protective measures should no longer be decided empirically, and that preference should be given to assessing the risks by quantifying them, as is already done in Great Britain (Jones).

4.6 Traffic, Signallization and Geometry

This session, under the guidance of M. Oud (NL) and W. Lathauwer (B), concentrated chiefly on traffic management. On one hand, projects such as tunnel controls along the "Transjura" highway (B. Boschetti) or the fourth tube for the Elbe River tunnel in Hamburg (K. Herzke, D), were presented. Other speakers dealt with systems already in operation and which have been tried and tested, such as the traffic guidance systems on the Lucerne bypass (H. Fricker, CH) and for the LImfjord tunnel in Denmark (P. Saidelin, DK).

H.L. Stembord (NL) spoke of the traffic capacity of road tunnels, and demonstrated the difference between design capacity, which may be calculated in several ways, and real capacity which is always higher, sometimes even a multiple of the theoretical capacity.

In a remarkable paper, M. Etienne (F) explained how the driver used information, perceived it, acted on it, and behaved generally when driving in tunnels, a notion he called "readability of the tunnels". He illustrated his statements with many examples of both good and bad, portal layout and tunnel signalling. On a similar theme, R. Lanz (CH) referred to the conclusions of a research work which indicated that, under certain circumstances, one can be dispensed with the hesitations of authorities (observed especially in Switzerland) over subsurface junctions and forks (see cover photo).

4.7 Policy/Development

Two papers to this last session dealt with tunnels in the Pyrenees on the E-89 European motorway between Toulouse and Barcelona. A. Jaquet (F) spoke of design work for the Puyymorens tunnel, and A. Serratos (E) analyzed the effects the Cadi tunnel, further South, has had on the region, traffic and the economy since it came into operation six years ago.

Finally, the last afternoon of the seminar was largely devoted to some projects which are marked with novel approaches, e.g. the idea (figure 4) of a floating tunnel presented by H. Ostlid (N). Using techniques already widely used for offshore drilling platforms, Norway now intends to intensify the construction of underwater roads.

Attention then turned to futuristic road tunnels in the Paris region. A. Broto (F) presented a paper on the progress of the project called LASER which has been in the offing since 1987, and by which promoters want to improve the very precarious traffic situation on the Paris network. The projected system of toll tunnels is exclusively for private passenger vehicles and small utility vehicles. The outstanding feature of the project is the limited headroom: the tunnel has an inside diameter of 9.50 m, and has two three-lane decks above each other, with just 1.8 m headroom. The initial plan had a central ring about 10 km long, and five 5 to 8 km branches linking it to the suburbs. After discussion with the authorities and further development of the design, the solution adopted follows
part of Paris' "boulevard périphérique" ring road which suffers from chronic saturation.

J. Marquet (F) presented a quite similar project called HYSOPE. Using the same general design as the above project, HYSOPE forms a "cross" of a total length of 43 km linking Paris' main centres of activity without any direct vehicular access to Paris itself.

4.8 Conclusions

J. Péra (F) concluded the seminar with a valuable paper describing how to achieve simpler maintenance and take better heed of user needs.

In his speech, Mr A. Ogi, Federal Councillor and Head of Federal Department of Transport, Communications, and Energy, encouraged participants to continue their efforts in these interesting and promising fields. However, he repeated that tunnels should not be built everywhere, indiscriminately, but only where really necessary. He underlined his point with a clear refusal of the far-from-declining trend to want a single tunnel between Basle an Lugano (approx. 250 km apart, at opposite ends of Switzerland!).

In the closing session, which was the opportunity for session leaders to take the floor, Sir A.M. Wood, Chairman of the PIARC Road Tunnels Committee, pointed out that the success of the seminar was principally due to two points: on one hand the "continuous thread" linking planning and operation played a stimulating role, and on the other, problems which have not (yet) been satisfactorily solved were able to be broached.
5. Special points

5.1 Introduction

This part of the Final Report summarizes a selection of important and contemporary topics dealt with by the speakers. With respect to this, it is interesting to note that interpretations and assessment of some problems were not always identical. In discussions there were certain divergencies in viewpoints, depending on the country concerned and the position of the speaker in the planner/owner/designer/operator/user chain.

The following list of topics is not exhaustive; it looks in hindsight at the problems considered most important for tunnel management.

5.2 Environment, Vitiated Air Discharge

It is obvious that the problem of vitiated air discharge is an important one, especially in countries with strict environmental protection regulations, e.g. Switzerland, Germany, Austria, and a good many other countries too. In Session II, 6 contributions discussed the discharge of air outside the tunnel, and 5 speakers discussed the quality of air inside tunnels.

Interest was focused on models for analysing dispersion of pollution, especially the jet of vitiated air at a tunnel portal. Dispersion of vitiated air form a vertical air stack did not attract the same attention. It transpires that air stacks are sufficiently well known to operators and create far fewer problems than portals which, in addition, are often in populated areas, and cause higher ground-level pollution concentrations than air stacks.

![Figure 5: Result of a Japanese study of pollution dispersal from an air stack](image-url)
The pollutants considered are carbon monoxide (CO) and nitrogen oxides (NOx), particularly nitrogen dioxide (NO₂) which is the most commonly measured and whose concentration is coming more and more to be a determining criterion.

Dust emission was not dealt with, which confirms that dust, i.e. particles, is not normally determining for appreciation of the pollution caused by tunnels.

It is seen that at the moment there are a large number of computer programs for dispersion analysis. Interest is therefore drawn all the more to far less numerous cases where field measurements are taken and compared to analytical results.

With respect to this, the following two contributions provided interesting information. A. Haerter (CH) commented on Japanese studies of pollution dispersion from an air stack (figure 5), and S. Larsen (N) presented the results obtained from study of an urban tunnel in Oslo (Valerenga tunnel, figures 6 and 7) which discharges vitiated air from its portal. In both cases, it appears that the results obtained with mathematical models are quite close to values actually measured. According to both papers, it is accepted that the analysis models selected are valid and sufficient for the intended purpose.

Another interesting point was the design of vitiated air stacks, or "restitution buildings", to use a word which goes down better with audiences critical towards road construction.

Two contributions dealt with this subject at some depth. The first (Berner, CH) examined more particularly some general points in the design of vitiated air stacks, and the second (Noguchi, J) referred to recent works in the greater Tokyo area. It transpires that the acceptability of air stacks is not quite the same in central Europe as in Japan. We know that in some parts of the world it has become practically indecent to design outlets that are recognizable as such. Yet this trend to try to hide such works is obviously due to neither technical nor aesthetic reasons, but rather to the desire to reduce the psychological impact.

The reduced height of outlets must therefore be compensated by high discharge velocities so as to prevent unacceptably high concentrations of ground-level pollution. This requires more costly plant and more power, especially if the discharge velocity is to be maintained for partial ventilation operation, e.g. with automatic dampers.

The compromise between stack height and discharge velocity does not always swing in favour of the latter, as was seen in the paper of H. Noguchi (J) who presented a large number of outlets in built-up areas in Japan. They are high stacks, up to 40 m high (see figure 2), and stacks combined with service buildings (figures 8 and 9) or even administrative buildings (figure 10). The speaker stressed the importance of harmonizing the structure with the surrounding urban grain, and expressed his opinion that proper architectural treatment provides perfectly acceptable solutions.
Figure 6: Valerenga Tunnel, Oslo - Northern portal
Figure 7: Concentration of tracer gas with distance from tunnel. The curve represents the dispersion model.
Figures 8 and 9: Air discharge works in Japan, incorporated into service buildings
With respect to this, two arguments proposed during the discussion at the end of the session on "Environment" should be mentioned, i.e.:

1. Tunnels generally pollute less than surface roads. This claim is maintained for two reasons:
   - specific emissions of pollutants (i.e. per kilometre travelled) are reduced in tunnels because of the smoother driving pattern;
   - in most tunnels, and especially in new tunnels, vitiated air is discharged to the exterior in controlled fashion, and is generally discharged upwards so as to limit perceptible concentrations at ground level.

2. Excessive local efforts and demands for protection of the air (and of the environment in general) often tend to make the general situation worse: they increase the cost of facilities as well as running costs, and exaggerate environmental pollution in general.

Figure 10: Air discharge works in Japan, incorporated into administrative building
5.3 Effect of Clean Engines on the Power Required to Operate Ventilation Systems

This gratifying phenomenon is relatively new, and there is not yet a great deal of experience in the matter.

As far as the ratings of ventilation plant are concerned, regulations for the calculation of fresh air requirements - which take account of evolution in vehicle emissions, considering a representative pool of vehicles classified according to type, country, and period of operation - are periodically updated (refer to 1987 PIARC report on "Pollution - Ventilation").

The presentation of W. Meyeroltsmann (D) gave accurate and up-to-date information - to be borne in mind for future tunnels - on decreasing exhaust levels.

But above all, interest turned to the real effects the increasing numbers of vehicles with exhaust-level control devices have on the operation of ventilation systems in existing tunnels.

The reports of J. Santner (A) and A. Henke (CH) gave interesting information on this topic from two major Alpine tunnels (refer to table on following page). The figures they give show that the power demand for ventilation has decreased significantly for both tunnels. In the 13 years of operation of the Austrian tunnels, it has dropped to 20% of the original value, and in 8 years of operation of the St Gotthard tunnel (figure 3) it has dropped to one third.

This reduction is attributed chiefly to two things:

- operating style: both tunnels have practically abandoned the transverse method, except for exceptional circumstances;
- vehicle emission factors have lowered, thereby gradually reducing the necessary air flow (figure 11).

![Graph](image)

**Figure 11:** Example of consequences of changing conditions. Fresh air requirements against traffic density (Saint Gotthard)

\[
V = \text{vehicles per hour} \\
Q = \text{total flow of fresh air} \\
1 = 1968 \text{ forecast} \\
2 = 1990 \text{ operating result}
\]
It should also be noted with respect to this that operators tend to provide air of better quality in their tunnels than that required by regulations, especially in long tunnels, and particularly with respect to visibility. As can be seen on the surveys of St Gotthard tunnel, the average concentration of CO throughout the entire tunnel rarely reaches the threshold of 100 ppm. It normally varies between 50 and 80 ppm.

<table>
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<th>Main Characteristics</th>
<th>Tauern &amp; Katschberg (A)</th>
<th>Saint Gotthard (CH)</th>
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<tr>
<td><strong>Tunnel</strong></td>
<td>6.4 + 5.4 = 11.8 km</td>
<td>16.8 km</td>
</tr>
<tr>
<td>Altitude (m asl)</td>
<td>1100 - 1300</td>
<td>1100 - 1200</td>
</tr>
<tr>
<td><strong>Opened to traffic</strong></td>
<td>1975</td>
<td>1980</td>
</tr>
<tr>
<td><strong>Ventilation system</strong></td>
<td>&quot;Reduced&quot; transverse ventilation (60% ventilated air)</td>
<td>Transverse ventilation, with 30% reserve on fresh air</td>
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<tr>
<td><strong>Traffic determining ventilation rating</strong></td>
<td>2,400 veh/h</td>
<td>2,000 veh/h</td>
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<th>Year</th>
<th>1976</th>
<th>1989</th>
<th>1981</th>
<th>1989</th>
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<tr>
<td><strong>Total traffic (millions veh/year)</strong></td>
<td>1.15</td>
<td>4.82</td>
<td>2.9</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td><strong>Total power consumption for ventilation (millions kWh/year)</strong></td>
<td>7.35</td>
<td>5.49</td>
<td>10.0</td>
<td>6.10</td>
<td></td>
</tr>
<tr>
<td><strong>Average specific power consumption for ventilation (kWh/veh.year)</strong></td>
<td>0.56</td>
<td>0.10</td>
<td>0.20</td>
<td>0.065</td>
<td></td>
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</table>

**Comparison of ventilation power consumption for two alpine road tunnels**

5.4 User Behaviour

In most countries there are directives for the functional requirements of technical plant and safety equipment in tunnels.

Despite all the care taken and the continual improvements made, road user behaviour remains one of the most important factors in tunnel performance. Nevertheless, it should be noted that studies on user behaviour are scarce, due, according to J. Péra (F), to the fact that engineers are hardly familiar with the idea of public opinion surveys.

Some interesting views were given on this point. In addition to the information provided by speakers referring to experience with existing tunnels, three papers dealt with the question at some depth.
M. Romana (E) analyzed the problem from the psychological point of view; H.-J. Kayser (D) presented some interesting results of research on the behaviour of drivers encountering obstacles in the tunnel and on the effect of lighting.

Finally, M. Etienne (F) proposed an analysis method based on the notion of tunnel "readability", which he defined as "all the information of any kind perceived and recorded by the driver and enabling him to position himself spatially and temporally, to derive a model of his future situation, and to adapt his behaviour to this prediction". This involves steps which should help lead to better driving and better dispensing of information to the driver, thereby reducing the risk of accidents and their consequences.

The data and recommendations of these contributions could be summarized as follows:

- Romana explains (unfortunately no written version of his presentation is available) the two types of standard human behaviour, i.e. claustrophobia (fear of confined spaces) and agoraphobia (fear of open places), which find expression in all situations of daily life. These two factors have increased importance in tunnels, where they have a direct effect on the frequency of accidents. The resulting recommendations can be summarized by this diagram:
- Actual driver behaviour is neither uniform nor predictable, as is demonstrated by extensive simulations performed in Germany (Kayser) involving an obstacle placed on the road near tunnel entrance. The graph of vehicle approach speeds gives very heterogeneous curves (figure 12). The author concludes that the bases applied to date for dimensioning the transition zone between the external environment with natural light and the darker tunnel would appear to need re-appraisal.

- M. Etienne (F) outlines different problems, their current appraisal, the errors to be avoided, and the essential principles to be respected, like:
  - disturbed spatial perception, causing:
    - loss of keen vision,
    - change in perception of contrasts,
    - reduction of peripheral vision,
    - modification of colours by artificial light,
    - difficulty appreciating distance;
  - change in perception of time; it is considered that time is felt to last twice as long as it actually does; and
  - prediction of future route - which is only possible by means of signage.

To reduce the human factor, the designer must therefore provide the driver with:
- the most familiar and comfortable environment possible so that he is less disturbed, and,
- the most relevant signage, so that he can locate his position and plan his route.

The latter point is especially important in the more frequented urban road tunnels which have complex interchanges at their portals.

5.5 Tunnel Repair

Tunnel repair was the principal topic of Session I. Several people spoke of the experience they have acquired in tunnel repair, and the information obtained is extremely valuable.

It is commonly known that it is above all the technical plant in tunnels that suffers from corrosion and rapid deterioration (but there are cases, like that of Klamm Tunnel in Austria, presented by H. Heidinger, where galvanized steel luminaries and their attachments show no sign of corrosion after 15 years in service!).

It is therefore important for all concerned to concentrate their efforts on the repair of existing tunnels. In so doing, the engineer must act with due consideration to the needs and experience of road users and operators. The choice of solutions must adhere to working procedures which match traffic needs and the special situation in tunnels (confined space, shorter work shifts due to air conditions, increased danger of accidents, etc.). It is then necessary to draw up a viable project using techniques and methods suitable for tunnel applications. It may even prove to be necessary to give priority in the choice of the repair project to the smooth performance of works rather than to oversophisticated technical requirements.

In addition, the engineer is confronted with a large number of new materials and combinations of materials whose performance he is expected to be familiar with. On this point, it is interesting to note the wide variety of grades of steel and methods for protecting steel, together with the complexities of synthetic materials and their behaviour when exposed to fire.
Figure 12: Survey in Germany:
Approach speed towards an obstacle on the road at tunnel entrance.
5.6 Dangerous Goods

Summing up the various papers to Session IIIb regarding safety with respect to the transport of hazardous loads, P. Dörfliger (CH) pointed out that all systems for restriction of transport of hazardous loads in road tunnels are drawn up arbitrarily, being based on no scientifically-founded data.

Yet these days the technique of risk analysis is no longer a struggling science.

Opinions expressed during the discussion at the end of the Session and the perspectives of post-1992 Europe clearly confirm the need for a programme of quantified risk assessment for the transport of hazardous loads to be drawn up by an appropriate institution, in association with those in charge of managing some of the main road tunnels.

This is seen as the best means of succeeding in harmonizing restrictions on the transport of hazardous loads through different road tunnels.

The hope that the OECD might set things in motion for such a programme to be conducted was also clearly expressed.

5.7 Costs

The question of tunnel costs is interesting, especially if one has comparable figures for different types of tunnels and different countries. In this respect though, the seminar was not the success anticipated, data being too slight for systematic analysis. This point apparently did not draw the same degree of attention as technical and operations concerns. The information given was nonetheless very valuable, for both those in charge of operation and designers.

In all, 9 papers gave information on the costs of tunnels.

They can be divided into 2 groups:

The first group (6 communications) includes occasional information on costs in connection with some other subject, i.e.

- 2 papers concerning watertightness and repair of immersed tube tunnels made with precast reinforced-concrete segments: S. Tomizawa (J) spoke of a new tunnel in Japan (Kawasaki Fairway Tunnel), where an expensive solution was chosen for watertightness. In this case, the sealing works, which accounted for 18.4% of the construction costs, should ensure a longer service lifetime. The economic reasoning behind this choice was that it involves no maintenance costs.
  And it is precisely maintenance costs that are the biggest problem for Danish tunnels (P. Christensen). The speaker presented a detailed analysis of different general methods for performing repair works, and gave economic comparisons.
  It is concluded that "as soon as possible" works, with additional post-tensioning for example, are distinctly cheaper than methods involving emergency work performed as and when required.

- 2 French contributions dealing with special repair works, i.e.:
  - the rehabilitation of side walls (H. Maillant, F) in a great many tunnels on the motorway between Nice and the Italian border. There are significant deviations in the cost of repair, especially between tunnels of the first generation which require costly works, and recent tunnels where the outside of the concrete lining segments is faced with a PVC membrane, thereby radically eliminating the problem of leaks
  - renovation of the lighting of Dullin tunnel (R. Naud) where, for cost reasons, partial renovation only was performed at a total cost of 7 million francs for 1,550 m of tunnel.
Operating costs, especially those corresponding to the electric power consumption of the Chamoise Tunnel in the Jura (J.-C. Roussel, F) and the Plabutsch Tunnel by-passing Graz (W. Gobiet, A).

The figures given are collected in figure 13.

The second group (3 reports) gave rather more consistent information on costs, especially:

- in H. Maillant’s (F) paper, there is some interesting information on investment costs for a series of engineering structures on the A8 motorway in the French Alps, with conclusions on the relationships between three aspects, i.e. surface earthworks, viaducts, and tunnels. Results show that, in general terms, the specific costs (per metre) of tunnels and viaducts are practically the same (tunnels are even slightly cheaper). The speaker’s conclusion reflects a trend already noted elsewhere, i.e. when looking for solutions for new urban motorway infrastructures, the cost criterion carries less weight than one might have thought, and that environmental considerations often swing heavy in the balance.

![Graph showing cost analysis](image)

* Figure 13: Summary of information given by U. Schlup (CH), O. Anelli-Monti (A), J.-C. Roussel (F), and W. Gobiet (A)
In the course of lively discussion on this topic, it was seen that opinions on investment costs were somewhat divided. On one hand, the majority of participants considered that viaducts were far cheaper than tunnels (Balz, CH, Maillant, F, and Schlup CH). As for operating costs, there are those who claim that viaducts are always cheaper (Boutet, F, tunnel operating costs are twice as high as viaduct operating costs), whereas, if replacement costs are included, the cost of viaducts is the same as that of tunnels (Etienne, F).

Finally, the contributions of U. Schlup (CH) and O. Anelli-Monti (A) made for interesting comparison of operating and maintenance costs of a series of large tunnels in Switzerland and Austria. The results are shown in figure 13, distinguishing the total operating costs and power costs of about 10 tunnels of different lengths.

This summary confirms the following:

- Swiss tunnels are more expensive than French and Austrian tunnels.
- Operating costs increase in proportion to the volume of traffic (cleaning, ventilation, emergency standby).
- Ventilation costs depend on the system. Transverse ventilation is significantly more expensive than semi-transverse or longitudinal ventilation. In addition, anti-pollution measures have an effect on power costs, as can be seen with the Gubrist tunnel (CH) where tunnel air is normally drawn in from the exit portal, brought to the centre of the tunnel, and discharged vertically through a ventilation shaft.
- Lighting costs are higher in short tunnels because of adaptation lighting.
- Long tunnels must have special emergency duty staff (fire) and separate staff for surveillance and monitoring, which engenders additional costs.
- When there are two one-way tunnels, the total costs is the same or even less than a single two-way tunnel.

The figures presented by U. Schlup demonstrate the impressive increase in maintenance costs for Swiss tunnels in the last five years. The main reason for this is less than increased length of the tunnels than their ageing. Half of the maintenance expenditure is for electro-mechanical facilities.
6. Conclusion

The following contributions are given here in conclusion to this Report.

6.1 Contribution to the Closing Session by Sir Alan Muir Wood

First, I would like to congratulate OECD for the initiative in setting up this conference. Those who have taken part in the proceedings of the three days will have found the experience well worth while.

For my part, this has been the most relaxed conference I have attended for years and I cannot claim any direct part in its success. But I am delighted that so many of my colleagues on the PIARC Road Tunnels Committee have contributed so great a measure to the proceedings. The PIARC Road Tunnels Committee and its four working parties engage the activities of many, mostly engineers, from several countries but, apart from the occasions of official representation at other conferences, we receive inadequate feedback. Our own Congresses, at four-year intervals, deal with a wide range of subjects concerning roads and we cannot expect to find many others there who take great interest in tunnels and their operation.

Design is said to constitute the "continuous thread" that pervades (or should pervade) all stages of a project from planning to operation. This "continuous thread" needs constant iteration for its sustenance. The iterations in Lugano have been stimulating.

We are looking towards the future and endeavouring to distil experiences from other people and other occasions, recognizing that no two tunnels or their users or operators are precisely the same. This conference has been particularly successful in the way that people have discussed what goes wrong as well as right. We learn far more quickly from mistakes and we all (or as engineers we should all) have our own experience of mistakes.

Tunnels are expensive but the incremental costs to ensure that we have made adequate provision for changes occasioned by an uncertain future is not high; the consequences of making economies where they cannot be justified may well, on the other hand, be high. Provision of space for additional unknown services or equipment may be highly beneficial. We benefit from some of the generous features in such respects from our predecessors who where not constrained by applications of strict cost/benefit analysis. We should always be receptive to opportunities of multiple-purpose facilities below ground and the benefits that may arise from combining public and private interests, occasionally allowing road tunnels to be built for negative cost to the owner of the road network.

We have been reminded that a tunnel should not be designed without adequate margin in capacity. It is excessively expensive to try to overcome a deficiency. We should surely consider a "standard of performance" in relating capacity to demand, incidence of accident and breakdown for the particular geometry and circumstances, provisions to be made for transport of dangerous materials and other similar features. We can then consider for the present and future years the percentage time during which the tunnel may be expected to meet traffic demand without excessive delay or intolerable conditions. This would constitute its "standard of performance" or utility rating.

Our greatest concern at the present day must be for the transport of dangerous materials, whose overall volume is increasing and whose diversity expands at a yet greater rate. While this is a problem for transport in general, the potential hazard for road tunnels is especially serious. We need urgently to tackle the problems in a systematic way on at least a European if not international scale. We are much more likely to find a rational basis for designation and control if the problem is addressed before rather than after a major incident. I remain of the view that electronic tagging of a vehicle from point of departure to destination is likely to be a key element of a reliable system.
It seems to me to be important to retain a balanced view on environmental issues. Expenditure on combatting imaginary environmental hazards means less financial resources to deal with real environmental issues.

There are examples elsewhere of legal limits set without adequate scientific base and without awareness of the technical problems in their attainment. I suspect that the limits established for nitrous oxides in the vicinity of a tunnel comes into such a category since they appear to entail cleaner air than would be tolerated in a city served by surface highways. And the cost of countermeasures is by no means negligible. Such measures usually demand increased consumption of energy and the minimizing of energy in tunnel operation must constitute an environmental benefit.

From this "horizontal" conference, one that brings designers, operators, users and others together, I see the possibility of more specialized conferences of a comparable "horizontal" element. One such on accidents in tunnels should attempt to identify contributory factors, including temperament and mental state of the user. Another on dangerous materials would have a yet broader set of tasks. I am unclear where the initiatives for such conferences would come from but the success of this conference, set up by OECD, strongly supported by PIARC and hosted by Switzerland sets an excellent precedent. More effective feedback and iteration between all parties involved in road tunnels must be an important feature for continued progress in the art.

6.2 Summary of the seminar by B. Horn

General

The seminar was built on a broad agenda of shared concerns in OECD Member countries. The high number of participants (over 250) including representatives from eighteen countries and four international organizations, clearly illustrated the need for exchanging experience, study results and ideas in this sector. The seminar discussed issues related to economics, technology, the environment, traffic safety, maintenance, traffic operation and the transport of dangerous goods, and outlined some of the major emerging policy lines and research and development needs.

Tunnel Needs

The seminar has provided evidence that the relative importance of tunnels and tunnelling will increase. There will be more tunnels in the future. There will be more short tunnels at neuralgic points in urban areas and at strategic locations in inter-city networks, as dictated by topographical factors, land use requirements, and environmental priorities.

There are also emerging developments to build large-scale tunnel networks in highly congested metropolitan areas and along transit corridors. There is a trend towards increasingly sophisticated tunnel facilities with integrated controls, electronics and advanced communication technologies. It is probable that in some countries, know-how and complex management strategies will be developed to build, equip and operate high-speed traffic tunnels as part of expressway networks. Private financing initiatives will promote more toll tunnels including the application of electronic toll collection. Finally, many existing "unmanned" tunnels, especially those on less important routes, need to be upgraded to conform to modern traffic, safety and maintenance standards.

Tunnel Classification and Standards

A classification of tunnels and tunnel types and agreed standards of performance and functional requirements for all such facilities (whether owned by public authorities or private operators) would be useful at the international level. Guidelines for minimum standards and equipment would help to improve the state of the art and enhance user behaviour.
Some Inferences for Future Work

The seminar and the papers enabled us to pinpoint some of the main problems and to develop a constructive agenda for future initiatives:

- on maintenance, it seems to me that more work is needed to develop more efficient management systems (similar to PMS or BMS - pavement management or bridge management systems), including access road, tunnel entries and exits and the continuous optimization of road surface characteristics;
- on ventilation and pollution, I believe that work should proceed to cut down the high energy consumption and to develop efficient purification techniques and procedures for nitrogen oxides;
- on traffic control, and particularly for tunnels operated under flow conditions nearing design capacity and suffering from recurrent conditions of congestion, the rigorous application of modern real-time traffic control and development of advanced/intelligent road/vehicle communication systems are essential;
- on safety, while we know the record is very good, this seminar clearly highlighted the areas where there is room for improvement (accident causes and types, specific tunnel areas, "unmanned" tunnels). Research from the road-user point of view and driver behaviour studies should be collected, analyzed and, if need be, enhanced. Special efforts on fire fighting including fire tests are undertaken in some countries but could be carried out on a larger scale and more efficiently in the framework of international co-operation;
- on traffic, safety and environment, it appears to me that more work is required on the whole complex of trucks - their behaviour in traffic flow, their involvement in accidents, the implications for the geometry of tunnels. On a related theme, instead of "marrying" trucks with general car traffic, should we separate them and advocate cargo routes and facilities, truck tunnels or separate new networks for goods transportation? I feel that the truck issue was not given high enough priority in this Seminar.

Transport of Dangerous Goods in Tunnels

Although traffic accidents involving dangerous substances, especially in tunnels, are rather rare events, incidents continue to occur on a fairly regular basis. During the discussions you heard of a proposal to launch a joint initiative in this sector to arrive at internationally harmonized operational standards and controls. What is needed is to take stock of the experience - perhaps through case studies - and to provide first of all a qualitative risk analysis and, hopefully, subsequently, a quantitative analysis. This should be done through international co-operation, focusing first on the most frequent commodities - for instance flammables - and taking account of typical production/distribution intercity corridors in Europe, Japan and the U.S. I also believe that such work should cover both road and railway tunnels.
"READABLENESS"

TO SEE THE END OF THE TUNNEL