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Railways and Energy

Liviu L. Alston

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Liviu L. Alston

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Abstract

A railway vehicle requires substantially less propulsive energy than a road vehicle of the same weight moving at the same speed. However, as explained in Part I, other factors favor road transport. As a result, the ratio of energy consumption by the two modes varies widely depending on service conditions including vehicle characteristics. Thus, railways have a substantial energy advantage for large volumes of bulk commodities, but for passenger transport they are generally no more energy-efficient than buses. Part I also contains a review of measures for increasing the railways' energy efficiency, and it is shown that significant gains may be achieved through operational improvements.

Railway electrification is discussed in Part II. Its economic viability depends on the opportunity cost of capital, the costs of diesel fuel and of electric power, the traffic mix and the nature of the terrain, as well as on the capital and maintenance costs of railway works and equipment needed with electric and with diesel traction. The return on electrification increases with traffic but there can be wide variations in the traffic needed for a given rate of return, depending on project conditions. A series of examples, which are not intended to be exhaustive, show that the traffic could range between 5 and 22 million gross tons for electrification projects yielding a rate of return of 12%. An analysis, suitable for pre-feasibility studies, is presented for estimating the traffic at which electrification becomes economically viable.

Extracto

Un vehículo ferroviario requiere una cantidad considerablemente menor de energía de propulsión que un vehículo de carretera del mismo peso que se desplaza a la misma velocidad. Sin embargo, como se explica en la Parte I, hay otros factores que favorecen al transporte vial. Como resultado de ello, la relación de consumo de energía de las dos modalidades de transporte varía ampliamente según las condiciones del servicio y las características de los vehículos. Así, tenemos que los ferrocarriles ofrecen una ventaja considerable en términos de ahorro de energía para el transporte de grandes cantidades de carga a granel, pero para pasajeros generalmente no son más eficientes en función del uso de energía que los autobuses. En la Parte I se incluye también un examen de las medidas para incrementar la eficiencia de los ferrocarriles en el uso de la energía y se demuestra cómo es posible lograr ahorros apreciables mediante mejoras en las operaciones.

En la Parte II se examina lo relativo a la electrificación ferroviaria. Su viabilidad económica depende del costo de oportunidad del capital, los costos del combustible diesel y la energía eléctrica, la composición del tráfico y la índole del terreno, así como de los costos de capital y mantenimiento de las obras y equipo ferroviarios que se necesitan cuando se utiliza tracción eléctrica o a diesel. La rentabilidad de la electrificación aumenta con el tráfico, pero puede haber amplias variaciones en lo que hace al volumen de tráfico necesario para obtener una tasa de rentabilidad dada, que dependen de las condiciones del proyecto. Diversos ejemplos, que no se pretende que sean exhaustivos, demuestran que en proyectos de electrificación una tasa de rentabilidad de 12% es posible con un tráfico anual entre 5 y 22 millones de toneladas brutas. Se incluye un método de análisis, útil para la preparación de estudios de prefactibilidad, para estimar el volumen de tráfico necesario para que la electrificación sea económicamente viable.

Il faut considérablement moins de puissance motrice pour déplacer, à la même vitesse, un véhicule ferroviaire qu'un véhicule routier du même poids. Cependant, comme on l'explique dans la première partie, d'autres facteurs jouent en faveur des transports routiers. La consommation relative d'énergie de ces deux modes varie beaucoup selon les conditions d'exploitation et les caractéristiques des véhicules. Ainsi, pour le transport en vrac de grandes quantités de marchandises, les chemins de fer utilisent l'énergie plus efficacement, mais pour le transport des voyageurs, leur rendement énergétique n'est généralement pas supérieur à celui des autocars. La première partie de ce document passe également en revue certaines possibilités d'accroître l'efficacité énergétique des chemins de fer et montre que l'amélioration de l'exploitation permet de réaliser des gains importants.

La deuxième partie est consacrée à l'étude de l'électrification des réseaux ferroviaires. La viabilité économique de cette opération est fonction de multiples facteurs : coût d'opportunité du capital; coût du carburant diesel et de l'électricité; composition du trafic et nature du terrain; coût d'investissement initial et d'entretien des ouvrages ferroviaires et du matériel nécessaires pour la traction électrique et la traction diesel. Si la rentabilité de l'électrification augmente avec la densité du trafic, le volume requis pour atteindre un taux de rentabilité donné varie considérablement selon les conditions du projet. Une série d'exemples, qui ne prétend pas être complète, montre que pour obtenir une rentabilité de 12 %, le seuil critique peut aller selon le projet de 5 à 22 millions de tonnes brutes. La deuxième partie du document présente également une analyse, susceptible d'être utilisée pour des études de préfaisabilité, permettant d'estimer à partir de quel volume de trafic l'électrification devient économiquement valable.

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SUMMARY

i. This paper addresses questions which arise in discussions about the effects which increases in oil prices have on railway development. Part I of the paper reviews the relative energy efficiencies of rail and of road transport, and measures for decreasing railway energy consumption. Only energy used for traction is considered. Part II is a review of the factors which determine the economic viability of railway electrification, and includes a methodology which can readily be used for prefeasibility analyses to determine whether a more detailed study is warranted.

ii. Two observations are needed to place these questions into perspective. First, the overall efficiency of a transport mode depends on the cost of all its inputs, of which energy is only one. There is no evidence that the increase in oil prices has done more than improve the competitiveness of railways at the margin. Second, railways account for only a small proportion--usually less than 4%--of national oil consumption. Reductions in the railways' consumption are therefore unlikely to have a major impact on national oil consumption.

Road-rail comparisons

iii. A railway vehicle requires substantially less propulsive energy than a road vehicle of the same total weight, moving at the same speed. However, other factors favor road transport. For freight, they include better utilization of available capacity by road services, and the consumption of energy for train formation (marshalling) by rail services. As a result, the relative energy efficiencies vary widely depending on the service provided, including the type and quantity of the commodity transported, and its origin and destination. Unfortunately, most data on energy consumption are averages covering a wide range of services, and cannot be used to determine the ratios

of energy efficiencies of different modes when rendering similar services. The data show, however, that railways are most energy efficient when performing services for which they use all resources efficiently--that is, when transporting large quantities of bulk commodities. While the transfer of such traffic to road would increase energy consumption substantially, transfer of road traffic to rail need not decrease energy consumption. However, modern distribution trends, involving the creation of large distribution centers, generate major traffic flows for which railways could be more efficient than road transport in the use of energy and of other resources. Of course, railways may also have energy advantages for other services. A test carried out by the U.S. Department of Energy showed that carriage of road trailers piggyback on rail cars between terminals in Chicago and in Minneapolis consumed half of the energy needed by trailers towed by road tractors. More measurements of energy consumed by rail and road transport when offering the same services, are needed to provide conclusive data.

iv. For passenger services, railway trains tend to be less energy-efficient than buses, mainly because it is easier to adapt bus frequency than train composition to variations of transport demand, and vehicle weight is lower for buses. However, railways are substantially more energy-efficient than private motor cars, and as they can be made to be faster and more comfortable than buses, they may be more effective in attracting passengers from private cars.

Reductions of Railway Energy Consumption

v. It has been explained that reductions in railway energy consumption are unlikely to be important in relation to national consumption. The incentive for such reductions is therefore derived from its impact on railway

costs. The proportion of railway expenses which is devoted to energy varies considerably for different railways. A review of railways in 17 countries showed that the share of energy ranged from less than 5% to 30% of total working expenditures. Part of the explanation of these differences is to be found in differences in the price of diesel fuel. If railways--and indeed all users--are to be encouraged to use diesel fuel efficiently, it should not be priced below cost.

vi. In some cases, substantial reductions of energy consumption may be possible through improved driving and train operations--notably lower speeds and fewer stops. Computer programs can be used to develop adequate strategies. Reductions may also be achieved through improved equipment designs, but their implementation may be costly, and it is usually relatively slow because of the long life of the railway equipment. Furthermore, for developing countries such improvements have to be weighed against greater complexity of maintenance and operation. In equipment design, the emphasis must be on reliability, taking into account the staff and maintenance facilities available.

Railway Electrification

vii. Electrification involves a large initial investment in fixed installations and locomotives, and produces operating and maintenance benefits which increase with traffic. As a result, there is a critical traffic above which in electrification becomes economically justified. This critical traffic, usually expressed in gross tons, varies considerably with project circumstances. In a series of examples recorded in Table 8, which are by no means exhaustive, critical traffic varied between 4.7 and 22 million gross tons. The viability of any electrification proposal therefore

has to be determined by a case-specific feasibility study. The factors to be taken into account are discussed in the paper and summarized below.

viii. The paper contains an analysis which can be used for pre-feasibility studies, to determine whether a more thorough study is warranted. That analysis yields the following expression for the critical traffic, T:

$$T = \frac{C_F + M_F - \frac{W}{s}}{E + M_L - C_L}$$

where C_F and M_F are the present values (PVs) of the capital and maintenance costs of fixed installations; W is the PV of the cost saving due to increased capacity; E and M_L are the PVs of energy and locomotive maintenance savings, and C_L is the PV of the cost of the electric locomotive fleet less the PV of the diesel locomotive fleet which would be needed in the absence of electrification. These costs and benefits are derived from more basic parameters such as locomotive utilization and train weight.

ix. The critical traffic (in gross tons) is strongly dependent on the opportunity cost of capital, the cost of fixed installations, the cost of diesel fuel and the cost of electrical power. Arguments sometimes advanced for placing a special premium on the price of diesel fuel are reviewed in the paper and found unconvincing. The cost of electrical power is discussed in some detail, and it is emphasized that the long-run marginal cost should be used in feasibility studies, rather than actual tariffs which may be different.

x. Critical traffic is substantially lower in circumstances in which full use can be made of the greater power (as distinct from tractive effort) of

electric locomotives. It depends strongly on the cost of the locomotive fleet--and of the diesel fleet needed in the absence of electrification. The cost of electric locomotives can vary widely, depending on the number produced. Standardization of manufacture will keep it low.

xi. The data needed for feasibility studies of railway electrification are normally either available or can be derived using established methodologies. However, a systematic compilation of maintenance data for typical designs of electric and diesel locomotives could facilitate electrification decisions, especially in countries in which the cost of electrical power is relatively high so that maintenance savings account for a greater proportion of benefits.

INTRODUCTION

1. Two main questions arise in discussions about the significance of effects which increases in oil prices have on railway development. One is to what extent the railways have gained in comparative advantage, given the fact that their energy consumption is relatively low in relation to the volume of traffic carried. The other is how to decrease the railways' oil consumption and, in particular, whether railway electrification should be accelerated; the possibility of electrification is sometimes advanced as an additional argument for extending the railways' role. These questions are normally discussed in terms of energy used for operations only, which is derived from oil except for electrified railways which are not supplied from oil-fired electrical power stations. In addition, energy is used for the construction and maintenance of transport facilities (including vehicles), but relatively little is known of the quantities involved; energy used for these purposes can be largely independent of oil, depending in part on the source of

electrical power. Only energy used for operations will be considered in this paper.

2. Before discussing these issues in detail, two observations are necessary to place them into perspective. First, energy is not the only resource used by transport services. The overall efficiency of a transport mode depends on the costs of all resources it consumes to produce a given unit of output (ton-km or passenger-km) of a particular quality. There is no evidence that recent increases in oil prices have done more than improve the competitiveness of the railways at the margin. Furthermore, the substitution of coal for oil tends to increase railway traffic. Second, railways normally account for only a relatively small share of total national oil consumption. In 1980, for example, railway direct consumption^{1/} was less than 2% of total consumption of oil products for OECD as a whole and did not exceed 4% in any OECD country (Table 1). For the European members of OECD taken together, the percentage is substantially lower (0.5%) because much of their railway traffic is carried by electrical services; had all their traffic been moved by diesel engines, the estimated consumption of the railways concerned would still have been only about 2% of total national consumption, which is intermediate between the railways' share in the USA (1.8%) and in Canada (2.7%) where there is little railway electrification. For developing countries, data are not available as systematically as for OECD, but Table 1 contains some information for different years. It will be seen that the railways' consumption did not exceed 4% in Brazil, Mexico, India, and Zambia, but was exceptionally high in Kenya (11%) and Zimbabwe (10%). High railway consumption in Kenya was due primarily to the use of oil-burning steam locomotives, which are much less efficient than diesels.^{2/}

1/ Direct consumption excludes oil used for the generation of electrical power.

2/ Steam locomotives, still in use in Kenya in 1976 when these data were obtained (Table 1), have since been replaced by diesels.

3. This paper is in two parts. The first deals with the relative efficiencies of rail and road transport, and with possible decreases of railways' energy consumption. The second part deals with railway electrification.

PART I

ENERGY CONSUMPTION

Comparisons of energy consumptions of rail and road transport

4. Two basic physical phenomena favor railway transport. One is that rolling resistance between steel wheels and steel rails is less than between rubber tires and road surfaces. The second is that aerodynamic resistance is less for railway vehicles because they normally move in trains while road vehicles move singly. As a result, a railway vehicle requires less propulsive energy than a road vehicle of the same total weight; a recent comprehensive paper shows that, when travelling at the same speed on level ground, the ratio of energy consumption is at least 4 to 1 in favor of railways (1).^{3/}

5. Freight services. However, energy consumption in the performance of a particular transport operation is affected also by other factors, notably ratios of the actual load to vehicle tare (by weight) and of the distances which vehicles travel loaded and empty. French data (2) show that while the ratio of maximum possible load to the weight of the loaded vehicle is roughly the same (typically 62-69%) for railway cars and their main road competitors (large trucks), the weight-carrying potential of rail vehicles is used less effectively. Again, the proportion of vehicles making the return journey

^{3/} Figures in brackets indicate references given at the end of the text.

empty is greater for rail than for road transport, partly due to the greater flexibility of road services, which is enhanced by specialization of railway vehicles. More effective marketing efforts by road enterprises, and notably by their drivers in seeking return loads, also plays a part. Thus, in France, the utilization of available load capacity ranges from 36% to 48% for different railway freight services, while a study of long-distance road services using large trucks (19-38 tons) yielded utilizations of 77-83% (2).^{4/}

6. In addition to the energy used for line-haul movements, railways use energy for switching services; the amount involved has been estimated at about 5% of total consumption of freight transport for British railways (3), 7% for French railways (4), and 10% for U.S. railroads (5). Energy must also be expended in connection with rail transport for collection and delivery by road, and for load transfers between road and rail vehicles, when railway traffic does not move from siding to siding. Again, distances by rail tend to be longer than by road, typically by about 10%, because railway routes avoid steep inclines; however, the increase in distance may be compensated by the reduction in hill-climbing. An important characteristic, which applies to all transport modes, is that energy consumption depends on speed and increases with the number of stops.

7. Thus, the energy needed to render a given transport service is affected by several factors, whose net effect depends on commodity type, route and other service characteristics. Confusion has arisen in past discussions of energy savings because modes were compared in terms of energy consumption per ton-km or passenger-km, which masks the great differences in the mix of services they perform. This is illustrated by Polish data,

^{4/} Available capacity includes vehicles travelling empty.

summarized in Table 2, which show that per ton-km carried, the average consumption of all road services is 6 times the average consumption of all railway services, rising to 8-10 times if steam traction is excluded. However, road services include local collection and delivery, which railways do not provide. If comparison is restricted to diesel-engine highway trucks and to railways exclusive of steam traction, which fulfill more similar though of course not identical transport tasks, the ratio falls to between 3 and 4.

8. The impact of some of the main factors affecting energy consumption is illustrated in more detail by Table 3, which compares consumption of large trucks used for long-distance services with that of different railway services in France. In both cases energy efficiency increases with consignment size. Per ton-km transported, a 38-ton articulated truck consumes only two-thirds as much as a 19-ton truck, notwithstanding a decrease of average utilization of capacity, from 83% to 77%. Unit train traffic consumes about 40% as much as the largest truck (also per ton-km transported), and about two-thirds as much as other car-load traffic.

9. French data included in Table 3 also show that fast car-load services are about three times as energy intensive as unit train traffic, and rather more energy intensive than the largest trucks.^{5/} This is partly because fast car-load traffic includes commodities which occupy a relatively large volume

^{5/} With reference to these data, the International Union of Railways (UIC) has pointed out that the total consumption of trucks, when aggregated from consumption of individual truck types, accounts for only 70% of known total truck consumption: after allowing for this discrepancy, the UIC estimates that average consumption of trucks of over 17 tons is about 1.8 times the average consumption of fast freight services (6). This highlights the need for careful measurements when comparing energy consumptions (para. 10) while providing a further illustration of the dependence of the relative energy efficiency of the two modes on the equipment used.

in relation to their weight (e.g., road vehicles, agricultural machinery, fruit and vegetables) and partly to the need for faster movement which involves, inter alia, a lower utilization of capacity (35%) than the other services (42% and 48%). Average consumption for fast car load traffic masks large variations corresponding to individual commodities; thus consumption for the transport of road vehicles by rail is 2.4 times that average (1).

10. It is thus evident that conclusive comparisons of energy consumptions can only be made on a case-by-case basis for similar services performed by different modes. Relatively little has been published on such comparisons but a study sponsored by the U.S. Department of Energy (DOE) includes a comparison of energy consumed in the Chicago-Minneapolis corridor by articulated trucks travelling between terminals, and trailer-on-flat-car (TOFC) services (7). Table 4 shows that the consumption of rail services was half that of road transport, and computer simulations indicated that the energy used by TOFC services could have been decreased by about a third by increasing the weight of loaded trailers from 17.1 to 20.25 tons and eliminating the cartage of empty trailers.^{6/} The DOE study shows also that TOFC consumption can be reduced by advances in equipment, and it will be seen that substantial energy savings can be achieved by decreasing speed (para. 17); however, improvements can also be made in truck operations. Another comparison of road and piggy-back services, which included the energy expended in collection and delivery by road, estimated an advantage of only 1.3-1.45 to 1.0 for rail in France (8). These conclusions highlight the importance of careful specifications of the equipment used and of other service conditions.

^{6/} This presupposes a balanced flow of traffic in both directions-- for rail as well as for road.

11. Since energy efficiency increases with load, choices have to be made between energy consumption and consignment size. If economic decisions were dominated by the energy used for transport, or even by the total cost of moving goods and people without reference to quality of service, then one would find production concentrated into centers which supply large regional distribution centers. The large volumes of traffic flows could justify rail transport between production and distribution centers, with distribution from the latter by road; such a system is in use in Romania. For certain types of traffic it constitutes, in fact, a least-cost solution for the distribution chain. Thus, in North America, it is not uncommon for lumber, potash, and fertilizer to be carried over very long distances--perhaps 3000 km--in unit trains from Canada to the U.S. where distribution to the final user is largely by road. Where higher-valued goods are concerned, aggregation to fill a unit train--or even one railway car--would involve large inventories at both production and distribution centers, thus increasing distribution costs. However, relatively large inventories may in any case have to be built up as part of distribution chains. Thus, in France, large production enterprises and more recently distribution enterprises, have developed distribution chains involving a hierarchy of storage facilities, with regional storage centers which generate large flows of traffic (9). This type of development offers new opportunities for railways to make use of their energy and other advantages in handling large traffic volumes. It should be remembered, however, that even with high volumes of traffic the railways' energy efficiency--measured per ton-km--would be less for light-weight products such as cereals and furniture, than for the bulk commodities which make up much of the unit train traffic.

12. Passenger Services. Vehicle weight and utilization of capacity again play a key role in the energy consumed per passenger-km. French urban data (Table 5) show that there is little to choose between trains and buses, but both are substantially more efficient than private automobiles and taxis. It is noteworthy that if automobiles were used for public transport, and their average occupancy increased to 4 passengers (from 1.3 in the French study) their range of energy consumptions would be almost the same as for other public transport. Buses have a slight edge over trains, mainly because it is easier to change bus frequency than train composition as transport demand varies, and the vehicle weight per seat is lower for buses. Polish country-wide data show an even greater advantage for buses, with energy consumption per passenger-km nearly 30% less than for trains (excluding steam traction, Table 2). However, as intercity trains can be faster and more comfortable than buses, they could be more effective in attracting certain passengers from automobiles and airplanes, which are more energy intensive.^{7/} Although high-speed trains are more energy intensive than conventional trains, they are substantially more efficient than private automobiles or air transport. By way of example, a recent study by the International Union of Railways (10) quotes the following energy consumptions per passenger-km: 16 grams equivalent of petrol (gep) for a 260 km/hr train (with 66% seat occupancy), 12 gep for a conventional train (46% occupancy), 28 gep for automobiles (averaging about 2 passengers each), and 60 gep for airplanes (65% occupancy).

^{7/} Of course, passengers' choice between buses and trains depends on price as well as on quality of service, and on passengers' income. Thus, in the U.K. much long-distance bus travel is by retired or poorer people, who place a relatively low value on their time.

Energy as a proportion of railway expenses

13. Since railways generally account for a small proportion of national oil consumption, any energy savings which they achieve are unlikely to have a major impact at the national level, though they could be important for the railways themselves. Railway energy expenditures, expressed as a percentage of total working expenses 8/, can vary considerably, from 20-29% in India, Korea, Thailand, and Pakistan, to below 5% in Mexico and France (Table 6). Part of the explanation of these differences is to be found in the price of diesel fuel; in Pakistan, the price paid by the railway has exceeded since 1980 the import price, thus contributing to the relatively high percentage. In Mexico, on the other hand, diesel fuel was only about \$0.06 per litre in 1979-81 (and the railways, as bulk buyers, may have paid slightly less), while its f.o.b. cost in the Caribbean market (Curacao) ranged between about \$0.13 and \$0.25 (11). Diesel fuel should not be priced below cost if railways--and, indeed, all users--are to be encouraged to use it efficiently.

14. Energy consumption depends on railway characteristics. It is greater in mountainous regions, and if trains are operated at high speeds. Much depends on the type of traction: steam locomotives are relatively inefficient, and their continued use is contributing to the relatively high energy expenditures in Pakistan and India. Replacement of steam by diesel traction normally improves railway operations substantially, quite apart from decreasing energy costs, but necessitates considerable investments. Railway electrification is a further improvement, but is even more capital intensive, as explained in Part II.

8/ Working expenses are total railway operational expenses excluding depreciation and interest payments.

15. Of course, the percentage of total costs which is accounted for by energy depends also on the prices of non-energy resources, and on the efficiency with which those resources are used. Thus, on the iron ore line between Minas Gerais and Port of Sepetida in Brazil--an inherently efficient operation--energy accounted for 49% of working costs in 1980. Under such circumstances, energy savings are clearly very important. But where energy accounts for a small percentage of total costs, reductions in non-energy costs have greater priority.

Reduction of Railway Energy Consumption

16. However, certain energy savings may be relatively easy to achieve. Typically, 85% of the railways' energy consumption is for traction and depends significantly on driving techniques. It may be useful to consider driver training as a first step for decreasing energy consumption, especially where consumption exceeds 6 litres of diesel fuel per 1000 gross ton-km of freight traffic--although consumption could exceed this rate in difficult terrain, even with good driving. French railways have developed a computer program, which calculates speed-distance diagrams for minimizing energy consumption (12). Tests have shown that when using these diagrams, drivers obtained energy savings of 6-15% for passenger trains and 4-10% for freight trains, while complying with existing timetables. However, trains cannot always be driven so as to optimize energy consumption: if a timetable disturbance occurs, it is usually more important to minimize delays, and speed variations may also be constrained by track capacity. System-wide savings can therefore be well below the percentages quoted above, but even so application of the energy optimization program--where and when possible--is likely to be very cost effective (4). In the French system, the speed-distance diagram is produced by a central computer, off-line. German railways are studying the use of an on-board micro-computer, which is expected to reduce consumption by 15-20%, rising to 25% in some cases (13).

17. Energy savings may be achieved by improving train operations, notably by reducing the number of stops and decreasing train speeds. A series of tests by Canadian National illustrates the energy savings achieved by increasing the train weight-to-power ratio, which results in lower average speeds (Fig. 1); thus a 30% decrease in the consumption of diesel fuel, from 1.4 to 1.0 imperial gallons (6.3 to 4.5 litres) per 1000 gross ton-km, is associated with a 12% decrease in running speed from 51 to 45 miles/hr (82 to 72 km/hr) (14). Speed reductions of this magnitude can often be tolerated, though care is needed not to weaken the railways' competitive position for passenger and certain freight services, and a limit may be set by track capacity.

18. North American experience shows that grouping cars to reduce wind resistance (especially with piggy-back trains) can reduce fuel consumption by as much as 10% on a given run (15). Improved marshalling strategies, including greater use of unit trains, which are normally introduced in order to improve the overall efficiency of railway operations, should also decrease energy consumption. Significant savings may be achieved by switching off diesel locomotives instead of allowing them to idle (though auxiliary heating facilities may be needed for locomotives operating in very cold climates), and by tightening security of oil storage and improving the operation of fuel handling equipment, for example the automatic cut-off equipment.

19. There appears to be considerable scope for energy savings through improvements in the design of locomotive and rolling stock. Thus, a workshop held in 1979 by the U.S. Department of Transportation concluded that energy consumption could be reduced by about 40% by improvements including locomotive waste heat recovery and better power management, tare weight reduction (facilitated, for locomotives, by improved slip control), and streamlining (Table 7) (16). However, these improvements can only be brought about relatively slowly, as the fleet is renewed, and involve considerable investments. Furthermore, for developing countries, such improvements have

to be weighed against greater complexity of maintenance, which may result from more sophisticated designs or a greater variety of equipment. For many railways, the most critical traction issue is locomotive availability which, in some cases, has been insufficient to carry the traffic on offer. The emphasis has therefore been, and should continue to be, on reliability, taking into account environmental conditions and maintenance facilities. Any equipment features which decrease consumption at the cost of increased sophistication of maintenance procedures may well be self-defeating if the railway lacks the staff or facilities needed for adequate maintenance.

Conclusion

20. Most data on energy consumption by different modes are averages covering a wide range of services, and cannot be used to determine the ratios of energy efficiencies of different modes when rendering similar services. To determine those ratios, it is necessary to carry out more tests under controlled conditions, such as that undertaken by the U.S. DOE for piggy-back and highway transport. It should be remembered, however, that energy is only one of the components of transport costs, and to determine the overall cost-effectiveness of different modes it is necessary to establish the values of all components of cost and benefits--notably labor costs. Such comprehensive knowledge of costs is needed to help railways develop those services for which they are more effective than other modes.

21. Some conclusions can nevertheless be drawn from existing data. For freight, railways use energy most efficiently (in terms of ton-km per gep), when carrying typical railway traffic--large volumes of bulk commodities. Transfer of such traffic to road services would increase energy consumption substantially. However, transfer of road traffic to rail need not decrease energy consumption significantly, especially if the largest available road units are to be displaced. Nevertheless, railways have an energy advantage in many cases, which increases their competitiveness at the margin.

22. For passenger traffic, railways are not normally more energy efficient than buses. It may be easier to attract private motorists to intercity railways than to buses, thus reducing energy used for transport, because railways can be developed to provide a higher quality of service than buses. Such developments, normally involving high speeds and frequent services, are quite costly in infrastructure and vehicles. Their economic viability depends largely on the demand which exists for them, itself depending largely on the quality of service; as they are used primarily by relatively high-income groups, it is difficult to justify subsidizing them. Of course, their economic viability depends also on operating costs, and energy efficiency helps.

23. An important contribution to increasing the railways' energy efficiency, for both freight and passenger services, would be a better utilization of capacity--which would also improve the productivity of staff and equipment, and reduce railway costs all round. Again, lightly loaded railway services, such as might circulate on uneconomic lines, may well use energy less efficiently than road services, whose capacity is more easily adapted to demand.

24. Substantial improvements in the railways' energy efficiency appear possible by improved driving techniques, and by changes in the design of traction and rolling stock. As regards the former, driver training and computer-assisted driving could have substantial impacts. As regards the latter, care is needed to ensure that design changes are consistent with maintenance facilities--reliability remains the highest priority for traction and rolling stock. In any event, fuel prices should be made to reflect costs, to ensure that railways get correct signals in determining the priority they should assign to reducing energy consumption in relation to other reductions in railway costs.

PART II

RAILWAY ELECTRIFICATION

25. The increase in oil prices has rendered railway electrification more attractive because of its potential for reducing energy costs. The extent of this reduction depends, of course, on the cost of electrical power and the future evolution of oil and electricity prices. Electrification brings also other benefits, the most important of which is, usually, a decrease in locomotive maintenance costs. There is normally an increase in train speeds, which can bring capacity and productivity gains. However, electrification necessitates large investments in fixed installations. As a minimum, these consist of the overhead conductor system and electrical power substations. There may be substantial additional expenditures, for example, for protecting existing structures and signalling and telecommunications facilities from the high-voltage traction system. Finally, investments are usually needed in electric locomotives, but their purchase generally obviates purchases of diesel locomotives which would be needed without electrification.

26. Investments in fixed installations are substantially independent of traffic, while investments in locomotives and all benefits increase with traffic; as a result there is, for any railway line, a critical traffic level above which electrification becomes economically viable. This traffic is normally expressed in gross ton-km per route-km, or more simply in gross tons, since gross tons are more directly related to costs and benefits than net tons or passengers carried (10).^{9/} It can vary widely for different lines, so that the viability of an electrification proposal has to be determined by a line-specific feasibility study, which is usually quite complex because of the many factors to be considered. The costs and benefits which have to be taken into account are discussed below, and will be illustrated by typical data, at early 1982 prices except where otherwise stated.

^{9/} Possible decreases of vehicle tare may have to be taken into account when preparing forecasts of traffic in gross ton-km, especially if traction and rolling stock are being modernized.

Estimate of critical traffic

27. Before deciding to embark on a fully-fledged feasibility study, it is desirable to estimate by a relatively simple analysis whether the combination of costs and benefits applicable to a specific line warrant a more rigorous analysis. Such a pre-feasibility analysis will now be presented, and will be used in the sections which follow to illustrate the sensitivity of the critical traffic to various changes in costs and benefits. The benefits of electrification will be taken as the avoided costs of diesel traction. Traffic will be assumed to be the same in both cases, increasing at 3% per annum; other rates of increase can readily be introduced into the analysis, including different rates for various periods of the project's life. The critical traffic is that level of traffic carried during the first year of the project for which the present value (PV) of total costs with electric traction equals the corresponding PV with diesel traction. The investment and maintenance costs of fixed installations will be taken as proportional to route length, while investments in locomotives and the costs of locomotive maintenance and energy will be taken as proportional to traffic, in gross ton-km. The following symbols will be used:

- r = Discount rate = Rate of return corresponding to traffic T.
- T = Critical traffic, gross tons.
- s = Route length, km.
- C_F = PV of capital cost of fixed installations, per route-km.
- C_L = PV of net locomotive investments (cost of electric fleet less cost of diesel fleet), per gross ton-km moved in the first year of the project.
- M_F = PV of maintenance cost of fixed installations, per route-km.
- E = PV of locomotive maintenance savings per gross ton-km moved the first year of the project.
- M_L = PV of locomotive maintenance savings per gross ton-km moved in the first year of the project.

W = PV of works needed to increase capacity without electrification,
less PV of similar works needed with electrification.

28. In accordance with these definitions, the present values (PVs) of the capital and maintenance costs of fixed installations are C_{Fs} and M_{Fs} , respectively. The present values (PVs) of locomotive investments, energy savings and locomotive maintenance savings are C_{LTs} , ETs and M_{LTs} , respectively. The present value (PV) of the benefit due to capacity increases is W . Depending on project conditions, certain other costs and benefits may be significant, though they are likely to be much smaller than those given above. For example, if train speeds are substantially greater with electric than with diesel traction, there could be significant staff savings (para 71). Again, continued operation with diesel traction may necessitate expansion of workshop capacities. In any event, it should be possible to express such additional costs and benefits in proportion to traffic (like ETs) or as lump sums (like W), so that they could readily be introduced into the analysis. For the cases considered in this paper, however, these additional costs and benefits will be assumed to be negligible.

29. The critical traffic, T , yielding a rate of return, r , is obtained from the requirement that the PVs of costs and benefits are equal, that is,

$$\begin{aligned} & (\text{PV of capital cost of fixed installations, } C_{Fs}) \\ & + (\text{PV of net locomotive investments, } C_{LTs}) \\ & + (\text{PV of maintenance cost of fixed installations, } M_{Fs}) \\ & = (\text{PV of energy cost savings, } ETs) \\ & + (\text{PV of locomotive maintenance cost savings } M_{LTs}) \\ & + (\text{difference between PVs of works needed to increase capacity without} \\ & \quad \text{and with electrification, } W) \end{aligned}$$

or, using symbols only

$$C_F s + C_L Ts + M_F s = ETs + M_L Ts + W \quad (1)$$

Dividing by s and separating those terms which exclude T from those which include it

$$C_F + M_F - \frac{W}{s} = ET + M_L T - C_L T = T [E + M_L - C_L] \quad (2)$$

whence
$$T = \frac{C_F + M_F - \frac{W}{s}}{E + M_L - C_L} \quad (3)$$

It is shown in Annex 1 how to derive the terms used in equation (3) from more basic parameters, such as the number of locomotives needed with and without electrification (and the impact thereon of locomotive availability and utilization, and of the average trailing load per locomotive); the capital and maintenance costs of individual locomotives; the cost of diesel fuel and its likely evolution; the cost of electrical power and its evolution; the rate of increase of traffic, and the rate of return. These parameters may vary within wide ranges, and as there are numerous possible combinations of parameter values, numerical examples given below are illustrative rather than exhaustive. However, for any specified set of values, the formula can be used for a rapid estimate of the critical traffic.

30. Numerical illustrations are for a single track line. It has been assumed that 0.5 net ton-km or 1 passenger-km generate 1 gross ton-km, and traffic increases at the rate of 3% per annum. As the price of diesel fuel changes in time, it is necessary to specify the first year of the project, which has been taken as 1985. For simplicity, it has been assumed that all works on fixed installations are completed that year; of course, they could have been spread over several years and discounted accordingly. Project life has been taken as 25 years, the discount rate has been taken as 12% except where otherwise stated, and residual values have been ignored. In most cases electrification became justified at traffic levels which can be accommodated

on single track (para. 72) and therefore the benefit, W, due to increased track capacity was ignored.

The Base Case

31. Table 8 presents illustrative computations of critical traffic levels corresponding to different values for the main determinants. The starting point in this table, itself illustrative, is called the base case. This refers to a mainly-freight railway, carrying on its business in the proportion of 3 net ton-km for every passenger-km, with locomotive-pulled trains on easy terrain and with passenger trains travelling at no more than 140 km/hr. In addition, the base case is made up of values selected for major cost items which are considered in detail in the following sections, together with plausible variations in those values.

32. At the values selected, and with the characteristics assumed, the critical traffic level for the base case is 13.7 million gross tons. We can immediately show the variation in the critical traffic level as the discount rate is varied (all other features of the base case kept intact):

<u>Base case, varying discount rate</u>				
Discount rate	10%	12%	15%	18%
Critical traffic (million gross tons)	11.3	13.7	17.3	21.5

Over this range of discount rates, therefore, the critical traffic level is proportional to the discount rate, as illustrated by Fig. 2.

Cost items: Fixed installations

33. For the base case, the cost of fixed installations, C_F , was taken as \$180,000 per single-track route-km (STRK). In addition, two further values were selected for illustration, one corresponding to a project necessitating only the minimum electrification works (para. 34) and the other to a project involving substantial additional works (paras. 35-37):

<u>Per STRK</u>	<u>Critical traffic level</u>
Projects involving no additional works: \$130,000	9.9 mm gross tons
Base case: \$180,000	13.7 mm gross tons
Projects involving substantial additional works: \$230,000	17.5 mm gross tons

For costs varying in this way, the critical traffic level changes almost in the ratio of 2 to 1. In fact, it follows from equation 3 (para 29) that with $W = 0$, and the maintenance cost of fixed installations proportional to their capital cost, the critical traffic is proportional to the cost of fixed installations.

34. All main-line electrification projects include the installation of an overhead conductor system along the track and of railway power supplies; the latter include substations, track sectioning posts and remote control facilities. Different voltages and frequencies have been used in the past, but railways are now standardizing on 25 kV and power frequency (50 or 60 c/s), on which this discussion will be based. Similar costs and benefits apply to 50 kV systems, which have been developed in the U.S. and South Africa.

35. Table 9 shows average costs and cost ranges for investments in fixed installations, based on a survey of recently completed electrification projects in several European countries, Japan and Zimbabwe. Some of these projects were on double track and others on single track lines; costs per double-track route-km were divided by 1.8 to yield equivalent single-track values. For the minimum electrification works -- the overhead conductor system and railway power supplies -- the costs in different countries

averaged \$129,000 per single-track route-km (STRK), within a range of \$106,000 to \$148,000. Additional works are usually necessary. Waterproofing of tunnels may have to be improved, and the track may have to be lowered in tunnels and under bridges to increase clearances. High-voltage power lines may have to be constructed to connect the railway substations to the main electrical power system. Telecommunication lines not belonging to the railway but situated in its vicinity may have to be protected. Maintenance facilities may have to be constructed or extended. There can thus be considerable variation in the total cost of additional works, depending on project circumstances; for the projects reviewed, they varied between \$4,000 and \$146,000 per STRK. These considerations led to the selection of three values for fixed installations which were used above and in Table 8.

36. Nothing has been said so far about the protection of railway signalling and telecommunications (S & T) facilities from interference from the electric traction system. The costs involved are very project dependent. If the railway is equipped with S & T facilities which are fully satisfactory for diesel traction, then replacement of components which are not compatible with electrification, which can be very costly, has to be debited to electrification. In many developing countries, however, S & T facilities have to be modernized, so that the necessary investment can be justified separately by the benefits it generates. Even so, the equipment needed to generate those benefits is usually more costly with electric traction (perhaps by 15% to 20%) and the difference between S & T costs corresponding to the two types of traction should be debited to electrification, not to S & T. An important question is whether overhead conductors rather than underground cables would be adequate for diesel traction. Strictly speaking, the values of C_F used above do not include an

allowance for S & T, and correspond therefore to a line which has already been fitted with electrification-compatible S & T — perhaps because when S & T was modernized it was expected that the line would be electrified sooner or later. However, apart from the lowest value of C_F (\$130,000 per STRK, corresponding to the cost of the overhead traction system and railway power supplies alone), the values of C_F include an allowance for additional works whose nature has not been specified, and could be taken to include the S & T costs which have to be debited to electrification if S & T is modernized at the time of electrification. Alternatively, estimates of critical traffic could be made with higher values of C_F ; this would almost certainly have to be done if existing S & T is satisfactory for diesel traction but major parts have to be replaced for electrification.

37. Railway substations normally draw power from only one of the three phases of the electrical power system. As the railway usually constitutes a small fraction (2-3%) of the load on the power system, the resulting system imbalance can usually be tolerated. If, however, the railway load accounts for a significant portion of the regional electrical power demand, say 10%, as could happen if the railway traversed an unpopulated region, special transformers may have to be used to reduce the imbalance. Again, the power control techniques used in electric locomotives may distort the current, and filters may have to be introduced. The cost of these special equipments was not allowed for above.

Maintenance of fixed installations

38. Annual expenditures for the maintenance of fixed installations are, typically, 1% of their capital cost. This will be used for this analysis, and as shown in Annex 1 (equation A1), the PV of the maintenance cost of fixed installations, at 12% discount, is

$$M_F = 0.079 C_F \quad (4)$$

The critical traffic is not sensitive to changes in the value of M_F , which is small in relation to other costs and benefits. For this reason alternative values of M_F have not been used, except that whenever the value of C_F was changed, M_F was changed in proportion.

Locomotive investments

39. The net investment in locomotives per gross ton-km, C_L , is the difference between the capital cost of the electric locomotive fleet, and of the diesel locomotive fleet which would be needed without electrification. As shown in Annex 1 (equation A7), with a 12% discount rate,

$$C_L = 8.31(P_{LE} - \frac{P_{LD}}{z}) \times 10^{-9} \quad (5)$$

where P_{LE} and P_{LD} are the CIF prices of an electric and of a diesel locomotive, and z is the ratio of the number of electric to diesel locomotives that would be needed for handling a given volume of traffic. The table below compares the base case, for which there is little difference between the costs of diesel and electric fleets, with cases which are particularly favorable and unfavorable for electrification.

	z	P_{LE}	P_{LD}	C_L	T
		--\$ million--		\$/1000GTkm	million tons
Base case	0.79	1.7	1.3	0.5	13.7
favorable	0.6	1.3	1.43	-9.0	8.2
unfavorable	0.79	2.2	1.18	5.9	22.0

Thus the critical traffic in the unfavorable case is nearly 3 times that in the favorable case. This illustrates the large impact which locomotive fleet costs have on the viability of electrification.

Factors affecting the ratio of electric to diesel locomotives

40. A diesel locomotive contains a mobile power station--a diesel engine and generator or alternator--which transforms the energy available in diesel fuel into electrical power. Electric locomotives draw electrical power from the overhead conductor. The advantages of electrification stem from this difference. Locomotives are usually designed so that their weight corresponds to the maximum permissible axle load on the track. For a given permissible axle load, weight can be increased by using more axles, but this increases locomotive cost; normally diesels and electric locomotives are the same weight if intended for the same type of operation. A substantial proportion of the weight of the diesel locomotive is taken up by the diesel engine and fuel reservoir; as a result, electric locomotives can normally deliver more power--say 5000 kW, compared to 2500 kW. Furthermore, electrical equipment can furnish a substantial overload, which a diesel engine cannot. An even greater power differential therefore exists over short periods, and this can enable electrics to maintain a higher speed on inclines, or to accelerate faster. However, the maximum pull (termed "tractive effort," in tons) a locomotive can exert is limited by wheelslip and hence by locomotive weight, which has been seen to be the same for diesels and for electrics. Increased power capacity is therefore reflected in higher speed (power being proportional to the product of speed and pull). This can be particularly useful for passenger trains, which can accelerate faster and travel at higher speeds with electric traction; if there are steep inclines, freight trains will also be able to maintain higher speeds. Track capacity increases with speed, but the speed differential between diesels and electrics can be decreased by using more diesel locomotives, including pushers on inclines. It should be remembered, however, that fuel consumption increases with speed (para. 17). As a result of higher speed, and also because they need not be refuelled, electric locomotives average more

km/day. For the base case the railway has been taken to operate in easy terrain, not exceeding about 140 km/hr, with no commuter services involving frequent stopping and starting. Under these circumstances, the additional power of electric locomotives has relatively little effect and it was assumed that electrification would result only in locomotive-km per day being 15% greater for electrics than for diesels, with trains of equal weight.^{10/} Under conditions in which the maximum available power is critical, this utilization advantage can be greater and the average train weight per locomotive can be greater with electric traction, as discussed in para. 70 in connection with operations in difficult terrain.

41. The diesel engine is more complex than electrical traction equipment and requires substantially more maintenance. As a result, diesel locomotives are out of service for longer periods. In industrialized countries, typical availabilities may be 85% for diesels and 95% for electrics. However, in many developing countries availability of diesels is much less, because of lack of trained manpower, inadequate maintenance facilities, shortage of foreign exchange needed for spare parts, and/or complications resulting from long delivery periods for spare parts. Considerable efforts, in which the World Bank is participating, are being made to resolve these problems, but for several years some countries, especially in Africa, may be unable to achieve and maintain availabilities of more than, say, 65-70% for diesel locomotives. Problems sometimes arise with electrics but these are normally due to design weaknesses in a specific group of locomotives, and are not inherent to electric locomotives.

^{10/} It would be worth considering the use of electric locomotives whose power rating is below the maximum possible for their weight. However, this is unlikely to decrease their cost by more than about 20%, as cost is not very sensitive to power rating. A more important consideration is standardization of manufacture (para. 44) so that a greater advantage could ensue from choosing a rating which facilitates larger scale production. Standardization with the existing locomotive fleet may also be desirable, to facilitate railway operations.

42. In feasibility studies, the numbers of electric and of diesel locomotives should be determined from analyses of traffic, train consists and timetables, locomotive schedules, and realistic estimates of availabilities. For this analysis locomotive numbers, and hence the net locomotive investment, were estimated from average train weights, locomotive-km per day and locomotive availability. For the base case, with electric traction, train weights were taken as 1200 and 600 trailing tons, for freight and passenger services, respectively, with corresponding locomotive utilization of 400 and 600 km/day, and 95% availability. Electric traction was taken to yield 15% more locomotive-km per day and 10% greater availability than diesels, with the same trailing load. Hence, the ratio of the number of electric to diesel locomotives that would be required for handling a given volume of traffic is $z = 0.79$. As shown in para. 39 and Table 8, calculations have been made also with $z = 0.6$, corresponding to 65% availability of diesel locomotives (para. 41) or to difficult terrain (para. 70).

43. Capital cost of locomotives

If, notwithstanding the implementation of an electrification project, the railway continues to purchase diesel locomotives, then electrification avoids the purchase of diesel locomotives which would have been needed to carry the traffic on the line being electrified. Avoided purchase of these locomotives will be taken as a benefit of electrification for this analysis.^{11/} Of course, if electrification resulted in a surplus of diesels, this benefit could be substantially smaller.

^{11/} As locomotives are not normally allocated to a specific line, this statement may require explanation. Consider a railway which is considering electrification of one of its lines. Assume that: (i) if that line were not electrified, the railway would purchase 100 diesel locomotives and 20 electric locomotives in 1985; (ii) if the line were electrified, it would need 10 more electric locomotives; and (iii) the traffic on the line considered for electrification would necessitate 12 diesels if the line were not electrified. Hence, if the line were electrified, the railway would purchase 30 electric locomotives and 88 diesels in 1985. Purchase of 10 more electric locomotives (30 instead of 20) is one of the costs of the new electrification scheme. Avoided purchase of 12 diesels (88 instead of 100) is one of its benefits.

44. Because of their greater complexity, diesel locomotives could be expected to be more expensive than electrics. However, the cost of each type can vary considerably, depending on the number built to a given specification and on the extent to which locomotives built to different specifications can use common components. Because of their relatively large market for diesel locomotives, U.S. manufacturers have produced them at relatively low costs, typically, \$1.3 million for a 3300 HP locomotive. The price of an electric locomotive of the same weight rated at about 4500-5000 kW, could range between \$1.3 million and \$2.5 million, depending on how many of the same type are produced. When planning an electrification scheme, therefore, a substantial cost advantage could result from the use of an existing type of locomotive, rather than of a new design. The advantages of standardization of manufacture have led Romania and Yugoslavia to specialize, the former on the production of six axle electric locomotives and the latter on four axle units, for use in both countries.

45. For the base case, the unit prices of diesel and electric locomotives have been taken as \$1.3 million and \$1.7 million, respectively. The impact of price variations was tested by using also electric locomotive prices of \$1.3 million and \$2.2 million. Furthermore, as the ratios of these prices could be affected by exchange rate fluctuations, which are difficult to predict, tests have been made with ± 10% variations in the cost of diesel units. Results have been given in para. 39 and Table 8.

Energy cost savings: energy consumption

46. For the base case, energy consumption per 1000 gross ton-km of trailing load has been taken as 6 liters with diesel traction and 23 kWh with electric traction. In addition, variations of ± 10% in the ratio of energy consumptions, and 10% and 20% reductions in the consumptions of both types of traction, were selected for illustrating operations in easy terrain.

Diesel fuel liters	Electrical Energy kWh	Critical traffic million gross tons	%
6	23	13.7	100
6	20.7	12.7	93
5.4	23	15.9	116
5.4	20.7	14.5	106
4.8	18.4	15.5	113

Thus, critical traffic is quite sensitive to the changes of energy consumptions, and in particular to changes in diesel consumption alone.

47. The efficiency of energy conversion is substantially the same for electric traction powered by oil-fired generating stations, and for diesel traction. Typically, an oil-fired power station consumes 241 grams equivalent of petrol (gep) to provide 1 kWh (2). On that basis, 1 liter of diesel fuel, which contains 830 gep, is equivalent to 3.4 kWh. Consequently, if the efficiency of energy conversion was exactly the same for the two types of traction, and if they performed exactly the same services, then the ratio of their consumptions would be 3.4 kWh per liter. A review of feasibility studies undertaken on four World Bank projects and on a French project (16) and of South African data (17) showed that the ratio of electrical energy (in kWh) to the quantity of diesel fuel (in liters) needed to carry a given traffic (in gross ton-km) ranged from 3.1 to 4.7 kWh/liter, with a mid-point of 3.9 kWh/liter. Since this exceeds 3.4 kWh/liter, it indicates more efficient use of energy by diesel than by electric traction. Undue precision should not be ascribed to the oil consumption used above for producing electrical energy (241 gep/kWh), but greater consumption by electric traction is consistent with the higher speeds of electric services. The ratio of 3.9 kWh/liter has therefore been used for the base case. As shown in para. 46, a 10% increase in this ratio due to smaller consumption of diesel fuel increases the critical traffic by 16%.

48. It has been explained (para. 40) that if the critical locomotive characteristic is its power output rather than the pull it can exert, the trailing load per locomotive may be smaller with diesel than with electric traction; the portion of the locomotive output used to move the trailing load is then a smaller proportion of the output of the diesel than of the electric locomotive (the weight of the locomotive being a greater proportion of the total train weight in the case of diesel traction). The resulting reduction in the energy efficiency of diesel traction is normally relatively small with locomotive-pulled trains, and especially for freight traffic having a high ratio of trailing tons to locomotive weight. However, a British study has shown that with certain multiple units, the greater weight of diesels increased their energy consumption by 22% (17).

49. Statistical data sometimes show substantially lower energy consumption for electric than for diesel traction. There are two reasons for this, which are usually more important than that given in the preceding paragraph. First, those comparisons are often made for different types of services; electric traction is normally introduced on the busiest services, for which energy can be used more efficiently. Second, the efficiency of energy conversion is greater for hydro-electric than for thermal power stations, because the former do not suffer the losses associated with a thermal engine. Hence electric traction can be more efficient, but this advantage results from the use of a different energy source--a waterfall instead of oil.

50. There can be considerable variation in energy consumption by different services, depending on line gradients, speeds and numbers of stops. Feasibility studies should therefore use energy consumptions derived from train-performance calculations made for the different services using the line considered for electrification, taking into account energy consumed in

shunting operations and with realistic assumptions about driving practices. However, for a prefeasibility analysis, average consumptions may be used, based on the diesel fuel consumption on the line proposed for electrification. In easy terrain with predominantly freight traffic, this may be about 5-6 liters per 1000 gross ton km. The estimate of electrical power consumption would be less accurate than that of diesel fuel consumption from which electrical power consumption would be derived. However, the examples given in para. 46 have shown that inaccuracies in electrical power consumption are generally less critical than in diesel fuel consumption; a 10% reduction in electrical power consumption alone reduced the critical traffic by only 7%, while a 10% reduction in diesel fuel consumption alone increased the critical traffic by 16%. Decreasing diesel fuel consumption has a substantial impact on the critical traffic even when accompanied by a decrease in electrical power consumption--a 20% decrease in both consumptions reduces critical traffic by 13%. When diesel consumption is high, it is therefore worth checking whether it could be reduced, especially by improved maintenance and operations.

Cost of diesel fuel

51. Two scenarios were used for the cost of diesel fuel, inclusive of storage and distribution within the railway, as shown below.

1985 Cost \$/liter	Annual increase in real terms		Critical traffic, T million gross tons
	1985-1995	After 1995	
0.26	3%	2%	13.7
0.26	1%	1%	17.3

Thus, for the lower rate of increase of diesel prices, the critical traffic is 26% greater.

52. During 1982, the average price of diesel fuel, f.o.b. Rotterdam, Curacao, Bahrain and Singapore, was about \$0.25 per liter. Its evolution will depend on the price of crude and on the demand for diesel fuel in relation to other petroleum products. The price of crude has been declining since 1981, but is expected to stabilize and increase in real terms after 1985. There are obvious difficulties in predicting the rate of increase, but a possible scenario, at 1982 prices 12/, would be

Year	1983	1985	1990	1995
price per barrel	\$28	\$27	\$31	\$37

Between 1985 (the first year of the project) and 1995, this cost evolution can be approximated by an annual increase of about 3%. By 1995 many synfuel technologies could be expected to be demonstrated in industrial-size plants, thereby creating a notional backstop to the price of petroleum, and this would argue for a slower rate of increase, say 2% per annum. These rates of increase--3% per annum during 1985-1995 and 2% per annum subsequently--have been used for the base case. A substantially lower rate of increase, 1% per annum after 1985, has also been used to test the impact of the rate of increase of oil prices.

53. Recent developments, such as increased efficiency of automobiles and substitution of coal and of other energy sources for fuel oil in the production of electric power, have reduced demand pressures for higher distillates and fuel oil, but demand has remained high for middle distillates. This has resulted in a high return on investments needed for

12/ The difference between early 1982 (used for other data) and 1982 prices is estimated at less than 1% and will be ignored.

further refining of fuel oil to produce more diesel fuel, and consequently large new conversion capacities have already come on stream in both the U.S. and Western Europe, and more are being constructed around the world, notably in the new export refineries of the Persian Gulf region. As a result, the ratio of price of diesel fuel to crude, which was 1.27 in 1982 (averaged for Rotterdam, Curacao, Bahrain and Singapore), can be expected to decline slightly to about 1.25 in 1985 and 1990, and 1.22 in 1995. Consequently, for the base case, the f.o.b. price of diesel fuel per liter could be expected to average \$0.21 in 1985, \$0.24 in 1990 and \$0.28 in 1995. This price evolution can be approximated by an annual increase of 3% (in real terms). Thus, the price of diesel fuel is forecast to increase at virtually the same rate as the price of crude between 1985 and 1995, and it has been assumed that it would continue to do so after 1995. An alternative scenario was also considered, based on an increase of only 1% per annum in the price of crude. The cost of diesel fuel to the railway has been calculated by increasing the f.o.b. price by 6%, to allow for insurance and freight, and by a further 15%, to allow for storage and distribution within the railway, yielding a 1985 cost of \$0.26 per liter. These considerations led to the choice of diesel fuel price and rates of increase given in para. 51.

54. If it is sometimes argued that even if electrification is not fully justified economically, it should nevertheless be undertaken because it decreases oil consumption. However, it was seen earlier that railways normally account for only a small fraction of national consumption so that the reduction achieved by a major railway electrification scheme is likely to be relatively small--a fraction of 1% in more industrialized countries like Brazil or Yugoslavia, a few percent in some African countries. Major electrification schemes are expensive--of the order of \$100 million--so that more cost-effective means should be available for decreasing oil consumption.

A further argument is that electrification would safeguard railway services in the event of a disruption of oil supplies; this presupposes that electrical power generation is not oil-based. Much more comprehensive measures than railway electrification would be needed in the event of a persistent disruption of supplies. Admittedly, if no preparation for such a disruption was made, railway operations in its immediate aftermath would be facilitated by electrification. However, a more effective measure than electrification could be to constitute an adequate reserve of diesel fuel, equivalent perhaps to several months' consumption, and the cost of such a reserve could be included in an analysis of the economic viability of electrification. If the cost of a 6 months' fuel reserve were taken into account, the base-case critical traffic would decrease from 13.7 million gross tons without a fuel reserve for diesel traction, to 12.8 million tons with a fuel reserve--a reduction of 7% (Annex 1, paras. 15-16).

55. Oil products have to be paid for with foreign exchange, while electrical power is produced from domestic resources. It is sometimes argued that a premium should be placed on the price of oil, because foreign exchange savings are more valuable than expenditures in local currency. This argument is valid only if local currency is overvalued, so that the rate of exchange does not reflect its true value. In that case, a premium has to be placed on foreign exchange, by using a shadow exchange rate for all imports and exports, including equipments and materials which have to be imported for railway electrification and for producing electrical power.^{13/}

^{13/} Both direct and indirect expenditures of foreign exchange have to be taken into account. Thus, if transformers are manufactured locally using imported copper, the cost of copper has to be treated as a foreign exchange expenditure.

Cost of electrical power

56. For the base case, the cost of electrical power was taken as \$0.05 per kWh, with no increase in real terms over the life of the project. To illustrate the effect of variations in this cost, the following examples were

used:

1985 cost per kWh,\$	% annual increase over project life	Critical traffic, T million gross tons
0.05	0	13.7
0.05	1	14.7
0.03	0	10.3
0.07	0	20.2

Thus, a 1% annual increase in real terms in the cost of electric power has only a modest impact on critical traffic. However, there can be wide variations in critical traffic as a result of the different electrical power costs which apply in different countries, as will be explained below. It is worth noting that with the diesel fuel scenario used for the base case, which implies a fairly steep increase of fuel costs in real terms, the PV of energy savings discounted at 12% would be zero if electrical power cost about \$0.09; the critical traffic would then be 34 million gross tons (Annex 1, para. 9).

57. The long-run marginal cost (LRMC) of electrical power, which should be used for economic analyses, often differs from electricity tariffs. The methodology for its calculation can be found, for example, in reference 21; only its main features will be reviewed here. The LRMC is made up of the marginal costs of capacity and of energy. The capacity component contains both generation and transmission costs. Since railway substations draw power at relatively high voltage, typically 132kV, the LRMC is lower than for power consumers connected at lower voltage.

58. The railways' power consumption varies throughout the day, and the capacity cost is determined by consumption during the period of peak demand on the electrical power system. Since railways normally operate round the

clock, they use capacity during off-peak as well as during peak hours. In Spain, during the period of peak demand, railway consumption is about equal to the average railway consumption during the 24-hour cycle, the railways' maximum power demand and the peak demand on the electrical system occurring at different times (22). Of course, the railway could further reduce capacity costs by restricting operations during peak hours, but that would be tantamount to constraining railway capacity in order to minimize the utilization of electrical power capacity. With energy accounting, typically, for 10-15% of railway expenditures, this constraint is unlikely to be generally acceptable.

59. Most power systems use a mix of energy sources, some of which operate most of the time, while others are switched on as needed. Thus it was shown in reference 21 that in Pakistan, which had substantial hydroelectric generating capacity, the marginal cost of generating capacity was determined by gas-fired facilities which supply the peak load. The other component of capacity is determined by increases in transmission facilities, down to the voltage level at which the railway is energized. At any given time, the cost of energy is determined by the efficiencies of the units supplying the load. As the load changes, these efficiencies and the mix of units or plants also change. However, the marginal cost is determined by the cost of the last unit to be switched in, which is generally the least efficient of those supplying the load. Since the mix varies with time, there are different marginal costs during peak and off-peak hours. Thus, while energy utilities may have made large investments in power stations which have low energy costs and which supply base load, the energy component of the LRMC is determined by the generating stations which supply marginal load. Marginal energy costs can therefore be substantially greater than the average energy costs of

a power system. A review of World Bank data on marginal capacity and energy costs in different countries for consumers supplied at high voltage (Annex 2), led to the selection of the electric power costs (LRMCs) given in para. 56 and Table 8.

60. Electricity can be substituted for certain oil uses--railway electrification is a case in point--and oil can be used for electricity generation. Significant increases of oil prices are therefore likely to be accompanied by at least some increases in electricity prices. Relatively little is known about the cross elasticities of those prices; they would vary in different countries, depending on the mix of energy sources used for electricity generation. However, to devise a scenario consistent with the base-case increase in diesel fuel prices, coal-based electricity generation was considered. Coal would then account for about half the cost of electrical power. Like the price of oil, the price of coal has been declining since 1981, but a possible scenario is an increase in real terms as from 1985, at 2% per annum to 1990, and at 1% per annum subsequently. On that basis, electrical power prices could be expected to increase at 1% per annum between 1985 and 1990, and 0.5% per annum subsequently. A rather greater increase has been used in para. 56 and Table 8--1% per annum throughout--and its effect was to increase the critical traffic by 8%.

Locomotive maintenance costs

61. Locomotive maintenance costs were taken as \$0.83 per locomotive-km for diesels and \$0.16 for electrics. This yielded, for the base case, a locomotive maintenance cost saving per 1000 gross ton-km, M_L , of \$6.3. An additional value of M_L , 30% lower, was also selected for illustration:

M_L , \$/1000 GTkm	T million gross tons
6.3	13.7
4.4	15.8

Thus, a 30% decrease in M_L has a significant effect on the critical traffic--a 15% increase. If M_L were a greater proportion of benefits, for example if energy savings were less due to electricity being priced at \$0.07 per kWh instead of \$0.05 (para. 56), the effect of variations in the value of M_L would have been greater.

62. The greater complexity of diesel locomotives results in higher maintenance costs, but there are practical difficulties in forecasting maintenance savings resulting from electrification. Maintenance costs of different types of diesels can vary considerably, as they can for electrics. Evolution of maintenance practices, to make them more cost effective, has complicated the interpretation of historical data. Costs vary from country to country, depending on wage rates, and on the staff and facilities available. In some countries, historical data are available only for locomotive groups, each of which includes several types of locomotives, and there are problems in determining the costs pertaining to individual types. Again, when electrification makes it unnecessary to purchase new diesel locomotives, the resulting maintenance savings should also relate to new locomotives, while historical data may be available only for an older fleet.

63. In most electrification studies, maintenance costs per locomotive-km are taken as constant over the life of the project, although they change as locomotives age. Choice of a representative "constant" value necessitates careful examination of the variation of costs with locomotive life and, as pointed out above, historical costs may require careful interpretation. In countries without previously-electrified lines, the cost of maintaining electric locomotives is sometimes taken as a fraction, e.g. one third, of the cost of maintaining diesel locomotives. For these reasons, there could be substantial errors in estimates of locomotive maintenance savings, M_L , based on constant maintenance costs per locomotive-km. The effect of these

errors on the outcome of a feasibility study depends on the relative magnitude of M_L and of other costs and benefits. If M_L is relatively small, a rough approximation may suffice; otherwise, a careful analysis must be made of man-hours, wage rates, and quantities and costs of spare parts.

64. Fig. 3 illustrates the variation of maintenance cost with locomotive type and age. Curve AD is based on data obtained from several U.S. railroads, and curve AE is based on Swedish, Swiss and U.S. data adjusted to U.S. labor costs and overheads (23). The other curves are based on French data, taking into account maintenance improvements--they thus represent future rather than historical costs. Curves FD1 and FE1 are for older locomotives, and curves FD2 and FE2 are for locomotives with the most up-to-date design (24). Additional information is given in Annex 1.

65. It is, of course, convenient to use a constant maintenance cost per km; otherwise separate calculations must be made for locomotives bought each year. A test was therefore made to assess the magnitude of the error introduced by using a constant maintenance cost per locomotive-km (m_D for diesels, m_E for electrics), equal to the average value of that cost over the life of the project. The average cost was determined for each curve over the first 25 years of locomotive life (curve AD had to be extrapolated beyond 16 years), and the result was entered in the second and third columns of the table below. For this test, the traffic was taken as constant over the life of the project, using trains of 1000 trailing tons and 12% discount rate.

	Average maintenance cost, \$/km		PV of maintenance savings, \$/1000 GTkm	
	m_E	m_D	using average values	true value
U.S. data	0.30	0.93	4.9	3.9
French data				
FD1 and FE1	0.48	1.20	5.6	5.6
FD2 and FE2	0.16	0.83	5.2	5.2

The fourth column shows the PV of locomotive maintenance savings calculated from the average values of maintenance cost per locomotive-km, using the methodology outlined in Annex 1. The fifth column shows the PV of locomotive maintenance cost savings, calculated rigorously by using for each year the maintenance costs (and hence the maintenance cost saving) given by the appropriate curves. It will be seen that the error introduced by using average values is insignificant for French data: this is consistent with the relatively small deviations from average values of curves based on those data (Fig. 3). Those deviations are much greater for U.S. data, and using their average values results in a 26% overestimate of maintenance cost savings.

66. Except where otherwise stated, maintenance costs per locomotive-km have been taken as constant, using the average values corresponding to curves FD2 and FE2. For the base case, this yielded a locomotive maintenance cost saving, M_L , of \$6.3 per 1000 gross ton-km, as shown in para. 61. It may be noted that decreasing trailing tons per locomotive increases the locomotive -km needed for a given traffic level, and therefore increases maintenance costs and hence maintenance cost savings (Annex 1, equation A 15).

67. The ratio of average maintenance costs used for diesel and for electric locomotives, m_D/m_E , is rather high (5.2:1), giving a relatively large saving. The saving corresponding to U.S. data has also been seen to be lower. That is why a lower value of M_L has been included in the numerical illustrations given in para. 61 and Table 8.

68. It must be remembered that the maintenance costs used in this analysis apply to industrialized countries; in developing countries maintenance costs could be quite different--lower if an indigenous skilled workforce is available, higher if it is not. A better knowledge of locomotive maintenance costs, and factors which could contribute to their reduction, is desirable for developing countries and its usefulness would extend well beyond decisions on electrification.

Traffic mix

69. A predominantly freight railway has been considered so far. For a predominantly passenger railway the critical traffic is lower, for two reasons. First, speeds are higher, resulting in greater energy consumption and hence greater energy savings. Second, the trailing load per locomotive is smaller, so that there are more locomotives per G_Tkm, increasing locomotive maintenance savings. To illustrate this, consider a railway carrying three passenger-kms per net ton-km, in locomotive-pulled trains only; maintenance savings would probably be greater if multiple unit trains were used, because there would be more power units. As shown in Table 8, energy consumption has been taken as 8 liters of diesel fuel or 31 kWh, 33% more than in the base case, to allow for greater speeds. Maintenance savings have been calculated as before. The result is a critical traffic of 10.1 million gross tons, 26% below that corresponding to the base case.

Operation in difficult terrain

70. The discussion so far related to operation in easy terrain, in which little advantage was gained from the higher power capability of electric locomotives. However, that capability can give electrification a considerable additional advantage if the major portion of the line lies in difficult terrain, with steep gradients. The impact of that capability has been tested using the mainly-passenger traffic mix. The differences from the base case are that trailing tons per locomotive have been taken to be 25% greater and locomotive-km per day 33% greater with electric than with diesel traction; furthermore, as shown in Table 8, energy consumption has been taken as 50% greater for electric traction and 58% greater for diesel traction. The difference between increases in consumption reflects differences in trailing tons per locomotive (para. 48). No allowance was made for reductions in train crew costs or in the number of cars (para. 71). Under these circumstances, the critical traffic is 6.5 million gross tons, less

than half that corresponding to the base case. Using the lower value of C_F decreases the critical traffic to 4.7 million gross tons.

Staff and car savings

71. Savings resulting from increased staff productivity and improved utilization of freight and passenger cars have not been taken into account in calculating critical traffic. Those savings are very project dependent, so that it would be difficult to provide a typical value, but they are relatively small when the difference between kms-per-day achieved with diesel and with electric traction is modest and train weights are the same, as has been postulated for almost all cases examined in this paper. The only exceptions are the difficult-terrain cases, in which differences in kms-per-day and train weights could have resulted in substantial reduction in crew costs, depending on contractual arrangements (including wage levels, and rostering and manning practices). There could also be significant car savings, because of greater speed. For any given project, these savings could readily be estimated and introduced in the calculation of critical traffic. It may be noted that in the cases discussed above in which these savings could have been important--difficult terrain--they would have to reach \$7.5 per 1000 gross ton km, or nearly two-thirds of the locomotive maintenance savings, to decrease the critical traffic by 20%. Any crew cost savings available through electrification would be reduced if total crew costs were reduced by operating changes--for example, by the introduction of longer trains, with two or more locomotives, operated with no more staff than needed for single-locomotive trains. Introduction of longer trains would also increase track capacity. A question to be borne in mind is whether increased productivity can be used effectively, either due to a corresponding increase of traffic, or by reducing staff and disposing of surplus cars.

Capacity increases

72. If infrastructure works are needed to increase track capacity, their postponement could be one of the benefits of electrification. The method of calculating that benefit, W , from the cost of the works involved, is described in Annex 1. That Annex contains also a calculation of the value of those works which would decrease critical traffic by 20%. If electrification postponed them by 5 years and the cost of fixed installations were as for the base case, those works would have to cost \$83000s (where s is the line length in route-km) or \$33 million for a 400 km scheme. If the capacity increase due to electrification were greater and the rate of growth of traffic were smaller, this cost would decrease, down to \$14 million. These costs, though substantial, would be exceeded if extensive double tracking were involved. However, electrification becomes viable in many cases--including most cases of Table 8--at traffic levels well below those at which double tracking is likely to become necessary.

Conclusion

73. It has been shown that there are wide variations in the critical traffic, at which electrification becomes economically viable. The examples given in Table 8 and Fig. 2, which are by no means exhaustive, cover a range of 4.7 and 22 million gross tons. Critical traffic is particularly sensitive to the opportunity cost of capital, the cost of fixed installations, and the cost of diesel fuel. It is sensitive also to energy consumption, the cost of electrical power and locomotive maintenance costs. It can vary widely depending on the cost of the electric locomotive fleet, and of the diesel locomotive fleet displaced by electrification. It can be substantially lower in difficult than in easy terrain, and for predominantly passenger than for predominantly freight traffic.

74. No single parameter can be used as an indicator of the viability of electrification. A separate--and usually complex--feasibility study has to be undertaken for each proposal. The factors to be taken into account have been discussed. It has been shown that the data needed are either available or can be derived by using established methodologies. A pre-feasibility analysis has been developed for determining whether a more detailed study is warranted.

75. Conclusions drawn from Part I of this paper have been given in paras. 20-24. A comment applicable to both Parts, is that energy costs are not normally the dominant factor in determining the railways' role. The increase in oil prices has opened new opportunities for railways, but to identify those opportunities necessitates a clear understanding of energy and other costs, for railways as well as for their competitors. This understanding is needed also to illuminate choices between electrification and other investments which can reduce costs or improve quality of service.

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References

- (1) P. Monneret and M. Walrave: Les Transports des marchandises et l'energie, Transports, February 1981.
- (2) Les consommations unitaires d'energie dans les transports, Documentation Francaise, December 1979.
- (3) Freight transport: short and medium term considerations. Paper No. 6. Advisory Council on Energy Conservation, HMSO, London 1977. (The paper states that shunting accounted for about 5% of total diesel fuel consumption in 1974, when only 5% of locomotive time used for freight trains was provided by electric locomotives.)
- (4) P. Monneret, French Railways, private communication, 1982.
- (5) J.B. Hopkins: Where does the energy go: A simplified perspective on fuel efficiency in rail transportation, Transportation Research Record 838, 1982.
- (6) Energy Savings--The Railways' Contribution. International Union of Railways, 1982.
- (7) K.M. Bertram, Projected Potential Piggyback Energy Savings Through the year 2000, Transportation Research Record 801, Transportation Research Board, National Academy of Sciences, 1981.
- (8) A. Levy, The Rail-road combined transport, IRCA/UIC Congress, September 1982.
- (9) Jacques Colin. Logistique et plates-formes industrielles de fret, Transports, February 1983.
- (10) Les possibilites d'economiser l'energie dans le chemin de fer, International Union of Railways, May 1982.
- (11) World Bank data.
- (12) D. Lancien and M. Fontaine, Calcul de Marches de Trains Economisant l'Energie de Traction, Revue Generale des Chemins de Fer, November 1981.
- (13) P. Horn and A. Winkler, Zur Energie-Optimalen Zugsteuerung und Fahrplanmodifikation, Energie et Transports, International Union of Railways, Paris 1980.
- (14) W. H. Cyr, Canadian National, private communication.
- (15) S.R. Ditmeyer, The contribution of railroads to energy conservation, IRCA/UIC Congress, September 1982.
- (16) Technical Proceedings of the Energy Management Workshop, U.S. Department of Transportation Report No. FRA/ORD-80, 1979.

- (17) N. Howard: A comparison between fuel efficiency of railway diesel and electric traction units, Electrical Engineering Transactions, The Institute of Engineers, Australia, 1980.
- (18) Modernisation des lignes de l'Etoile d'Angers, SNCF Report OIS Ell No. 968, 1978.
- (19) J.B. Quail: Economics of the use of electric traction by the South African Railways for the transport of coal on the Richards Bay Line, presented at the Annual Meeting of the Transportation Research Board, January 1981.
- (20) Price prospects for major primary commodities, World Bank report, Volume 5, July 1982.
- (21) M. Munasinghe and J.J. Warford: Electricity Pricing--Theory and Case Studies, published for the World Bank by the Johns Hopkins University Press, 1982.
- (22) M. Losada, Indicators for measuring the energy efficiency of railways and other forms of transport, IRCA/UIC Congress, September 1982.
- (23) E.G. Schwarm, Arthur D. Little, Inc., private communication, 1982.
- (24) J.M. Jomard and P. Meyreau, SNCF, private communication, 1982.

ESTIMATE OF CRITICAL TRAFFIC

1. The methodology used for estimating the critical traffic will now be explained in more detail, using the data corresponding to the base case. The methods used for evaluating the benefit resulting from capacity decreases (para. 72 of the main text) and from decreasing a possible national reserve of diesel fuel (para. 60 of the main text) will also be detailed.

2. The parameters for the base case are:

Project life: 25 years, starting in 1985.

Terrain: easy, with no major gradients or sharp curves.

Traffic: T million gross tons in 1985, increasing at 3% per annum; 0.5 net ton-km or 1 passenger-km generate 1 gross ton; passenger traffic in locomotive-pulled trains, not exceeding 140 km/hr.

Train weights: trailing tons of freight trains with electric and with diesel traction, $t_{EF}=t_{DF}=1200$ tons; trailing tons of passenger trains, $t_{EP}=t_{DP}=600$ tons.

Locomotive utilization: Electrics, 400 km/day for freight and 600 km/day for passengers; diesels 348 km/day for freight and 522 km/day for passengers. Ratio of electric to diesel utilization: 1.15:1.

Locomotive availability: Electric, 95%, diesel 86%. Availability ratio: 1.1:1.

Locomotive prices: Electric, $P_{LE} = \$1.7$ million; diesel, $P_{LD} = \$1.3$ million.

Locomotive maintenance costs per locomotive-km: Electric, $m_E =$
\$0.16; diesel, $m_D =$ \$0.83.

Cost of diesel fuel: 1985 cost, $p_D =$ \$0.26 per liter, increasing
at 3% per annum to 1995, and at 2% per annum subsequently.

Cost of electrical power: $P_E =$ \$0.05 per kWh.

Energy consumption: 6 liters or 23 kWh per 1000 gross ton-km.

Capital cost of fixed installations: $C_F =$ \$180000 per
single-track route-km.

Yearly maintenance cost of fixed installations: 1% of capital
cost.

Rate of return: 12%.

Residual values will be ignored.

Extensive use will be made of the formula:

$$\sum_{n=a}^{n=b} x^{n-1} = \frac{x^{a-1} - x^b}{1 - x}$$

x being a function of the discount rate and of various growth rates, as shown
below.

Maintenance of Fixed Installations

3. Since yearly maintenance cost is 1% of the capital cost of fixed
installations, the PV of maintenance costs at 12% discount is:

$$M_F = \frac{C_F}{100} \sum_{n=2}^{n=25} \left(\frac{1}{1.12}\right)^{n-1}$$
$$= 0.079 C_F \quad (A1)$$

So that, with $C_F = \$180,000$, $M_F = 14 \times 10^3$ per single-track route-km.

Locomotive Investments

4. The traffic, T gross tons in the first year of the project, increases to 1.03 T in the first year of operation with electric traction. With a route length, s (km), freight traffic will generate 0.88Ts GTkm and passenger traffic 0.15Ts GTkm, during the first year of service (the second year of the project). For the train weights, locomotive utilization and locomotive availability (given in para. 2 of this Annex) the number of electric locomotives to be purchased during the first year of the project (to be available during the second year) will be

$$N_{E1} = \frac{0.88 Ts}{1200 \times 365 \times 400 \times 0.95} + \frac{0.15 Ts}{600 \times 365 \times 600 \times 0.95}$$
$$= 6.49 Ts \times 10^{-9} \quad (A2)$$

The equivalent number of diesel locomotives can be derived from this expression, remembering that electrics cover 15% more km/day than diesels and their availability is 10% greater.

$$N_{D1} = 6.49 \times 1.15 \times 1.1 T_s \times 10^{-9} = 8.21 T_s \times 10^{-9} \quad (A3)$$

5. Locomotive purchases will continue through the life of the project, as traffic grows, and it will be assumed that the additional locomotives needed for each year will be bought the previous year. With a yearly traffic growth of 3%, traffic in the (n)th year will exceed traffic in the (n-1)th year by

$$0.03 \times 1.03^{n-1} T$$

and since N_{E1} electric locomotives correspond to a traffic of 1.03 T, the number of electric locomotives to be purchased in the (n-1)th year is

$$N_{En} = \frac{N_{E1}}{1.03} \times 0.03 \times 1.03^{n-1} \quad (A4)$$

Since P_{LE} and P_{LD} are the unit costs of locomotives, the present value (PV) of the investment in electric locomotives is:

$$\begin{aligned}
 C_{LE}^{Ts} &= N_{E1} P_{LE} \left[1 + \sum_{n=2}^{n=24} \frac{0.03 \times 1.03^{n-1}}{1.03 \times 1.12^{n-1}} \right] \times 10^6 \\
 &= N_{E1} P_{LE} \left[1 + 0.0291 \sum_{n=2}^{n=24} \left(\frac{1.03}{1.12} \right)^{n-1} \right] \times 10^6 \\
 &= 1.28 N_{E1} P_{LE} \tag{A5}
 \end{aligned}$$

The net present value (NPV) of locomotive investment is the difference between the PVs of the electric locomotive fleet and the diesel locomotive fleet, that is,

$$\begin{aligned}
 C_L^{Ts} &= 1.28 [N_{E1} P_{LE} - N_{D1} P_{LD}] \\
 &= 1.28 N_{E1} \left[P_{LE} - \frac{P_{LD}}{z} \right] \tag{A6}
 \end{aligned}$$

where $z = \frac{N_{E1}}{N_{D1}}$; using the value of N_{E1} from equation A2,

$$C_L = 8.31 \left[P_{LE} - \frac{P_{LD}}{z} \right] \times 10^{-9} \tag{A7}$$

From equations A2 and A3, $z = 0.79$. Using the values of P_{LD} and P_{LE} given in para. 2 of this Annex,

$$C_L = 0.5 \times 10^{-3} \quad (A8)$$

Energy savings

6. The derivation of X, the PV of the cost of diesel fuel, will be illustrated by using the symbols p_D for the 1985 cost of diesel fuel per litre, k_1 for the annual rate of increase of that cost for the first m years of the project, and k_2 for the corresponding rate of increase for the remainder of the project life. As stated in para. 2 of this Annex, consumption will be taken as 6 litres per 1000 gross ton-km, traffic growth as 3% per annum and the discount rate as 12%. Then

$$X = \frac{6p_D T_S}{1000} \left[\sum_{n=2}^{n=m} \left[\frac{1.03(1+k_1)}{1.12} \right]^{n-1} + \left[\frac{1.03(1+k_1)}{1.12} \right]^{m-1} \sum_{n=m+1}^{n=25} \left[\frac{1.03(1+k_2)}{1.12} \right]^{n-m} \right] \quad (A9)$$

Inserting the numerical values for the base case ($m=11$, $k_1=3\%$, $k_2=2\%$, $p_D=0.26$) yields

$$X = 19.8T_S \times 10^{-3} \quad (A10)$$

7. The derivation of Y, the PV of the cost of electrical power, will be illustrated by using the symbols p_E for the cost per kWh, and k for its annual rate of increase over the life of the project. Consumption will be taken as 23 kWh per 1000 gross ton-km, and traffic growth and the discount rate as before. Then

$$Y = \frac{23p_E T_s}{1000} \sum_{n=2}^{n=25} \left[\frac{1.03(1+k)}{1.12} \right]^{n-1} \quad (A11)$$

and inserting the numerical values of the base case ($p_E = 0.05$, $k=0$)

$$Y = 11.4T_s \times 10^{-3} \quad (A12)$$

8. For the base case, the PV of energy savings is therefore

$$E T_s = X - Y = 8.4T_s \times 10^{-3} \quad (A13)$$

and the PV of energy saving per ton-km is

$$E = 8.4 \times 10^{-3} \quad (A14)$$

9. It may be noted that energy cost savings would fall to zero if electrical power cost \$0.087; the PVs of diesel fuel and of electrical power costs would then be equal.

Locomotive maintenance savings

10. It will be remembered that m_D and m_E are the maintenance costs per km for diesel and for electric locomotives, and t_{DF} and t_{EF} be the trailing loads per locomotive for freight trains. The traffic mix corresponding to the base case is 3 net ton-km per passenger-km, and since 1 net ton-km generates 2 gross ton-km and 1 passenger-km generates 1 gross ton-km, freight traffic accounts for 0.86Ts GTkm, and passenger traffic for 0.14Ts GTkm, during the first year at the project. Services with electric traction start in the second year of the project. Hence for freight traffic, the PV of locomotive maintenance savings is

$$\begin{aligned}
 M_{LF} Ts &= \left[\frac{m_D}{t_{DF}} - \frac{m_E}{t_{EF}} \right] 0.86Ts \sum_{n=2}^{n=25} \left(\frac{1.03}{1.12} \right)^{n-1} \\
 &= 8.5 Ts \left[\frac{m_D}{t_{DF}} - \frac{m_E}{t_{EF}} \right] \quad (A15)
 \end{aligned}$$

Hence, with $m_D = 0.83$, $m_E = 0.16$ and

$$\begin{aligned}
 t_{DF} &= t_{EF} = 1200 \text{ Tons,} \\
 M_{LF} &= 4.75 \times 10^{-3} \quad (A16)
 \end{aligned}$$

Similarly, for passenger traffic (600 trailing tons)

$$M_{LP} Ts = 1.55 Ts \times 10^{-3} \quad (A17)$$

so that the PV of total locomotive maintenance saving becomes

$$M_{LTs} = 6.3Ts \times 10^{-3} \quad (A18)$$

and

$$M_L = 6.3 \times 10^{-3} \quad (A19)$$

11. An additional comment is needed regarding the graphs of locomotive maintenance costs against locomotive age (Fig. 3) from which m_D and m_E have been derived (paras. 64-65 of main text). Those graphs depend locomotive-km per year, since some maintenance costs depend on usage and others on elapsed time. The table below shows the km per year corresponding to each curve:

AD	160,000
AE	320,000
FD1	96,000-120,000
FE1	130,000
FD2	180,000
FE2	300,000

12. Under the assumptions for the base case, diesels would cover 139,000 km/year and electrics 160,000 km/year, while for the "mainly passenger" case these values would be 170,000 and 190,000 km/year,

respectively. For diesels, the values are fairly close to FD2, on which m_D was based. For electrics, values were substantially lower than FE2, but as the maintenance savings are dominated by the cost of diesel locomotives, this difference does not affect significantly the discussion given in this paper. However, the dependence of the curves such as those of Fig. 3 on locomotive usage has to be taken into account in feasibility studies.

Base-case critical traffic

13. From equation 3, the critical traffic is given by

$$T = \frac{C_F + M_F - \frac{W}{S}}{E + M_L - C_L}$$

For the base case, $C_F = \$180,000$, and $W=0$. The values of M_F , E , M_L and C_L are given by equations A1, A14, A19, and 8A, respectively, so that

$$T = \frac{180000 + 14000}{8.4 \times 10^{-3} + 6.3 \times 10^{-3} - 0.5 \times 10^{-3}} = 13.7 \times 10^6 \text{ gross tons}$$

14. These data have been entered in Table 8 where, for convenience of presentation, C_F and M_F are expressed in thousands of dollars; E , M_L and C_L are expressed per 1000 gross ton km, and T is expressed in millions of gross tons.

Fuel reserve

15. It was explained in the main text (para. 54) that governments may set up an oil reserve in order to cushion their economies against a possible disruption of oil supplies. If the railway is electrified - and electricity generation is not oil-based - the oil reserve is reduced by the amount needed to supply diesel locomotives in the absence of electrification. It is arguable whether this reduction should be counted as a benefit of electrification, since the fuel reserve can be considered as one of the governmental measures taken to protect national interests, such a food reserve or a standing army. However, a calculation has been made to assess the impact of this benefit on the viability of electrification. Conditions corresponding to the base case will be used.

16. It will be assumed that the reserve equals six months' consumption and contains diesel fuel. Electric services start in the second year of the project, when traffic is 1.03 Ts. Consumption is 6 litres per 1000 gross ton-km and the price of diesel fuel is \$0.26 x 1.03 per litre. Hence the PV value of the cost saving for that year (the second year) is:

$$R_2 = \frac{1.03^2 \times 6 \times 0.26 \text{ Ts}}{1.12 \times 2} = 0.74 \text{ Ts} \quad (\text{A20})$$

The reserve would have to be increased each year, to take into account the increase in traffic, which is 3% per annum. For the first 11 years the price of diesel fuel increases by 3% per annum, so that during that period, the PV of the additional reserve needed for the ninth year is

$$\begin{aligned}
 R_n &= 0.03 \times \frac{6}{2} \times 1.03^{n-1} \frac{T_s}{1000} \times 0.26 \times 1.03^{n-1} \times \left(\frac{1}{1.12}\right)^{n-1} \\
 &= 0.023 T_s \times \left(\frac{1.032}{1.12}\right)^{n-1} \times 10^{-3}
 \end{aligned}
 \tag{A21}$$

and the PV of the reserve over the life of the project becomes

$$\begin{aligned}
 R &= T_s \times 10^{-3} \left[0.74 + 0.023 \sum_{n=3}^{n=11} \left(\frac{1.032}{1.12}\right)^{n-1} \right. \\
 &\quad \left. + \left(\frac{1.032}{1.12}\right)^{10} \times 0.023 \sum_{n=12}^{n=25} \frac{1.03 \times 1.02^{n-11}}{1.12} \right] \\
 &= 1.0 T_s \times 10^{-3}
 \end{aligned}
 \tag{A22}$$

The PV of the reserve per gross ton-km is therefore

$$F = \frac{R}{T_s} = 1.0 \times 10^{-3}
 \tag{A23}$$

Taking this benefit into account, the formula for the critical traffic becomes

$$T = \frac{C_F + M_F - \frac{W}{S}}{E + M_L - C_L + F}
 \tag{A24}$$

and inserting the base-case values, and the value of F from equation A23

$$T = \frac{180000 + 14000}{8.4 \times 10^{-3} + 6.3 \times 10^{-3} - 0.5 \times 10^{-3} + 10^{-3}} = 12.8 \times 10^6 \text{ gross tons}$$

Thus, if a 6-month reserve of diesel fuel is taken into account, the base-case critical traffic decreases by 7%.

Capacity increases

17. If the cost of works needed to increase track capacity is W_c , and they have to be undertaken in the j th year of the project with diesel traction and b years later with electrification, and the discount rate is 12%, the PV of this benefit is

$$W = W_c \left[\frac{1}{1.12^{(j-1)}} - \frac{1}{1.12^{(j+b-1)}} \right] \quad (A25)$$

18. The value of W_c needed to achieve a significant reduction, taken as 20%, in the critical traffic, can be related to the cost, C_F , of fixed installations. From the expression for T (equation 3), if $W = 0$ yields $T = T_0$, then a finite value of W yields $T = 0.8 T_0$, so that

$$0.8 = \frac{C_F + M_F}{C_F + M_F - \frac{W}{B}} \quad (A26)$$

and since M_F is much smaller than C_F ,

$$\frac{W}{s} = 0.2C_F \quad (A27)$$

Using the data for the base case, it will be assumed that electrification increases capacity by 15%; as traffic grows at 3% per annum, $b = 5$. If capacity-increasing works would have to be executed during the first year of the project in the absence of electrification,

$$W = W_c \left[1 - \frac{1}{1.125} \right] = 0.43 C_c \quad (A28)$$

Hence, with $C_F = \$180,000$

$$W_c = 2.3W = 0.46C_F s = \$83,000s \quad (A29)$$

Of course, the value of W_c needed to decrease the critical traffic by 20% would be smaller if the capacity increase due to electrification were greater, since that would increase b . In the limit, if b exceeded the life the project (which would imply a very slow growth of traffic),

$$W_c = W = 0.2C_F = \$36000s. \quad (A30)$$

For a 400 km scheme, these values of W_c become \$33.2 million and \$14.4 million, respectively. Hence, fairly extensive works would have to be involved to affect the critical traffic significantly.

19. These values of W_c would be exceeded if extensive double tracking were needed. However, for the base case, with trains of 1200 trailing tons for freight and 600 trailing tons for passengers, the critical traffic of 13.7 million gross tons could be carried by 18 pairs of trains per day, rising to 38 pairs by the end of the project. This is within the capacity of single-line operation, so that there should be no need for any extensive double-tracking, although investments may well be needed, for example, for additional signalling facilities or additional crossing loops. Furthermore, it should be possible to combine some of the trains, to yield freight trains with 2400 trailing tons, thus reducing pressure on track capacity in other cases with mainly-freight traffic and greater critical traffic. Single-track operation is also possible in the mainly-passenger case because, while there are more trains for a given traffic level, the critical traffic is smaller. Thus, for most cases recorded in Table 8, electrification becomes viable at traffic levels at which no extensive double tracking should be needed.

COST OF ELECTRICAL POWER

1. As explained in the main text, the cost of electrical power has two main components: one related to the generation and transmission capacity to be provided as the demand for electrical power grows and the system expands, and the other related to energy consumed in order to generate electrical power. Operation and maintenance costs are usually included in capacity costs. Energy is normally generated from a mix of sources, which may include oil, gas, coal, nuclear, hydro, or possibly other sources, selected so as to give a least-cost solution. Some of the power stations, supplying the base load, operate most of the time and others are switched on when needed.
2. It is necessary to divide the daily load cycle on the electrical power system into two periods: peak and off-peak. Their duration depends on system characteristics: the peak load period is about four hours in Pakistan, 7 hours in Yugoslavia. In some cases the daily load cycle is divided into more than two periods, and there may also be seasonal variations, but for this discussion, it suffices to consider simply a two-period daily cycle. It will also be assumed that, as is usually the case, capacity costs arise only from the increment of demand which occurs when the power system supplies its peak load. However, for certain systems, which include hydroelectric generation, a cost may also be incurred in respect of off-peak capacity because of the need to provide a reserve for dry years.

3. Power plants supplying the peak load normally operate only a few hours a day, and it is therefore important that they should have low capacity costs rather than low energy costs. Such plants often consist of gas turbines or peaking hydro, and they normally determine the marginal cost of generating capacity. In addition, it is necessary to take into account the capacity increases in the transmission network--but only down to the voltage level at which railway substations are connected, typically 132 kV. The resulting capacity cost per kW, annuitized over the life of the equipment, will be denoted by q .

4. The marginal cost of energy is the cost incurred in the generating stations to be used last in order of merit to meet the incremental demand; it will normally be lower during off-peak than during peak periods and will be denoted, respectively, by w_0 and w_p per kWh. As explained in the main text, these energy costs can be substantially greater than average energy costs.

5. To determine the LRMC per kWh of electrical power, it is necessary to establish the railway contribution, d_r kW, to the peak demand, and the aggregate yearly railway consumptions, c_p and c_0 kWh respectively, during the peak and off-peak periods. Two possible cases were considered for deriving d_r : first, it was taken as the average value of railway consumption (which implies that the irregularity of railway demand is absorbed by the power system at no extra cost), and, second, it was taken to result from a railway load factor of 0.7, with the railway peak demand coinciding entirely with the system peak and having a 100% responsibility in the expansion of capacity.

Then for the first case

$$d_{r1} = \frac{c_p + c_o}{24 \times 365} = \frac{c_p + c_o}{8760} \quad (A31)$$

and for the second

$$d_{r2} = \frac{c_p + c_o}{24 \times 365 \times 0.7} = \frac{c_p + c_o}{6132} \quad (A32)$$

For the first case, the cost of a year's consumption of electrical power is given by

$$\begin{aligned} y, = & \text{ (capacity cost, } qd_{r1}) \\ & + \text{ (peak-hours' energy cost, } w_p c_p) \\ & + \text{ (off-peak hours' energy cost, } w_o c_o) \end{aligned}$$

The LRMC per kWh is obtained by dividing the total cost of a year's consumption by the total energy consumed, so that

$$LRMC_1 = \frac{qd_{r1} + w_p c_p + w_o c_o}{c_p + c_o} \quad (A33)$$

and substituting for d_{r1} from equation A31,

$$LRMC_1 = \frac{q}{8760} + \frac{c_p w_p + c_o w_o}{c_p + c_o} \quad (A34)$$

and similarly

$$LRMC_2 = \frac{q}{6132} + \frac{c_p w_p + c_o w_o}{c_p + c_o} \quad (A35)$$

6. c_p and c_o have to be determined from the timetable of railway operations and the timing of the peak period. In the absence of this information, it is possible to establish only a range of values within which the LRMC must lie, the lower end of the range applying if all energy consumption was off-peak, and the upper if it was during the peak period. The table below gives LRMCs for several countries, based on data derived from studies undertaken at various times since 1978 and updated using price indices only. These LRMC values are therefore approximate, but they nevertheless illustrate the dependence of LRMCs on consumptions during peak and off-peak hours, on energy costs, and on country conditions.

	<u>U.S. cents (1982) per kWh</u>	
	<u>LRMC₁^{a/}</u>	<u>LRMC₂^{a/}</u>
Zimbabwe ^{b/}	1	1
South East Brazil	3-4	3-5
South Brazil	3-5	4-5
Portugal ^{c/}	5	6
Yugoslavia	4-6	4-6
Pakistan	7	8
Tunisia	6-10	7-10

a/ Source: World Bank data and reference 21. Capacity costs, q , used for compiling this table have been annuitized using discount rates of 10-12%, presumably corresponding to the opportunity cost of capital in the countries concerned. In countries with more than one off-peak energy cost, w_o was taken as their average. Similarly, for countries with more than one peak energy cost (due to seasonal variations), w_p was taken as their average.

b/ Cost given only for peak period.

c/ Energy cost averaged over peak and off-peak periods.

7. The low cost in Zimbabwe is not typical, and it was shown in Annex 1 (para. 9) that energy cost savings fall to zero if the cost of electrical power rose to 9 cents per kWh, other conditions being as for the base case. The range of LRMC values used for the numerical illustrations was therefore taken as 3-7 cents per kWh, with 5 cents per kWh for the base case.

8. For feasibility studies, it is necessary to ensure that LRMCs are based on current utility plans. As explained in the main text, increases in oil prices can be expected to put pressure on the cost of electrical power, but any resulting increase would be country specific. For most numerical illustrations given in this paper, the cost of electrical power was taken as constant in real terms over the life of the project, but a test was also made using an increase of 1% per annum in conjunction with a steeper increase in the price of diesel fuel (main text, paras. 56 and 60).

9. It should be remembered that the LRMC of electrical power for railway electrification is significantly smaller than that applicable to low voltage consumers, who must cover also capacity costs and energy losses in the distribution network and in the transmission network below the voltage level to which the railway substations are connected.

Table 1

Railway consumption of oil products as a percentage
of total consumption 1/

	up to 0.5%	0.5-1.0%	1.0-2.0%	2.0-4.0%	10-15%
OECD COUNTRIES (1980 Data)	Greece Italy Netherlands Norway Spain Sweden Switzerland	OECD-Europe Japan Austria Belgium Denmark Finland France Germany Ireland Luxembourg Portugal	OECD Total U.K. U.S.A.	Canada Australia	
			Brazil (1976) Mexico (1976)	India (1976) Thailand (1981) Zambia (1981)	Kenya (1976) Zimbabwe (1980)
SOME DEVELOPING COUNTRIES (year in brackets)	up to 0.5%	0.5-1.0%	1.0-2.0%	2.0-4.0%	10-15%

Sources: Annual Oil and Gas Statistics, International Energy Agency, 1982; Workshop on energy data in developing countries, OECD, 1978; Bank and consultants' reports.

1/ Total consumption excludes international marine bunkers.

Table 2

Comparison of Energy Consumptions in the Transport Sector in Poland
Figures are Energy Consumption in kg Equivalent of Coal per 100 ton-km
or 100 passenger-km

	<u>Passengers</u>	<u>Freight</u>
Railways - overall average <u>a/</u>	3.6	2.4
Railways - steam traction	7.6	6.0
Railways - electric traction	2.6	1.5
Railways - diesel traction	2.7	1.8
Automobile	7.5	-
Bus	1.9	-
Aeroplane	11.4	-
Truck	-	14.5
Truck (diesel engined, highway use)	-	5.7
Truck (gasoline engine)	-	21.9
River transport (on the Vistula and Oder)	-	2.6
Pipeline	-	0.6

Source: S. Bolewski, Problem of energy and fuel for railway traction, Problemy Kolejnictwa Varsovie, 1980; abstract included in Energy and Transport published by the International Union of Railways, Paris, 1980.

a/ The relatively high average consumption reflects the use of steam traction, which most of the Bank's borrowers have virtually eliminated.

Table 3

Comparison of Energy Consumptions for Transport of Freight by
Large Trucks and by Railways in France a/

<u>Road</u>	<u>gcp/tkc^{b/}</u>	<u>gcp/tkt^{c/}</u>	<u>Utilization of capacity %</u>	<u>gcp/tkt^{c/} divided by gcp/tkt of 38 ton truck</u>
19 ton truck	24.0	29.1	83	1.52
21 ton articulated truck	23.3	28.5	82	1.48
38 ton articulated truck	14.9	19.2	77	1.0
<hr/>				
<u>Rail</u>				
Unit trains	3.5	7.3	48	0.38
Car load excluding unit trains				
Ordinary	4.7	11.0	43	0.57
Fast	7.9	21.8	36	1.14

Source: Les consommations unitaires d'energie, Documentation Francaise,
December 1979 (2)

a/ Data refer to energy consumed on board of vehicles. For railways it includes switching and appropriate allocations for service trains. These account for 85% of total energy consumption by railways, the balance being used in buildings and other fixed installations (4). Data have not been corrected for circuitry; distances are, on average, about 10% longer by rail than by road.

b/ Gram equivalent of petrol per ton-km capacity.

c/ Gram equivalent of petrol per ton-km transported.

Table 4

Comparison of Energy Consumption for the Transport of
Truck Trailers Towed by Road Tractors and Trailers
Carried Piggyback by Rail (TOFC) in the U.S.

<u>Item</u>	<u>Truck</u>	<u>Rail</u>
Distance (miles)	420	412
Speed (mph)	42.6	38.2
Trailing Gross Weight (tons)	23.1	1,466 <u>a/</u>
Fuel Consumed (gallons)	82.3	1,283.2 <u>b/</u>
Loaded/Empty Trailers	1/0	42/3
Trailer Miles Per Gallon	5.1	13.5
Trailer Gross Weight (tons) <u>c/</u>	23.1	18.1
Gross Ton Miles Per Gallon	117.7	257.8
Trailer Revenue Weight (tons)	17.1	12.1
Revenue Ton Miles Per Gallon	86.9	172.9
Energy intensity (BTU/revenue ton mile)	1596	802

Source: Railway Age, January 1980, and Reference 7. Based on tests made during October 1978-March 1979.

a/ Total train.

b/ Includes linehaul and terminal fuel use.

c/ 45-foot highway trailers; 40-foot railroad trailers.

Table 5

Comparison of Energy Consumption for the Transport of Passengers
by Road and Rail in France a/

<u>Passenger Traffic</u>	<u>gep/skc</u> ^{b/}	<u>gep/pkc</u> ^{c/}	<u>gep/pkt</u> ^{d/}
Automobile ^{d/}	14-20		61-74
Taxi ^{e/}	21-24		104-122
Bus ^{e/}		4.6	19.4
Metro ^{f/}		4.2	23.6
Suburban train		3.5	20.0

Source: Les consommations unitaires d'energie, Documentation Francaise, December 1979 (2).

a/ See footnote a/, Table 3.

b/ gep per seat-km available.

c/ gep per passenger km of capacity.

d/ gep per passenger km transported.

e/ Paris region.

f/ Total energy consumption, including that used in fixed installations, is 31% greater.

Table 6

Energy Expenditures as a Percentage of Total Working Expenditures
(Exclusive of Depreciation and Interest Payments)

<u>up to</u> <u>5%</u>	<u>5-10%</u>	<u>11-15%</u>	<u>20-24%</u>	<u>25-29%</u>
France	Argentina	Canadian National	Korea	Thailand
Mexico	Japan	U.S.-Burlington Northern	India	Pakistan
	Yugoslavia			
	Bolivia	U.S.-Southern Pacific		
	Ivory Coast -Upper Volta	Brazil -RFFSA		
	Romania	Turkey		

Data for 1980 or for fiscal year 1979-80. 1980/81 data for Japan.

Source: World Bank reports, and railways' annual reports.

Table 7

Estimates of Potential Energy Savings for Rail Transport

<u>Improvements</u>	<u>Incremental Fuel Savings As Percent of Total Rail Fuel Consumed if Universally Implemented</u>
Equipment Efficiency Improvement	19% (compounded) <u>b/</u>
Locomotive Waste Heat Recovery	6%
Seal Torque Reduction Loco Power Management, parasitic load, etc.	4% 10%
Rolling Stock Tare Weight Reduction	16% (compounded) <u>b/</u>
Cars	12%
Loco with Posi-Traction <u>a/</u>	4%
Miscellaneous Equipment Changes	14% (compounded) <u>b/</u>
Locomotive Streamlining	7%
Car Streamlining	6%
Other Car Improvements	<u>2%</u>
Compounded Total	41% <u>b/</u>

Source: U.S. Department of Transportation, Report No. FRA/ORD-80, 18, entitled Technical Proceedings of the Energy Management Workshop, November 1979.

- a/ Posi-traction is a system of wheel-slip control which enables more effective use of locomotive weight.
- b/ Compounded savings are generally less than the product of individual savings, because many individual savings overlap.

Table 8: Critical traffic yielding a rate of return of 12% under different conditions

	Base case	----- Deviations from base case ----- ----- (where no entries are shown, base case entries apply) -----																
														Mainly passenger ^{b/}				
Traffic	mainly ^{a/} freight																	
Terrain	easy															More diff.		
PV of fixed installations, CF, \$1,000/km	180	130	230														130	
PV of maintenance of fixed installations, MF, \$1000/km	14	10	18														10	
Number of Electric Locos = z Number of Diesel Locos	0.79			0.6												0.6	0.6	
Cost of one locomotive Diesel, P _{LD} , \$million	1.3			1.43	1.18													
Electric, P _{LE} , \$million	1.7			1.3	2.2													
NPV of locomotive investment, C _L , \$/1000GTkm	0.5			-9.0	5.9											-3.9	-3.9	
Consumption per 1000 GTkm, liters/kwh	$\frac{6}{23}$					$\frac{5.4}{23}$	$\frac{6}{20.7}$	$\frac{5.4}{20.7}$	$\frac{4.8}{18.4}$							$\frac{8}{31}$	$\frac{9.5}{34.5}$	$\frac{9.5}{34.5}$
1985 diesel fuel cost, \$/liter	0.26																	
Real-term increase of diesel fuel cost, % p.a.	3% - 1995 then 2%									1%								
1985 electric power cost, \$/kwh	0.05										0.03	0.07						
Real-term increase of electrical power cost, % p.a.	0												1%					
PV energy saving, E, \$1000/GTkm	8.4					6.4	9.5	7.6	6.7	5.4	13.0	3.8	7.4		11.0	14.2	14.2	
PV of locomotive maintenance saving, M _L , \$/1000GTkm	6.3													4.4	8.8	11.6	11.6	
Critical traffic, T, million gross tons	13.7	9.9	17.5	8.2	22.0	15.9	12.7	14.5	15.5	17.3	10.3	20.2	14.7	15.8	10.1	6.5	4.7	

a/ 3 net ton-km for each passenger-km

b/ 3 passenger-km for each net ton-km

Table 9

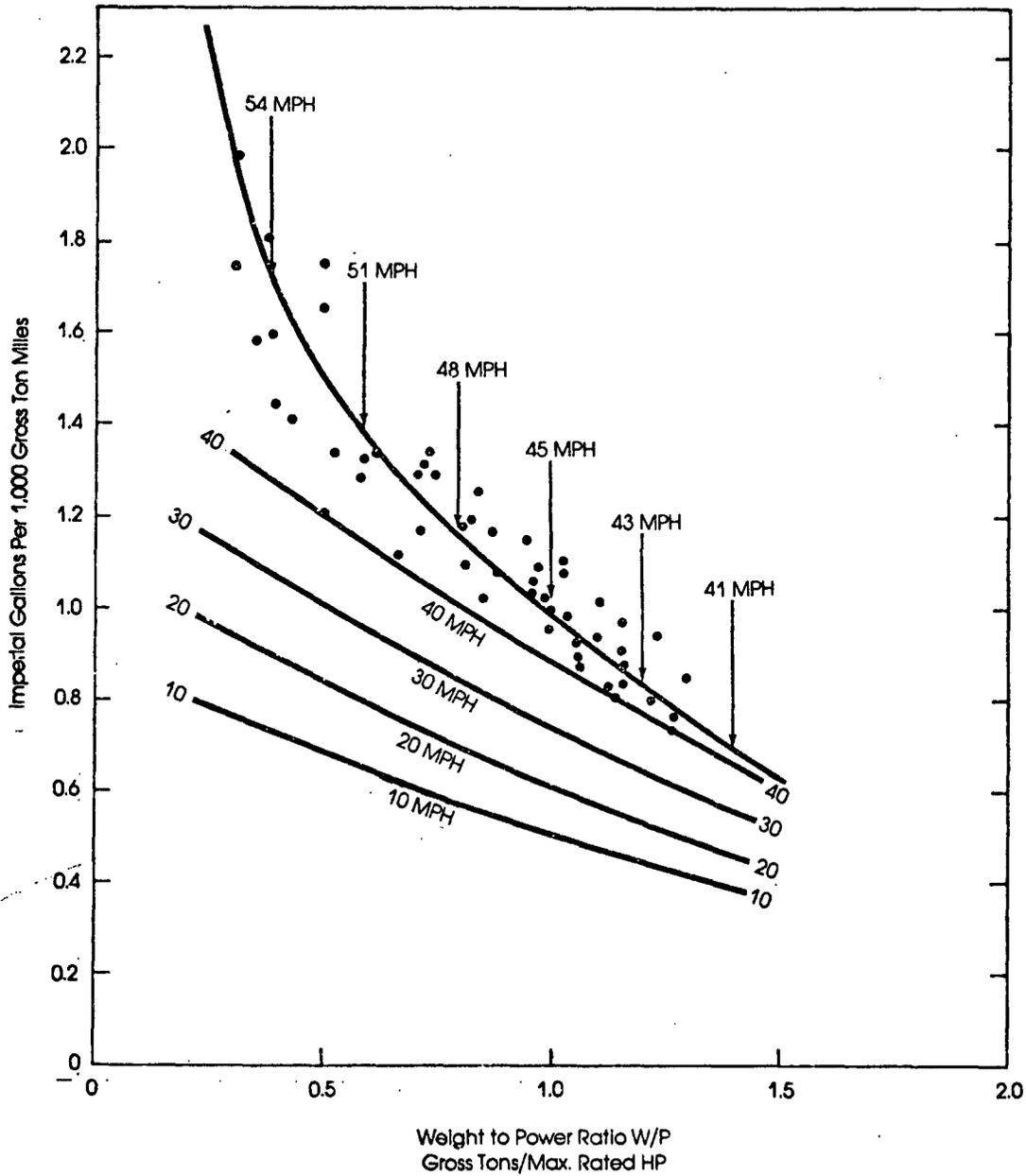
Cost ranges for fixed installations for railway electrification
(early 1982 prices)

	<u>\$000</u> <u>Range</u>	<u>Average</u>
Overhead conductor system, inclusive of masts, per track km	64-87	75+16%
per STRK <u>1/</u>	86-104	96+11%
Railway power supplies for STRK <u>1/</u>	16-48	31+55%
Overhead conductor system and railway power supplies per STRK <u>1/</u> <u>2/</u>	106-148	129+18%
Additional works, excluding railway S+T, per STRK <u>1/</u>	4-146	51+186%
Total cost per STRK	148-252	179+41%

Source: Recently-completed electrification schemes in Finland, France, Japan, U.K., Yugoslavia and Zimbabwe. All schemes were at 25 kV, except 20 kV in Japan. French and Japanese data were for double-track routes and were converted to costs per single-track routes by dividing by 1.8. Data for specialized high speed lines such as Tokaido or TGV were not included.

1/ Single track route km.

2/ Based on total cost of these items in separate electrification schemes, not the sum of the two ranges given in this table.



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Fig. 1. Dependence of energy consumption on the weight-to-power ratio and on speed.

The top curve is based on measurements, as indicated. Average speeds given on it were derived from computerized train performance calculations (TPCs). The four lower curves were obtained from TPCs, for average speeds of 40, 30, 20 and 10 miles per hour, respectively.

Source: Reference 14

Fig. 2. Variation of Rate of Return with Traffic for the Base Case

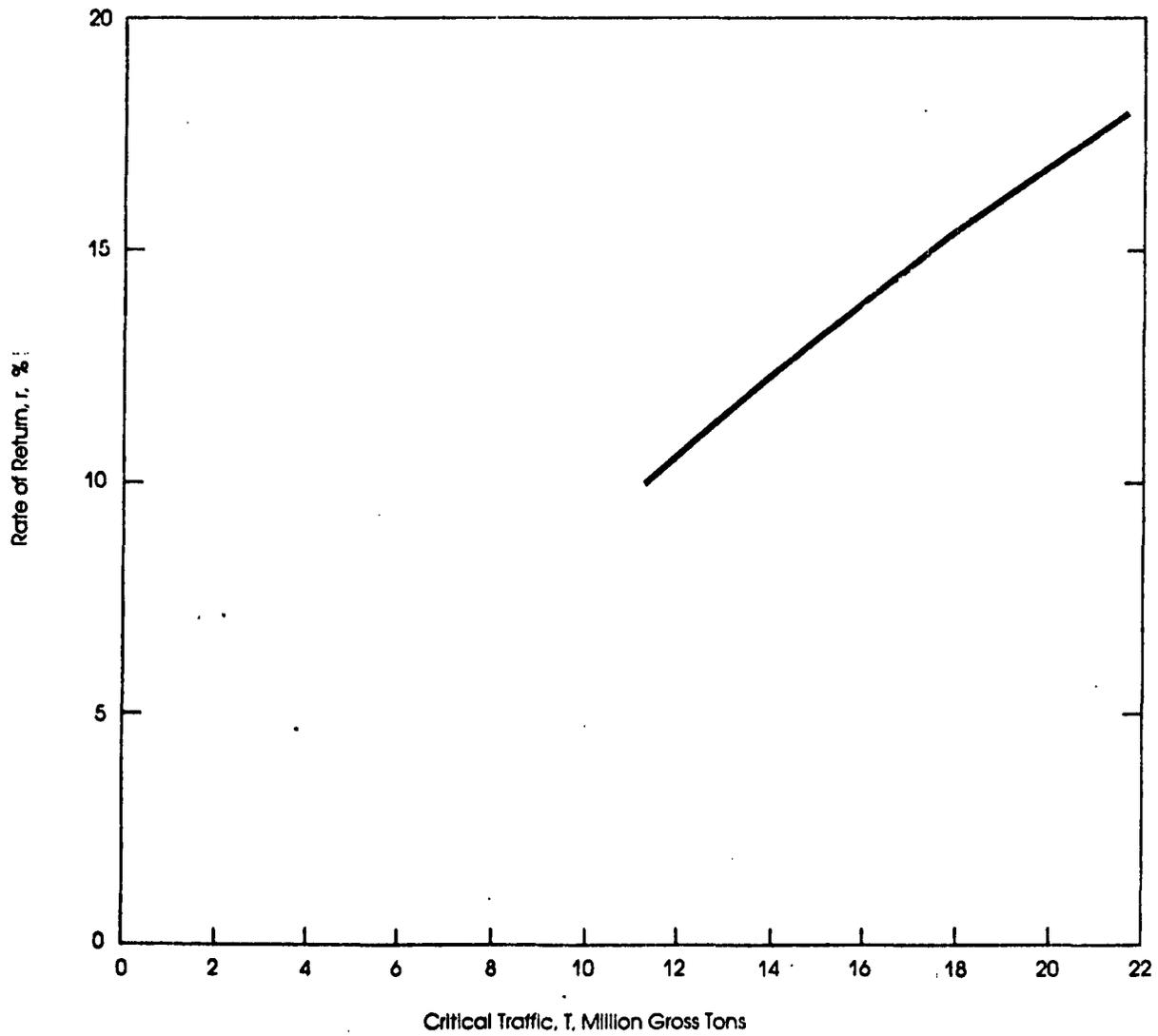
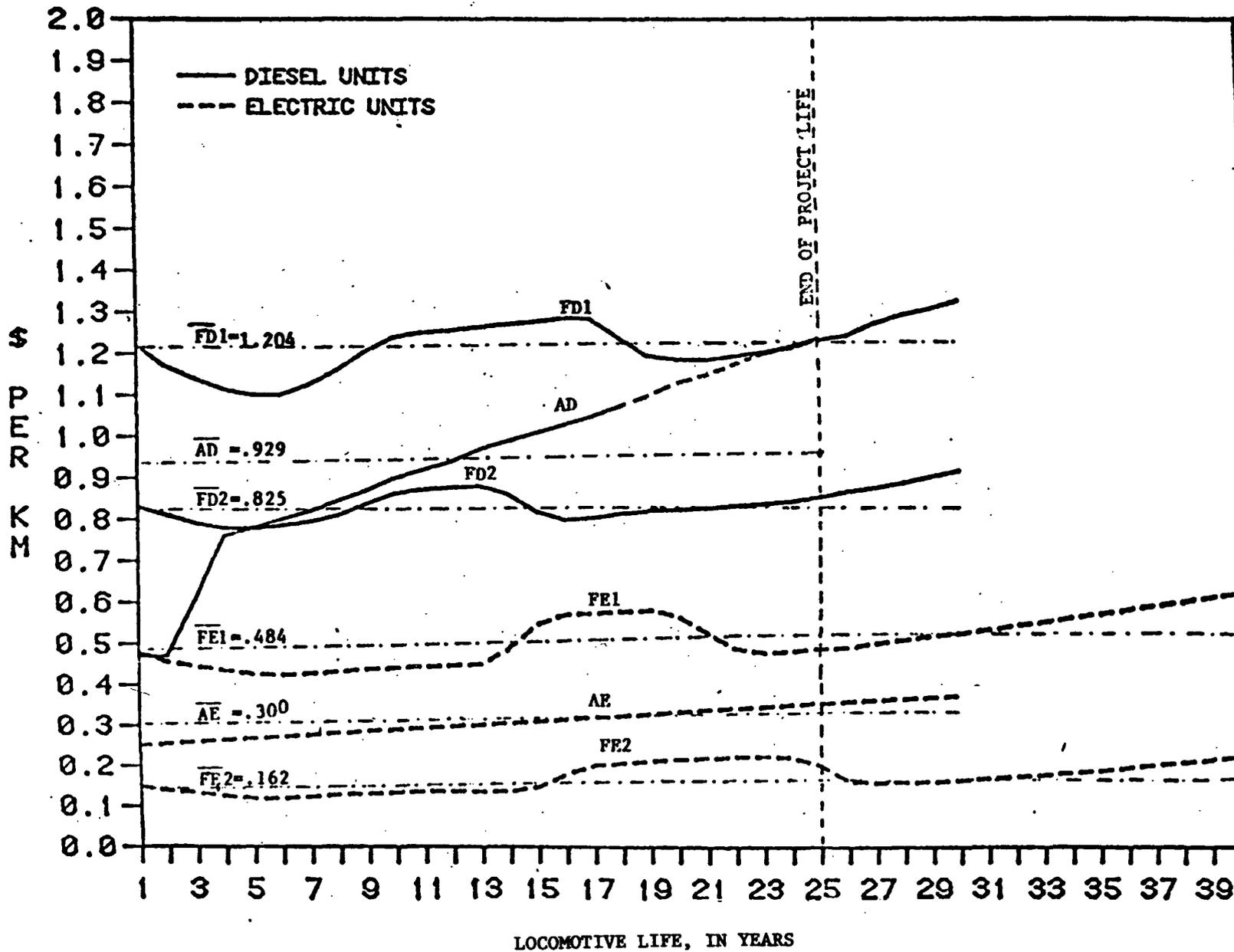


Figure 3

LOCOMOTIVE MAINTENANCE COST \$ PER UNIT KM



World Bank Publications of Related Interest

Alcohol Production from Biomass in the Developing Countries

Explains the techniques for manufacturing ethyl alcohol from biomass raw materials; analyzes the economics of and prospects for production and government policies needed to accommodate conflicting needs of various sectors of the economy in promoting production; and discusses the role the World Bank can play in assisting developing countries in designing national alcohol programs. (One of three publications dealing with renewable energy resources in developing countries. See *Mobilizing Renewable Energy Technology in Developing Countries: Strengthening Local Capabilities and Research and Renewable Energy Resources in the Developing Countries.*)

September 1980. ix + 69 pages (including 12 annex figures). English, French, Spanish, and Portuguese.

Stock Nos. EN-8002-E, EN-8002-F, EN-8002-S, EN-8002-P. \$5.00.

The Economic Choice between Hydroelectric and Thermal Power Developments

Herman G. van der Tak

A logically correct method for handling the economic comparison of alternative systems.

The Johns Hopkins University Press, 1966; 4th printing, 1974. 80 pages (including 2 appendixes).

LC 66-28053. ISBN 0-8018-0646-1. \$5.00 (£3.00) paperback.

The Economics of Power System Reliability and Planning: Theory and Case Studies

Mohan Munasinghe

A completely integrated treatment of system reliability. Indicates that application of the reliability optimization methodology could help realize considerable savings in the electric power sector, which is especially important for developing countries with limited foreign exchange reserves.

The Johns Hopkins University Press, 1980. 344 pages (including tables, maps, index).

LC 79-2182. ISBN 0-8018-2276-9. \$27.50 (£16.75) hardcover; ISBN 0-8018-2277-7, \$12.50 (£6.25) paperback.

NEW

The Effect of Discount Rate and Substitute Technology on Depletion of Exhaustible Resources

Yeganeh Hossein Farzin

The succession of sharp price increases of oil in the early 1970s raised several issues related to competition against OPEC as a supplier of oil and competition against oil as a form of energy. This paper considers the latter form of competition and develops a model to analyze the validity of some basic propositions in the economics of exhaustible resources in the presence of substitutes.

World Bank Staff Working Paper No. 516. 1982. 51 pages (including references).

ISBN 0-8213-0004-0. \$3.00.

Electricity Economics: Essays and Case Studies

Ralph Turvey and
Dennis Anderson

Argues the merits of relating the price of electricity to the marginal or incremental cost of supply and deals with interactions between pricing and

investment decisions, income distribution, and distortions in the pricing system of the economy.

The Johns Hopkins University Press, 1977; 2nd printing, 1981. 382 pages (including tables, maps, index).

LC 76-9031. ISBN 0-8018-1866-4. \$30.00 (£13.50) hardcover; ISBN 0-8018-1867-2, \$12.95 (£5.75) paperback.

French: L'économie de l'électricité: essais et études de cas. Economica, 1979.

ISBN 2-7178-0165-0, 58 francs.

Spanish: Electricidad y economía: ensayos y estudios de casos. Editorial Tecnos, 1979.

ISBN 84-309-0822-6, 710 pesetas.

Electricity Pricing: Theory and Case Studies

Mohan Munasinghe and
Jeremy J. Warford

Describes the underlying theory and practical application of power-pricing policies that maximize the net economic benefits to society of electricity consumption. The methodology provides an explicit framework for analyzing system costs and setting tariffs, and it allows the tariff to be revised on a continual basis. Case studies of electricity pricing exercises in Indonesia, Pakistan, the Philippines, Sri Lanka, and Thailand describe the application of the methodology to real systems.

The Johns Hopkins University Press, 1982. 399 pages (including appendixes, index).

LC 81-47613. ISBN 0-8018-2703-5. \$29.50 hardcover.

NEW

Emerging Energy and Chemical Applications of Methanol: Opportunities for Developing Countries

Methanol, or methyl alcohol, is among the major basic chemical raw materials produced today. This report reviews the major chemical and, particularly, fuel applications of methanol as a basis for projecting the minimal methanol market size during the 1980s and it concludes that there

is a significant potential for additional methanol capacity in developing countries that possess low-cost gas resources, yet, in most cases, do not have an adequate supply of oil. Complements the World Bank report, *Alcohol Production from Biomass in the Developing Countries* (September 1980).

April 1982. viii + 73 pages.

ISBN 0-8213-0018-0. \$5.00.

Energy in the Developing Countries

Discusses the energy problem of the 1970s and the perspective for the next decade. States that by tapping reserves of oil, gas, coal, and hydroelectric and forest resources previously considered uneconomical and by vigorous conservation efforts, oil-importing countries could halve their oil-import bill by 1990. Outlines measures for saving energy without reducing economic growth and exhorts industrialized and industrializing countries to adjust energy prices, incentives, and investments to emphasize domestic production. Proposes a World Bank program for energy lending and explains the operational aspects of the program.

August 1980. vi + 92 pages (including 5 annexes).

Stock No. EN-8001. Free of charge.

Energy Options and Policy Issues in Developing Countries

Darrel G. Fallen-Bailey and Trevor A. Byer

World Bank Staff Working Paper No. 350. August 1979. vi + 107 pages.

Stock No. WP-0350. \$5.00.

Global Energy Prospects

Boum Jong Choe,
Adrian Lambertini, and
Peter K. Pollak

A background study for *World Development Report, 1981*. Examines adjustments in the use of energy that have taken place in five major country groups since the 1973-74 oil price increase. Based on these trends, energy conservation and efficiency, and assumptions about income levels and of a 3 percent annual increase in real energy prices, the paper provides energy projections by major fuels for these country groups in the 1980s.

World Bank Staff Working Paper No. 489. August 1981. viii + 63 pages.

Stock No. WP-0489. \$3.00.

India: The Energy Sector

P. D. Henderson

Summary review of the sector, providing technical, historical, and statistical background information.

Oxford University Press, 1975. 210 pages (including map, 2 appendixes, index).

ISBN 0-19-560653-1. \$12.95

(£3.25; Rs30) hardcover.

Mobilizing Renewable Energy Technology in Developing Countries: Strengthening Local Capabilities and Research

Focuses on the research required to develop renewable energy resources in the developing countries and on the need to strengthen the developing countries' own technological capabilities for using renewable energy. (One of three publications dealing with renewable energy resources and issues in developing countries. See *Alcohol Production from Biomass in the Developing Countries and Renewable Energy Resources in the Developing Countries*.)

July 1981. iv + 52 pages.

Stock No. EN-8101. \$5.00.

Renewable Energy Resources in the Developing Countries

Examines the contributions that renewable resources can make to energy supplies in developing countries and discusses the role of the World Bank in renewable energy development over the next five years. (One of three publications dealing with renewable energy resources and issues in developing countries. See *Alcohol Production from Biomass in the Developing Countries and Mobilizing Renewable Energy Technology in Developing Countries: Strengthening Local Capabilities and Research*.)

November 1980. iv + 33 pages (including annex).

Stock No. EN-8003. \$5.00.

Rural Electrification

Discusses the prospects for successful investment in rural electrification and considers implications for World Bank policies and procedures.

A World Bank Paper. October 1975. 80 pages (including annex). English, French, and Spanish.

Stock Nos. PP-7505-E, PP-7505-F, PP-7505-S. \$5.00.

REPRINTS

Absorptive Capacity, the Demand for Revenue, and the Supply of Petroleum
Salah El Serafy

World Bank Reprint Series: Number 213. Reprinted from *The Journal of Energy and Development*, vol. 7, no. 1 (Autumn 1981): 73-88. Stock No. RP-0213. Free of charge.

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Robert Goodland

World Bank Reprint Series: Number 198. Reprinted from *Environmental Conservation*, vol. 7, no. 1 (Spring 1980):9-26. Stock No. RP-0198. Free of charge.

Optimal Electricity Supply: Reliability, Pricing, and System Planning
Mohan Munasinghe

World Bank Reprint Series: Number 201. Reprinted from *Energy Economics*, vol. 3, no. 3 (July 1981):140-52. Stock No. RP-0201. Free of charge.

The Economic Analysis of Rural Road Projects

Curt Carnemark,
Jaime Biderman, and
David Bovet

World Bank Staff Working Paper No. 241. August 1976. 92 pages (including annexes, tables). English and French. Stock Nos. WP-0241-E, WP-0241-F. \$3.00.

The Economics of Road User Charges

A. A. Walters

Marginal cost pricing and consumer surplus criteria for investment decisions.

The Johns Hopkins University Press, 1968; 3rd printing, 1978. xiii + 243 pages.

LC 68-8702. ISBN 0-8018-0653-4, \$7.50 (£4.50) paperback.

Port Pricing and Investment Policy for Developing Countries

Esra Bennathan and
A. A. Walters

Principles of cost-based prices that can be used to plan port tariffs and practical ways of introducing tariff schedules to improve the allocation of resources and financial performance.

Oxford University Press, 1979. 245 pages (including glossary, bibliography, index).

LC 78-26143. ISBN 0-19-520092-6, \$27.50 hardcover; ISBN 0-19-520093-4, \$12.50 paperback.

Reappraisal of a Road Project in Iran

Herman G. van der Tak and
Jan de Weille

The Johns Hopkins University Press, 1969. 142 pages (including 2 annexes).

LC 68-57489. ISBN 0-8018-1030-2, \$5.00 (£3.00) paperback.

The Road Maintenance Problem and International Assistance

Examines the road maintenance problem in developing countries and describes the Bank's experience in this field.

December 1981. 71 pages. English, French, and Spanish.

Stock Nos. PP-8102-E, PP-8102-F, PP-8102-S. \$5.00.

Road User Charges in Central America

Anthony A. Churchill

The Johns Hopkins University Press, 1972. 188 pages (including bibliography).

LC 70-187219. ISBN 0-8018-1334-4, \$6.00 (£3.50) paperback.

Sector and Project Planning in Transportation

Hans A. Adler

The Johns Hopkins University Press, 1967; 3rd printing, 1973. 88 pages (including annex, bibliography).

LC 67-28574. ISBN 0-8018-0009-9, \$5.00 (£3.00) paperback.

Urban Transport

Attempts to analyze the long-term implications of alternative urban transport strategies and investments in the context of accelerated urban growth in developing countries.

Sector Policy Paper. May 1975. 103 pages (including 7 annexes). English, French, and Spanish.

Stock Nos. PP-7504-E, PP-7504-F, PP-7504-S. \$5.00.

REPRINTS

Determination of Economically Balanced Highway Expenditure Programs under Budget Constraints: A Practical Approach

Thawat Watanatada and Ciell G. Harral;
J. Stuart Yerrell, editor

World Bank Reprint Series: Number 224. Reprinted from Transport Research for Social and Economic Progress, Proceedings of the World Conference on Transport Research, London, 14-17 April 1980, vol. 3 (Gower, 1980).

Stock No. RP-0224. Free of charge.

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