THE CRAFT OF HIGHWAY ENGINEERING

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There are, it is said, more scientists alive now than have existed in previous generations since man emerged. Similarly with highway engineers. Fifty years ago, there were approximately 15,000 men in the world who would describe themselves as highway engineers; now there are at least ten times that number. And with them is an enormous army of other specialist professional people concerned with roads and road transport; traffic engineers, transport economists, statisticians and mathematicians, planners, medical men and psychologists concerned with road safety, environmentalists, and perhaps the latest specialization to emerge, the professional protester. This expansion reflects, of course, the huge growth of road transport during the present century and the changing attitudes of the public to it.

Over this period, four stages can be distinguished. In the first, the aim was to provide the roads needed for the rapidly expanding numbers of road vehicles, and the primary need for expertise was in road building. It soon became apparent that this great increase in man's mobility had brought with it a new plague, the scourge of road accidents. The science of medicine was developing alongside, and as man learned to control the diseases which afflict him, the toll of road accidents increased to the extent that in North America and Europe, it killed and maimed more active people than any of our more traditional diseases. Stage 2 came with the growing concern for road safety with new forms of professional specialization in which highway engineers were joined by law enforcement officers, statisticians and medical men.

Traffic control measures were first introduced to promote road safety. But soon, it became evident that they were needed for another purpose, to ease the flow of the large numbers of motor vehicles that were by now crowding on to the roads, particularly in towns and cities. By this time, road building had become a major item of capital expenditure in most countries, and there was a need to determine priorities and standards for road building in a way which was manifestly logical and apparently fair. The third branch of the profession to sprout produced the transport economists and planners with a new armory of expertise, benefit-cost analysis, origin and destination surveys, mathematical modelling, economic and physical planning, and so on.

Then, in the last two decades has come the fourth stage, a growing concern about the impact of road transport on man's living environment. New roads had been driven through our towns and cities breaking up the existing patterns of community life, and road traffic had joined industry as a major pollutant of the air we breathe. The din from road traffic afflicted the lives, the work and the sleep of urban dwellers. In rural areas, new roads penetrated into areas of natural beauty, and the road builders were branded as the despoilers of the countryside. To these deleterious effects of road transport has been added concern at our profligate use of the world's energy resources.

It was natural that these developments should first become manifest in North America, and it follows that the techniques for coping with them generally first emerged in the USA. At this conference, our concern is with low volume roads. So our emphasis on those four stages is somewhat different from the attitude of say the urban planner, or the U.S. Federal Highway Administration. With my colleagues from the World Bank, I have a special concern with roads in the developing countries of Africa, Asia and South America. Our overall aim is to build up the resources of developing countries so that they can take their place fully fledged socially and economically in the comity of nations. Part of these resources lies in the stock of professional people who are able to cope with the planning, building, and maintenance of their road networks. And this is the theme I want to take for this paper. It is a huge theme, impossible to cope with comprehensively in one short paper. So I shall concentrate on three particular aspects and on these I shall be dealing with where I believe that things have gone wrong. The three aspects are:

1. Soil mechanics as applied to highway engineering;

2. Bituminous road surfacings;

3. Economic evaluation of highway projects.

I shall be primarily concerned with roads in developing countries, but I believe that much of what I have to say will be relevant to those of you who are concerned with lightly constructed roads here in North America.

The first and obvious comment is that the highway engineers from developing countries coming to America and to Europe for their academic training, have found much of what they have been taught irrelevant to their highway problems at home. Behind this lies a more basic problem--the deep rift between the "scientific" and the practical approach to highway engineering.

The hope was that if our graduates in training could be instructed on the scientific principles which lie behind highway engineering practice, they could return to their own countries and apply these principles to the solution of technical problems in their own countries. This hope has proved illusory. Some, but not many useful scientific principles have emerged.

The body of knowledge in highway engineering remains empiric rather than rigorously scientific. So, the knowledge taught in our engineering colleges is generally derived from a synthesis of local experience. No wonder it is often irrelevant and sometimes downright misleading in other parts of the world.

This is very obvious in the use to which soil mechanics has been put in highway engineering, and I want to illustrate it with a story. A major landslide in an East Asian country had carried away half a mile of road and part of a village. A huge crowd had gathered to decide what to do, including the Minister of Public Works (himself an engineer), the Chief Highway Engineer and many of his technical staff. They were all charging around discussing where to rebuild the road and the houses. Not one of them was asking why the landslide occurred. No one was saying, "Let's find out what happened and why. Then when we rebuild, we can be reasonably sure it won't happen again." This was a failure in comprehension. Despite their training as engineers (many of them in America and Europe), they did not comprehend that it was possible to find out what had happened. Still less did they comprehend that it would be useful to do so. Their engineering courses had dealt with slip-circle analysis and with drained and undrained tri-axial tests, but they didn't see the relevance. And they had had no instruction on the soils of their own country, on their properties and their engineering defects and uses. This was bad ground. It had always been bad ground. They would rebuild the road and perhaps this time, with luck, it would stay there.

Science had produced an understanding of some of the mechanisms of landslides, but in those engineers' minds, this had no connection with real life. This illustrates very clearly our dilemma. The scientific approach involves setting out to acquire a basic understanding of why things happen as they do, of the stability of slopes, of the stresses and strains in road pavements under traffic. This is proving to be a long and tedious business; witness the tremendous research effort still going into establishing a rigorously scientific method of pavement design. The practical people, impatient to produce technical answers to the problem which beset them, produced ad hoc tests which aimed to simulate in an approximate way, the reactions between the loaded vehicle and the road structure. In America, the crop of such tests was formidible: R. R. Proctor and his compaction test, later followed by the heavier Modified AASHO Compaction Test; Plate Bearing Tests and later the California Bearing Ratio Test originated by O. J. Porter then with the California State Highway Department; Benkelman in the Bureau of Public Roads with his deflection beam, and in the field of bituminous materials; Bruce Marshall of the Mississippi State Highway Department, Prevost Hubbard and F. C. Field of the Asphalt Institute; and Francis Hveem of the California State Highway Department, all produced mechanical testing regimes for the design of asphaltic concrete mixtures. And there were others perhaps less notable in the Highway Engineers Hall of Fame. Very little comparable came from Europe over this period. The American dominance does not only derive from the earlier motorization of America. It springs also from something deep in the American culture, an innate optimism expressed in the belief that it is possible to produce simple, mechanistic models of natural phenomena and a determination to produce an answer which could be adopted for rapid industrial use. Some waste might be implied by the approximations that were necessary, but this was of no consequence in a society dedicated to technical innovation and change.

The ad hoc approach produced immediately useful solutions in the areas where they were developed. The physical tests they used were extensions of the eye and hand of experienced men. They were, in effect, a means to make this experience numerate, and their value depended a great deal on the skill with which the test results were correlated with road behavior in the area in which they are being used.

There is an intrinsic danger in this approach; the correlations with road behavior are necessarily local in character. When one moves away into another environment, for example into a different climate or to use different road making materials, the correlation disappears and the test results can be quite misleading.

The CBR test provides a graphic example. As originally conceived, its main use was intended for testing road making gravels. A good road making gravel would have a CBR of 100%. It was the U.S. Corps of Engineers which pushed the test as a means of evaluating subgrade soils. They had a wet environment in mind, and it was they who decreed that the test should be done on compacted samples which had been soaked in water for four days. Their aim, of course, was to design for the worst conditions they were normally likely to encounter. And they can have had little idea of the confusion that their edict would have. I have met, many times, engineers working in arid parts of Africa and other areas of the world, who were solemnly soaking CBR specimens for four days and declaring that the resultant CBR value indicated the soil strength which should be used in designing their pavements. That provides an example of experience being translated from one part of the world to another with wasteful effects.

Fortunately, this subject provides an example of science and practice combining to produce a sound engineering answer. The strength of a subgrade soil depends not only on the nature of the soil; it depends also on the state to which it has been compacted, and above all, it depends on the prevailing moisture conditions in the soil.

The state of compaction achievable is a matter to be judged from local engineering experience. Prevailing moisture conditions may also be determined from local engineering experience. But science has gone one better. Experts in physics and climatology have joined to produce a theoretical basis for determining the critical moisture conditions in soils under sealed surfaces over the range of physical and climatic conditions encountered in different parts of the world. And, important to us as engineers, this theory has been tested by field observations and found to be correct. Some engineers may have sufficient curiosity to want to explore the theory. But for most of us, it will be sufficient to see the results incorporated in design recommendations we can easily understand. An example of this is shown in

Table 1. This table, incidentally, illustrates a trend which is likely to continue, to use the CBR value as an index rather than a directly measured entity. Indeed, in some parts of the world, the trend is to delineate design CBR values on a basis of soil identification, together with a knowledge of the achievable state of compaction and the prevailing moisture conditions at the site concerned.

Table 1. Estimated minimum design CBR values under paved roads for subgrades compacted to 95 per cent of Proctor maximum dry density.

	Minimum CBR (per cent)[b]					
Depth of water table[a] from formation level	Non-plastic sand	Sandy clay Pl = 10	Sandy clay Pl = 20	Silty clay Pl = 30	Heavy clay Pl ⩾ 40	Silt
0.6m (2 ft)	8	5	4	3	2	1
1.0m (3.3 ft)	25	6	5	4	3	2
1.5m (4.9 ft)	25	8	6	5	3	
2.0m (6.5 ft)	25	8	7	5	3	
2.5m (8.2 ft)	25	8	8	6	4	See
3.0m (9.8 ft)	25	25	8	7	4	Note
3.5m (11.5 ft)	25	25	8	8	4	
5.0m (16.4 ft)	25	25	8	8	5	3
7.0m (23 ft) or more	25	25	8	8	7	

Notes:

1. With structured clays, such as the red coffee soils of East Africa, laboratory CBR tests should be undertaken whenever possible. Soils of this type can be identified by the fact that their plasticity, as indicated by the Atterberg limits, tends to increase when the soil is worked and its structure is broken down. If CBR tests cannot be undertaken, an approximate estimate of the effective subgrade CBR for this soil type will be obtained by using the values quoted in the Table for sandy clays (Pl = 20 per cent).
2. This Table cannot be used for soils containing appreciable amounts of mica or organic matter. Such soils can usually be identified visually.
3. Laboratory CBR tests are required for pure silt subgrades with water tables deeper than 1.0m (3.3 ft).

[a] The highest seasonal level attained by the water table should be taken.

[b] This table is abridged from Road Note 31 (Third Edition), "A guide to the structural design of bitumen-surfaced roads in tropical and subtropical countries," (HMSO 1977), and these CBR values are for use with the design chart in that Road Note.

Poorly consolidated soils present special problems to the road builder. They are usually transported soils and are commonly found in river deltas. They occur in the lower reaches of the Mississippi, along the coast of West Africa, in the delta areas of the great Indian rivers, in the rice plains of Thailand, in Malaysia and Indonesia and in many other parts of the world. They are generally saturated, i.e., all the voids in the soil are filled with water. A good basis for the scientific approach to road building over these soils was provided by the consolidation theory developed by Terzaghi. Again, the theory is somewhat complex and will be examined only by engineers who are scientifically curious. But its application is relatively simple; the amount and rate of consolidation of these soils under load is determined by using laboratory consolidation tests on soil samples. As load is applied to the soils, pressure is generated in the water. If the load is applied too quickly, these pressures become excessive and shear failures will occur. But under a controlled load, the pressures are gradually dissipated as water moves away into unloaded areas and the soil is compressed to an ultimate value at which the load is carried by the soil particles. The theory and the associated laboratory test provided a reliable means of determining ultimate settlement under load, and hence, of designing embankments over such soils. The test was also used to indicate the rate of settlement and generally it indicated that settlement would take a very long time, usually several years. This experience was at least partly responsible for the development of vertical sand drains, used to provide an artificial drainage path and so increase the rate of consolidation.

But, in practice, it was often found that these soils consolidated much more rapidly than the theory and the laboratory tests suggested. The reason when found, was an obvious one. It is that frequently these soils contain thin bands of more pervious sandy soils, bands which were laid down when, for some reason, the water which carried the original deposits was running faster than usual. These lenses of sandy soil proved horizontal drainage paths through which the pressures generated in the soil water under load can be fairly rapidly dissipated. The theory has now been elaborated to take account of this phenomenon.

I am in some danger of appearing to wander from the subject of this conference. But, in fact, it is very relevant. It is to support my belief that the basis for training young highway engineers in soil mechanics lies in giving them a knowledge of the soils and the rocks of their own countries, of what they are, why they occur where they do, and what are their engineering properties and uses and their limitations. And this applies with particular force to engineers concerned with low cost roads. They, above all, must know what can be done with the materials which are cheapest and ready to hand.

I could rattle on for hours about different facets of it. About black cotton soils, those highly montmorellinitic clays found in poorly drained areas and which present formidible problems to the road builder, about the halloysitic clays which form in areas of volcanic activity and which, though texturally classified as clays have an open porous structure which is free draining, and of the dangers of overcompacting these soils; about laterized soils, and about decomposing rocks--rocks which, on hand inspection, appear sound, but when they are used in the building of a road, the feldspars they contain collapse to become kaolinitic clay. It is a fascinating subject and one likely to fire the imagination of any young civil engineer. It would have given those engineers in East Asia the knowledge to understand why landslips occur in that part of the world and what they can do about them. This brings me to my main thesis. Road engineers are like doctors or carpenters, like teachers, or, for that matter, like lawyers and economists. To do their jobs well, they need to be craftsmen. They need to know the materials of their trade thoroughly, how they behave in given circumstances and how to modify this behavior to get the best results. It is useful, too, if they can explain things in scientific terms. But, the first requirement is the art, the almost intuitive understanding of the materials of one's trade built up by experience.

This theme is well-illustrated in the history of the use of asphaltic materials as road surfacings. We pick up the story at the end of the last century. Natural asphalts had been in use for some time to make durable surfacings for city streets. Refined bitumen from crude oil had appeared on the market, and there was a rush to use this material on roads, both in America and in Europe. Small enterprising companies set up in production, generally trying to make synthesized mixtures imitating the natural asphalts. Secret formulas and trade names proliferated. At this stage, the trade was well ahead of the buyer. Most engineers were content to buy on the assurance from the contractor that his was the best product that modern technology could produce. The more discerning soon realized that it wasn't so, that often they were getting a bad bargain. Amongst these discerning people was Clifford Richardson, Asphalt and Concrete Inspector to the District of Columbia. He decided to do something about it. He set out on a tour of Northern America and Europe examining asphalt surfacings. His aim was to determine why some asphaltic concretes proved very durable and satisfactory whilst others didn't, and then to indicate how to make sure you could get a durable asphaltic concrete every time. His method was to enquire from engineers as to how well their asphaltic concretes had performed, and then to take samples of both the good ones and the bad ones analyzing them to determine what they were made of. He spent several years at this task; and at the end of it, he was able to prepare and publish his conclusions. They were sand asphalts for the most part, and he produced specifications on how to choose the best sands, and on how much bitumen of what hardness to use in order to obtain very durable asphalt surfacings. He showed how the composition should be varied--softer bitumen, and more of it in cold climates; harder bitumen and less of it on more heavily-trafficked roads.

This was the craftsman's approach. It paralleled what Fanny Farmer had been doing a generation earlier. His specifications were essentially recipes for producing good asphalt surfacings and they included variations to take account of the effects of climate and traffic. The primary regard was for quality in the finished product and the method involved searching out the best materials locally available and combining them in cookery book style to produce extremely durable asphalts. One example, laid on the Thames Embankment in London in 1906, was still doing duty under very heavy traffic in 1955 and was then replaced, only because there were so many trenches cut through it to repair power mains, sewers, and water mains.

This tradition continued in Europe. In Germany, it was responsible for producing gussasphalt, that immensely durable mastic asphalt used on most main roads in Germany. In Great Britain, it produced rolled asphalt to BS 594.

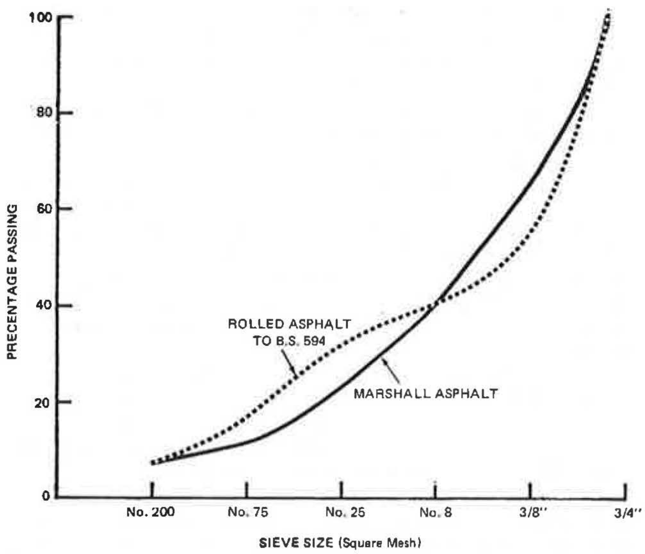
Richardson was not so much honored in his own country. In any case, a new prophet arose in the U.S.A.--Bruce Marshall of the Mississippi State Highway Department. He took another line altogether. His aim, a very worthy one, was to be able to make asphaltic concrete out of materials you could readily find nearby. He used mechanical tests aiming to measure physical properties of the asphalt which were relevant to their performance on the road. Other prophets followed the same line, producing the Hubbard-Field testing regime and the Hveem testing regime.

Then, the Corps of Engineers took a hand. They had a problem with the increasing weight of aircraft in providing adequate airfield surfacings, and immediately after World War II, another problem hit them, the advent of jet aircraft. Aircraft tire pressures increased enormously. Airfield surfacings had to withstand huge increases in weight and pressure, far higher than were needed on roads. Those mechanical tests, particularly the Marshall test were ideal tools to use in developing asphaltic concretes suitable to withstand these high pressures. In America, these "Marshall" asphalts came to be used as the standard surfacings for roads and airfields. They spread over the rest of the world, too. They spread to South America, to Africa, and to Asia. It was so convenient to quote the excellent specifications produced by the Asphalt Institute and the ASTM. They spread to Europe for airfields. But they were not used in Europe for roads. Europe remained entrenched in its traditional methods of making asphalt surfacings. In Great Britain, particularly, the line of evolution started by Clifford Richardson continued in the development of rolled asphalt specified in successive editions of British Standard 594.

The two materials Marshall asphalt and rolled asphalt are markedly different in composition and in performance. Marshall asphalt is usually made with crushed rock in a continuous gradation approximately to a fuller curve. Rolled asphalt was traditionally made with natural sand fines and with crushed rock as coarse aggregate, a gap grading (See Figure 1). Marshall asphalt is generally made with one grade of bitumen the same all over the world. With rolled asphalt, the hardness of the bitumen is adjusted according to the climate and the intensity of traffic.

You may think that these differences are natural and hardly worth bothering about. Some of you may even say, "Shucks, why don't they do it the good old American way? It works for us, why shouldn't it work for them?". But does it work for you? Particularly does it provide a good surfacing for the more lightly trafficked roads which are the theme of this conference? I think not. In the design of Marshall asphalts, the primary requirement is high stability. In cookery book terms, they are short, like Scottish shortbread. In scientific terms, they have quite a

Figure 1. Aggregate gradation for Marshall asphalt and rolled asphalt.



high modulus of elasticity which gives them good load spreading properties. But they cannot tolerate high strains; their tensile strength, particularly under dynamic loading, is not high. The specifications do give different test criteria for asphaltic concrete to be used under heavy, medium and light traffic. But these adjustments are not large and Marshall asphalts can generally be characterized by their high stiffness and resistance to deformation. They are eminently suitable for use on airfields and on the stiff, strong pavements used on heavily trafficked roads. But they are not so good on more lightly constructed roads which deflect under load. Rolled asphalt, on the other hand, has a lower stability. It is more prone to deform under load. Rolled asphalt, on the other hand, has a lower stability. It is more prone to deform under heavy loads. But it is more able to tolerate repeated flexure and has, therefore, some slight advantage over Marshall asphalt for use on more lightly trafficked roads.

Surface dressing or seal coat is even more effective under these circumstances. The thick film of asphalt effectively seals the road surface, binds it together and prevents water from getting in. But road engineers, particularly in developing countries, don't like seal coats. Seal coating requires skilled and experienced operators, and these skills may not be locally available. But the real reason is that they have accepted a technological myth--that Marshall asphalt is the most advanced, and most civilized and the most effective way of surfacing all asphalt roads. And this simply is not true.

In passing, it is worth recording that there are signs of a rapprochment between the American and the British methods of asphalt design. It is started in South Africa, which is perhaps not surprising. They are exposed to the technical influences of both America and Europe, and they have no vested interest in either. They have accepted that there are virtues in gap-graded mixtures for their conditions, i.e. the plums in the pudding mixtures produced by British Standard 594. And to design their mixtures, they use mechanical tests on the pudding, the fines-filler-asphalt mixture, employing design criteria derived from local experience. Great Britain has followed this lead, and in the latest edition of the British specification contains as an alternative, a mechanical testing procedure which can be used to determine the optimum asphalt content of the fine fraction of the mixtures.

But I want to return to consider what kinds of bituminous surfacing we should be using on the low volume roads which are the subject of this conference. By low volume, I am assuming that we mean roads likely to be carrying up to say 500 vehicles per day. Within this spectrum, we can expect that roads carrying over about 150-400 vehicles per day will require bituminous surfacings; that the pavement construction of these roads will be relatively light and that many of them, forestry roads for example, will be called upon to carry quite heavy vehicles with axle loads up to 11 tons or more.

What is the function of the bituminous surfacing under these circumstances? Clearly it will not be expected to add very much to the intrinsic strength of the pavement. If an asphalt premix is contemplated, it is not likely to be more than 2 inches thick. And if we are thinking of hot climates, the extra stiffness it will provide to the road structure is little more than would be provided by an extra 2-inch thickness of road base. The main functions of the surfacing are:

1. To seal the surface, preventing the entry of surface water which would weaken the road structure.

2. To protect the base from the disruptive effects of traffic.

These traffic forces between the tire and the road are very complex. In addition to the vertical gravitational forces, there are forces tangential to the wheel deriving from traction, braking, and turning; and there are other disruptive forces between local protruberances in the road and the tire. And when the road is wet, quite high dynamic stresses both compressive and tensile are generated in the water trapped in interstices, particularly when the pavement is deformed under passing loads. There are interesting side effects that have been observed. For instance, that road surfaces tend to polish and become smoother in dry weather; that on a given surface, the extent of this polishing is arithmetically proportional to traffic intensity; and that when weather comes, this polishing action ceases and the surface texture recovers at least some of its original roughness. This phenomenon is important in improving the skid resistance of heavily trafficked roads. To us, it is an interesting but not very relevant digression.

Our concern is to decide what form of asphaltic surfacing best provides the waterproofing and resistance to traffic wear, which are the prime requirements on more lightly trafficked roads. And we have to consider three influences on our choice:

1. The materials locally available for road building.

2. The effects of the local climate, predominantly the temperature range and the prevailing moisture conditions.

3. The technical and social influences, e.g. what levels of technical competence can be expected and what form of technology is appropriate to the region, ranging from the highly mechanized processes used here in America to the labor intensive methods of road building used in India.

All the time, we shall be bearing costs in mind, since our objective is to produce the cheapest solution. All these considerations lead in the same direction, that what is needed on the more lightly trafficked roads is some sticky substance which will seal the surface of the base and impart some cohesion to resist the disruptive forces of traffic. In some parts of the world, there are waste products available that can do this job, molasses residues and lignin sulphites, waste from one method of wood pulping, even waste sump oil from internal combustion engines. But they are not very durable and generally are worth using only in the immediate area of production. The predominant products are bitumen from crude oil and tar from coal. These materials can be applied to the base in fairly thick films so that they waterproof and remain intact under traffic stresses. Because they are sticky, they need the protection of a layer of stone chippings. This does raise some difficulties in parts of the world where there is no rock or gravel easily available. But elsewhere, the answer is clearly surface dressing. Surface treatment, seal and chip.

There is not time to go deeply into the mystique of surface dressing. Suffice it to say the specification can be adapted to meet almost all the climatic extremes encountered throughout the world, that the materials required are readily available in most of the world, that it is a cheap process (generally about a fifth of the cost of asphalt premix surfacings per unit area) and that it is readily adaptable for both highly mechanized work and for work using hand labor with simple equipment. Add for good measure that most of the secondary roads in Europe were built and improved using this process, and that in Australia and New Zealand the normal expectancy is that roads built with crushed stone bases and single surface dressings with traffic up to 2000 vehicles per day will last for at least 10 years, usually longer before periodic maintenance is required.

Where is the snag? Why isn't this process being more extensively used? There are some technical reasons. Surface dressing in rainy and cold weather can be a chancy business. But there are remedies for that. The predominant reason is that the process needs skill. Skill of the engineer in specifying the right combinations of bitumen and aggregate in given circumstances and above all, skill of the operators working on the road to ensure that the bitumen is spread uniformly at the rate required and skill that the stone chippings are clean, fairly uniform in shape and are uniformly spread. In Africa, and for that matter, in parts of America, surface dressing has been falling into disuse because there is no premium for such skills. We are back with craftsmanship and the need for training and motivation. Here, I must frankly confess I do not know how to cope. But I am utterly convinced that surface dressing is the preeminent method for the surfacing and periodic maintenance of lightly trafficked roads and that very large economics in the use of resources can be made by the more widespread, proper use of this process.

Now we turn to the last of the themes--the economic appraisal of highway projects. I move with some trepidation because my primary discipline is engineering--not economics. I had always believed that the benefit/cost study was invented by engineers and was built up to its present level of complexity by economists. I was heartened in that belief by discovering that John Loudon McAdam used benefit/cost calculations to convince a British Parliamentary Committee in 1820 of the need to spend more on the approach roads to London by considering possible savings in vehicle operating costs. But the confidence which this engendered evaporated when I remembered that McAdam was initially trained as a lawyer.

This lack of confidence tends to inhibit us as engineers when we are called to join in economic appraisals of our work. This is a pity because it is part of our function to demonstrate that the solutions we offer do represent the best value that can be obtained with the resources available. Behind the economists' calculations of costs and benefits, there are engineering realities and it is our duty to make sure that these realities are correctly interpreted in the calculations.

In recent times, we have come in for some criticism that we wish to push ahead with our road schemes with inadequate consideration of the economic and social consequences of what we want to do. Sometimes there is justice in this criticism, for instance in the wholesale advocacy of urban freeways during the 1950s and 1960s. But it is not an apt criticism with low cost roads. Our weakness lies elsewhere, that we have often not been able to express in precise economic terms those engineering realities to which I referred earlier.

Economic calculations presume an ability to predict future events with some certainty. How much will the road cost to build? How long will it last? What kind of maintenance will be needed and how much will it cost? How much traffic will it be called upon to carry; how will the traffic develop? How much will the nature of the traffic determine the design of the road we build and its costs? How much will the standards to which we build and maintain it affect the costs of operating the traffic over it? And in development roads, how much will the roads we build affect the economic and social life of the communities served by the roads? The engineer has a contribution to make in answering all these questions and it is vital that he should make, and be seen to make this contribution.

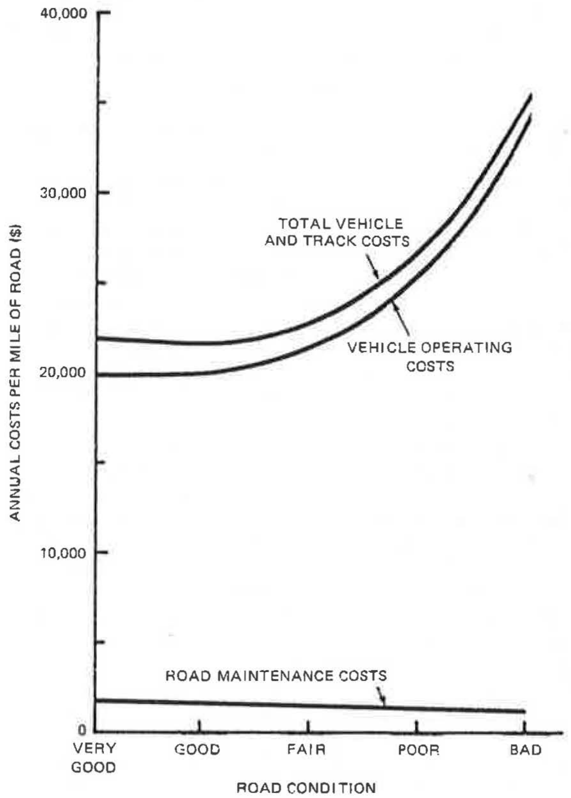
Engineering costs are frequently underestimated in preliminary studies. There are several reasons for this, one that detailed engineering frequently reveals foundation problems that were not discovered during preliminary studies, and another that the complexities of arranging site operations so that work can proceed smoothly are not adequately appreciated. There is also the temptation to underestimate costs in order to enhance the apparent viability of the project. The durability of engineering works often does not come up to expectation. Sometimes, this is traceable to faults in the design or inadequacies in the specification. More often, it is because work is not executed as planned, i.e. poor workmanship and inadequate control. Present traffic can be measured but there is often uncertainty in predictions of traffic growth; and if traffic loadings, particularly individual axle loads, exceed expectation, then early failure is likely to result.

One of the economic questions concerns the length of life to be assumed for a road. The question itself contains a fallacy, that a road pavement is an expendable commodity like a bar of soap, to be replaced as soon as it is used up. Roads are rarely discarded and replaced. Usually, they are strengthened and widened as traffic increases. The question is better rephrased as, "What is the most economical form of construction, improvement and maintenance strategy for the traffic that is likely to develop over say the next 20 years?"

Almost all countries in the world now have quite extensive road systems. Whilst some still need to improve and extend their main road networks, emphasis has been moving towards building up their minor road systems and above all towards more objective ways of planning and funding road maintenance. In Northern America, Europe, and Australasia, there are usually very capable highway maintenance organizations within state and local authorities, backed by an efficient private industry. In many parts of Africa, Asia and Southern America, these organizations are still embryonic.

On an existing road system, track costs are very much lower than vehicle operating costs. For example, on a well-maintained road carrying 100 vehicles a day, vehicle operating costs are in the region of $20,000 per mile per year. If, for any reason, the standards of road maintenance are relaxed, vehicle operating costs will rise. The interaction of the two costs is illustrated in Figure 2. The dominance of vehicle

Figure 2. Typical annual costs on a road carrying 100 vehicles per day.



operating costs is obvious even at the low traffic flow of 100 vehicles per day. It is also evident that total costs are scarcely affected by changes in the road condition between very good and good, but that once the road condition drops below fairly good, total costs rise sharply. I must immediately hedge any conclusions from this diagram, with reservations. It applies to an existing road or road system which does not need substantial investment to bring it up to good conditions. The terms good, fair, poor, and bad are subjective, and the vehicle operating costs, though of the right order, are imprecise. Nevertheless, the conclusions are obvious that it pays to maintain roads in a condition such that vehicle operating costs are not deleteriously affected. The practical application of this conclusion is prejudiced throughout the world by two things. One that the capital costs of bringing the road system up to a "good" standard may be high, and the other that the costs of building and maintaining the roads falls on the public purse whilst most of the savings accrue to road users, most of whom are in the private sector. It is interesting that in well-managed private organizations which operate their own vehicle fleet over their own roads, such as tea estates, rubber estates, timber concessions, the roads are often built and maintained to a high standard. I can take you to a timber concession in New Zealand where the road layout and the road standards and the vehicle types and operation have been determined by calculations aimed at minimizing total transport costs and where the timber extraction vehicles are under on-line computer control. On this estate, they have all the data available to work in this rational manner, and the roads are good, and well-maintained.

Over much of the world, we work in a climate in which public expenditure must at all costs be restrained. In road transport, "at all costs" is a misleading phrase because often vehicle operating costs are not known. Or, if they are known, they are subjects of considerable controversy.

Our attempts to build roads as economically as possible may be frustrated by outside interests. Here are two examples. Under supposed market pressures, road making machinery has become increasingly large and sophisticated. It is often now no longer possible to obtain the simple rugged machines that are most suitable for building low cost roads, particularly in developing countries. And government regulation or the absence of it may frustrate our efforts for instance in the enactment and enforcement of regulations on vehicle and axle loading.

Now, after all this mayhem, I must try to be constructive. First, it must be clear that economic appraisals are absolutely necessary. The days are long gone when road schemes could be initiated to meet an obvious but unquantified public need. We need to make sure that expenditures on roads will produce real economic and social benefits in the areas they serve. And we need economic calculations to determine the engineering standards to which individual roads should be built and road networks maintained. Now to look at some of the individual aspects which I have sprayed with cynicism.

There are ways in which the preliminary estimates of engineering costs can be made more accurate. On major road works, risks of unexpected foundation problems can be reduced by more detailed site investigations. This is not a remedy open to us on lightly trafficked roads. Our remedy is to find and employ engineers who know the area and who are aware of the foibles of the different kinds of terrain through which the roads are being built. We are back with the need to educate engineers on the resources of their own countries. Similarly, it is this local experience which can anticipate local difficulties in mobilizing effective construction teams. And, I think that we are learning that the deliberate underestimation of costs in order to promote a particular project, is a self-defeating exercise.

I am not certain how well we shall do in improving our estimates of the long term performance of highways. That many roads do not perform as well as expected is sometimes due to false economies in design. More often, it is because the roads are not built as designed. In this, I see a decay in workmanship. One of the beliefs was that the increasing sophistication of road building machinery would, by eliminating "human error," produce a more uniform product, more consistently close to what the design engineer intended. There are examples in which this improvement has been demonstrated, for instance in sprayers for liquid asphalt. But, overall, although quantity of output has increased, the effects on quality have often not been good. Workmanship has further declined; there are fewer and fewer engineers and road foremen who understand the materials of their trade and the subtleties of road making processes, and when the machines go wrong, the consequences can be quite large. On the bright side, there has been a considerable growth in expertise in the mechanics of quality control. Ready-mix concrete producers, for instance, have improved their competitiveness considerably by employing statistical methods of controlling their materials and mix-proportioning. And, perhaps I am somewhat conditioned by the indifferent quality control I see on many road building works in developing countries. If so, we are back with training, on the need in training engineers to emphasize the importance of quality control and to indicate how best it can be done. In this field, at least, physical and social environment are not relevant; the value of adequate quality control is the same everywhere. It is a necessity in getting good value for money in road engineering works.

Predictions of traffic growth are always likely to remain uncertain, and it is usual to undertake sensitivity analyses to determine the effects over the likely range of traffic growth. Fortunately, some calculations, for instance in the design of new pavements, are not very sensitive to variations in traffic growth. But all calculations are very sensitive to the assumptions made on the effects of road conditions on vehicle operating costs. Until recently, the data base for relating vehicle operating costs with road conditions was very scanty. In effect, it consisted of data collected by Robley and Winfrey on rural mail trucks in Iowa in the late 1930s; some information on the costs of operating trucks and buses India reported to the Indian Roads Congress in 1961; a study of the costs of operating some 200 trucks and buses over roads in East and Central Africa reported by Bonney and Stevens in 1967; and a review by deWeille in 1966 in which reported experience is nicely balanced with judgements to fill gaps in knowledge. Those of you with speculative minds may wish to ponder this small effort and its costs and benefits in comparison with the enormous worldwide research effort which has been put into pavement design over the same period. Fortunately, we have gone a long way to redress this imbalance in the last decade, and the results of some of this more recent work are being reported at this conference.

The important advance is that vehicle operating costs can now be related to a measured quality of the road surface, its roughness. Previously, a subjective assessment of road condition was used, generally "good, fair, poor, and bad," as I have used in Figure 2. This subjective assessment led to some lack of credibility. It was easy to believe that vehicle operating costs were not really as high as the economists made them out to be. Yours wasn't really a "bad" road. Considering the effects of last year's rain, and the miserable pittance available for maintenance, it was really "fairly good."

Now we can measure the roughness or the riding quality of the road and derive from it what the operating costs of the expected traffic will be. We can go further. We can measure the roughness over a complete highway network, and knowing the pattern of traffic movements, we can estimate the vehicle operating costs over the network. And we can examine the effects of changes in road roughness over the network on total vehicle operating costs. We can, for the first time, indicate how variations in the standards to which we maintain a road network affect the costs of operating the road transport system. This is an enormous step forward. Although it is too early to judge the ultimate impact of this work, it is in use in at least eight countries to help in planning highway maintenance and strengthening programs. Perhaps its most important benefit so far has been in gaining the agreement of financial officials to larger maintenance budgets by demonstrating the much higher total costs of neglected maintenance. For the first time, we have the prospect of being able to establish on a sound economic basis, what the level of expenditure on road maintenance should be.

There are three limitations on this ambition:

1. That in many countries, the roads have not yet been brought up to a standard at which they can be kept in reasonable condition by normal routine and periodic maintenance.

2. That though measurements of surface roughness can indicate what parts of a road network are in need of treatment, they will not usually indicate the nature and the scale and the cost of the work required.

3. There are other aspects of road maintenance for which different criteria apply, such as the slipperiness of the road surface, the need for traffic lane markings and the need for structural maintenance of bridges, side slopes and verges.

None of these is a disabling limitation. On one at least, there have been parallel advances towards becoming more numerate. In most countries, the network of asphalted roads has been vastly extended during the past 30 years. On many of these roads, the pavements are reaching the end of their useful lives. Under the fatiguing strains of traffic, cracks and potholes are becoming more evident. The pavements must be strengthened soon; otherwise, their condition will deteriorate still further and it will be necessary to spend much more money in reconstructing the pavements completely. When should they be strengthened, and by how much?

Earlier, I mentioned one Harry Benkelman of the US Bureau of Public Roads, as a member of our Hall of Highway Fame. It was he who, in the 1940s, introduced the use of a long beam and fulcrum to measure the deflection of pavements under a slowly rolling load. Since then, other forms of apparatus have been developed, all aiming to measure the in-situ strength of pavements. Some measure deflection and curvature under load, others use indirect methods of indicating the stiffness of pavement layers. All are empiric and all need careful correlation to make sure that the measurements mean in the prevailing local climate and with the particular road making materials employed. So far, the most careful and extensive correlation has been undertaken with the Benkelman Beam or its automated derivative, the Lacroix deflectograph. Such instruments have been used for the last decade to indicate when and by how much individual roads need to be strengthened. And in two countries at least, France and Ivory Coast, deflection measurements are being used to plan road strengthening programs on a regional and national scale. Skid resistance is not normally a critical aspect of the maintenance of low cost roads, but it is germane to note that methods and criteria are now available for examining the adequacy of road networks in this respect.

This paper is already over-long, and I am conscious of many interesting omissions. Finally, I must touch on roads and rural development.

Low cost roads tend to be roads associated with rural development. Often, therefore, we are planning and preparing economic justifications for road systems that do not yet exist. Much of the benefit will lie in the development which the construction of the roads will make possible. Here, there is an important difference in principle. In benefit/cost studies for the improvement of existing roads, we are aiming to make the most economic use of available resources. With development roads, the aim is quite different; it is to extend man's capacity to use the earth's natural resources, i.e. to create new sources of wealth. The building of the roads will not of itself insure that the new sources of wealth are efficiently exploited. In more developed countries, America and Australia, for example, or rural France, the prompting for the building of new rural roads can come from an articulate and vociferous rural population; or it can derive from the plans of rural development enterprises such as forestry departments or private logging concerns. In these situations, there is always a group of people with the power and the interest to set about the use of the natural resources to which the roads will give access. But in developing countries, the presence of this enterprise is often less certain. The local people are often not articulate and sometimes suspicious of change and innovation. Sometimes, in this situation, the effects of road building can be dramatic. In the early 1950s, feeder roads were being built in the West Nile area of northern Uganda. For the first time, itinerant Indian traders entered the area with bush-pan radios and cheap cotton goods for sale; within three years, there was a four-fold increase in the production of raw cotton from the area. About the same time, roads were being built into a low-lying area of Borneo eminently suitable for the cultivation of wet padi. In one part of the area, the local people did start to grow rice for market. In a contiguous area, they did not. The system of land tenure enabled the village elders to resist this innovation.

More generally, when crops are being produced for local consumption, the demand is obvious and the system is self-regulating. But when crops are being grown for export to international markets; cocoa, coffee, palm oil, rubber, etc., the pace of development will depend very much on world prices, and on the extent to which governments move to control farm gate prices.

Thus, there are often difficulties in making reliable estimates of the economic and social benefits of new rural roads. An input-output model suggests itself. The input consists of the costs of building and maintaining the roads and the output in some measure of the increased prosperity which is assumed to derive from providing roads where there were none before. Such a model may be simple in concept, but it is very complex in application. There may well be other necessary inputs, water supply, irrigation, agricultural extension services. And as I mentioned earlier, the increase in prosperity is likely to be critically affected by other factors than increased motorization. There are some clear examples in which the building of feeder roads has been followed by a surge in local production and presumably by the opportunity for the local inhabitants to live happier and more useful lives. But there is a growing feeling that such surges in local development do not automatically follow on the building of new roads.

One obvious solution is that road building should be planned in the context of overall rural development plans. The road network will then be planned and built as part of a staged development in line with other essential aspects. The need disappears for a separate and rather hypothetical economic justification of the road network; but economic calculations will of course, be used to determine the standards to which the roads should be built and maintained; they may even be pushed further to indicate the optimum density and layout of the road network.

But there are still pressures to consider programs of feeder road building as a primary means of accelerating rural development. They are tangible, quick and fairly capital intensive, all of which makes them attractive as subjects for the investment of capital aid. And our economists have been struggling for the last decade to evolve reliable methods of measuring and predicting the value of such schemes. Simple methods have failed and the current trend is to enlist a wider and wider range of expertise--sociologists, anthropologists, market analysts, and so on. Their work will be of enormous interest, and it should help in a better understanding of the intricacies of rural development. But it is not likely to produce analytical methods which can predict the future with the certainty normally expected in economic evaluations; there are too many external uncertainties.

The more hospitable and fertile parts of the world are already being farmed. They have been farmed for centuries. Indeed, it is the surplus produced from farming these areas which set us off on the path of social and economic development. It was used to build towns and cities, to establish culture and civilization. Now we are pushing into the more inhospitable areas of the world where living conditions are harsher, where the climate is more extreme and uncertain, and where the soils are generally less fertile. We have two motives, one to produce more food and other natural products to meet the needs of the world's rapidly expanding population and the other, a desire on the part of those of us who happen to have been born in more hospitable and prosperous parts of the world to extend this prosperity to those less fortunate people who struggle to make a living in areas where nature has been less bountiful. This latter is very much a twentieth century phenomenon; cynical people say that it is an attempt to expunge the guilt about the exploitations of the colonial era. This is nonsense. The real reason lies in the vast improvement of world communications. Fifty years ago, the farmer scratching his land-hoe in Senegal might have been on another planet; now he is our next-door neighbor.

Three considerations follow.

1. That the intention to improve the productivity of these fringe lands usually implies a considerable investment in infrast ucture (including, amongst many other things, feeder roads).

2. That this investment, of its nature, is generally not likely to produce quick economic returns. Indeed, attempts at rapid exploitation may produce irreparable damage to the environment--as in the dust bowl of North America and more recently in the forests of Indonesia and South America.

3. That it would be a gross error to seek to impose this development from outside.

It is this last consideration which causes the most difficulty. This is the method which worked in the past; it was invading people who brought agriculture to Western Europe, and in more recent times to America and to Australia. But those days are gone. Now the task is infinitely more complex. And I like to think that this is what the World Bank is now really all about. It started as a means to provide capital to war-torn Europe. The capital funds went to people who already knew what they wanted to use it for, and recovery was rapid. Now the Bank is engaged in a much larger enterprise to assist in building up the resources of the developing world. Part of this is, of course, in distributing the earth's wealth in a more equable way from richer to poorer. This can be a difficult business as is demonstrated in the demoralizing squabbles in the North/South dialogue between Europe and Africa. The more rewarding part is in building up the institutions of developing countries so that they, too, know how best to manage their own natural resources and the development funds available to them from outside. This is a cooperative enterprise, an educative process for all of us. And oddly enough, the preparation of this paper has helped in my own education. I have been reacting against the attempts to refine the economic analysis of feeder road projects by introducing a wider range of expertise. I now realize that this was an over-reaction, engendered by the fear that it would lead to even greater emphasis on the preeminence of short-term economic returns in determining the viability of projects. Perhaps temporarily, it will. But there is an overriding benefit that it will lead to a better understanding of the development process. And if we can bring in the local people, not as specimens to be studied, but as participators who want to learn how best to develop their country's natural resources, there is a chance that some practical good will come of it. Indeed, amongst the most promising feeder road projects, are those where local participation is strong, as in Mexico and in East Africa where local cooperatives are being mustered and provided with simple equipment and leadership to build roads which will connect them with the countries' main highway networks. A virtue of this approach is that it is self-regulating. The technology and funds are supplied from outside; the motivation and effort are from the local people themselves; they are not likely to build more roads than they can afford; nor less than they need.

This has been a somewhat rambling paper. I seem to have concentrated on attitudes rather than on technology. This was deliberate. It stems, oddly enough, from my belief in systems; in human systems and their capacity to adjust to new circumstances. And it voices my disquiet that things seem to be going wrong with our technology in a way which hampers us from adjusting to new circumstances. It tends to put obstacles between us and our real objectives. The CBR value and the economic rate of return become objectives themselves, rather than a help in defining the reality they are supposed to represent, the load carrying capacity of the soil and the value of a particular endeavor in promoting the welfare of mankind. The realities are, of course, always more complex than the simple models we try to build to represent them. And, as things change, as we move from one physical environment to another, or from one culture to another, our simple models may prove to be downright misleading. The safeguards against these errors come from an awareness of the physical environment and the culture in which we are working, from an intimate personal feeling for what is really going on and why it is going on like that. And here we have a definition of the purpose of education and training. There are some enormous fallacies about the purposes of education and training of technologists. One is that it is to turn them out fully equipped to move into practice. Another is that it is to make them better able to compete for their individual share of the world's resources. Both are wide of the mark. The real purpose is to equip us so that our eyes and our ears are open and our minds are ready to gain experience of how the world works and to put this experience to good practical use.