# Analysis of Competitive Relations between Railway Operation Systems

## GENERAL PRINCIPLES AND THEIR APPLICATION TO ELECTRIC AND DIESEL-ELECTRIC TRACTION

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# PREFACE

When the Danish Academy of Engineering Sciences a few years ago started an investigation with a view to elucidating the conditions for a change-over from steam operation to electric or diesel-electric traction on some main lines in Denmark, and a part of this investigation was entrusted to me, I found myself confronted with a problem that was not easy to treat in an exhaustive manner by means of the methods of calculation which were available at that time. However, it proved difficult to find some other and better way out. For this reason, the above-mentioned Danish investigation, which for my part terminated in an expert report dated November 15th, 1954, gave me an impulse to a continued study of the conditions which must quite generally be satisfied in objective investigations of this kind.

The results of this study are embodied in the present publication. The study, however, was not based on the Danish investigation referred to in the above. It was founded on the development of methods of calculation which has been necessitated by the electrification of the Swedish State Railways, and which has been carried on during nearly a whole generation. The outcome of this study is a general method for determining the competitive relations between various means of traction used in railway operation, a method which seems to constitute a natural conclusion of the above-mentioned development.

The method can be applied to all kinds of railway operation. It is simple in principle. It gives reliable results on condition that its application is based on incontestable data which have been verified by experience. Accordingly, a relatively large part of the present publication is devoted to the presentation of the numerical data used in the examples which illustrate the application of the method.

The subject under consideration has been treated by me in an earlier paper entitled "Elektrolok eller diesellok?" (Electric Locomotives or Diesel Locomotives), which was published by the Swedish Association of Engineers and Architects on January 20th, 1956. The present study is an elaboration and expansion of that paper. A few errors which had unfortunately been overlooked in it were amended in this publication.

I hope that the method in question, whose development has been rendered possible by the sustained efforts of many persons in the course of many years, will encourage those solutions of railway traction problems which combine low cost with high quality. This is the only way to achieve true rationalisation and durable success in railway operation.

Stockholm, December 1st, 1956.

*Th. Thelander.*

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# I. INTRODUCTION

Throughout the period from the advent of electric railway operation up to now, its economic aspects and its competitive capacity have been dealt with in many studies. These studies have in the main been concentrated on comparisons between electric operation and other kinds of traction, among which steam operation originally appeared as a self-evident object of comparison. It was soon found from such studies that electric locomotives were enabled by their tractive power and their ruggedness to perform a far greater amount of work than steam locomotives. Hence it followed that no particularly high density or large volume of traffic was required in order that electric operation might be able to outstrip steam operation. It was furthermore found that the superiority of electric operation progressively increased as the traffic became greater.

In a report entitled "Some Results of Electric Traction on the Swedish State Railways", which was submitted to the Fuel Economy Conference of the World Power Conference, The Hague, 1947, I presented a survey of the experiences relating to the economic results and the competitive power of electric railway operation in Sweden at that time. It was demonstrated in that report that electric operation on the Swedish State Railways, as compared with steam operation of the same scope, had resulted during the period of the Second World War alone, from 1939 to 1945, in savings which were more than twice as great as the total capital invested in the electrification of the Swedish State Railways.

This survey was criticised in French quarters, and it was objected that the actual gain must have been greater than the stated gain, since the latter included the savings in fuel costs calculated on the basis of a relation between the fuel consumption in steam traction and the energy consumption in electric traction which, in the opinion of the French specialists, unduly favoured the former kind of traction. Subsequent investigations made in Sweden proved that this objection was to be regarded as justified, and that the miscalculation was due to underestimation of the fact that the fuel consumption in steam traction increases at a higher rate than the energy consumption in electric traction when the train speed becomes greater.

In actual fact, the quality of traction work is the cardinal point in all comparisons between different kinds of traction. If there are differences in quality, then the comparisons are misleading. This circumstance has been realised more and more clearly in the course of time. It has been understood that it is not possible to shun the problem of making reliable comparisons between different kinds of traction on the basis of the tractive parity. As will be shown in what follows, the condition that the alternatives subjected to comparison must stand at tractive parity does not only imply that the costs of fuel and energy as well as the other expenses involved in these alternatives must be referred to identical car tonnages, train speeds, etc. This condition has far more deep-reaching effects, namely, if the condition of tractive parity is satisfied, then it ensures, first, that the different kinds of traction shall enable the railway to derive an adequate income from traffic, and second, that the aggregate resources of the railway, such as permanent way, rolling stock, staff, etc., shall be adequately utilised in each alternative. These are two prerequisites to comparability.

The principle of tractive parity is simple and natural, but it is not easy to apply because the qualitative differences in transportation performance between various kinds of traction are, as a rule, so great as to exclude direct comparisons. It is therefore usually necessary to establish a parity level, i.e. a performance level, by means of calculations. This is an intricate problem, which has given rise to many divergent opinions, and which has attracted attention for a long time.

A step towards the solution of this problem was taken in the 1940ies, when a special method of calculation was evolved at the Royal Swedish Board of Railways. This method has subsequently been used in the course of many years for estimating the economic conditions for change-over from steam operation to electric traction on the Swedish State Railways. The origins of the method in question have been touched upon in some of my earlier studies, e.g. "The Electrification of the Swedish State Railways, Its Economic Aspects and Future Possibilities" (1945) and "Electrification of the Swedish State Railways in Its Engineering and Economic Aspects" (1952). This method is based in principle on the reasoning outlined in what follows.

If steam operation of a railway is to be replaced by rationally utilised electric traction, then it is to be expected that the tractive standard will be raised on account of the superior performance of the electric locomotives. For the purpose of calculation, the change-over to a higher tractive standard may be imagined to be carried out in two stages. In the first stage, steam operation is assumed to be replaced in a reliable manner by electric traction, while the performance level remains identical. In the second stage, the tractive standard is supposed to be raised to a performance level which is natural to electric traction. The capital investment which corresponds to the first stage is brought into relation with the savings which can be expected to be effected in the same stage owing to the change-over from steam operation to electric traction. If these savings are so great that they may be regarded as a satisfactory return on the above-mentioned capital investment, then it has been demonstrated that the change-over to electric operation is justifiable from an economic point of view. This is easily seen since, if steam operation were retained, the transition to a higher tractive standard in the second stage would entail higher costs than in the event of change-over to electric traction.

It follows from the above that the method in question is correct in so far as the calculation is referred to one and the same performance level in both kinds of traction subjected to comparison. Nevertheless, this method has some serious drawbacks. Since the comparison is made with reference to that performance level which is natural to the less efficient kind of haulage, the calculations do not do justice to the more efficient kind of traction. Furthermore, electric operation, as treated in such a calculation, is inevitably charged with a capital which vitiates the comparison. The reason is that the measures which are taken in the imaginary first stage include, among others, the purchase of electric locomotives and stationary electric equipment, which increase the capacity of electric traction above that of steam operation from the very beginning. Consequently, this method leads to undervaluation of electric traction, both because the gains are underestimated and for the reason that the capital charges are overestimated.

It may be surprising that this method has been used on the Swedish State Railways so extensively, in spite of its drawbacks indicated in the above. However, this appears less astonishing in view of the fact that approximate calculations are sufficient when electric operation is compared with a kind of traction which is as inherently primitive as steam operation, and when the comparison relates to railway lines which handle heavy or at least medium heavy traffic. On the other hand, the error margin is too wide to permit the application of this method in those cases where the traction work has not to comply with sufficiently great requirements, and where the kind of traction to be superseded is more economical than steam operation. In such cases it is necessary to resort to some other, more accurate method of calculation. What method, then, should be used?

An answer to this question is given in what follows. The answer is presented in a generally applicable form, and is illustrated by examples, which are based on the numerical data presented in Chapters II and III. These chapters touch on some questions relating to the type of current and transmission in electric traction as well as on the performances and costs to be expected on the basis of experience in the various kinds of railway traction. Steam traction is used in this connection as a common measure which makes possible an indirect comparison of the maintenance costs of locomotives in electric traction and in diesel-electric traction.

# II. ELECTRIC TRACTION SYSTEMS

## a. Type of Current and Transmission

The problems of electric railway operation have always been bound up with questions relating to type of current. The earliest traction systems used low-voltage D.C., and were therefore little suited for extensive railway electrifications. Then came A.C. systems, and one of them, the single-phase A.C. system, rapidly obtained a firm footing. The development of this system is illustrated in Fig. 1.

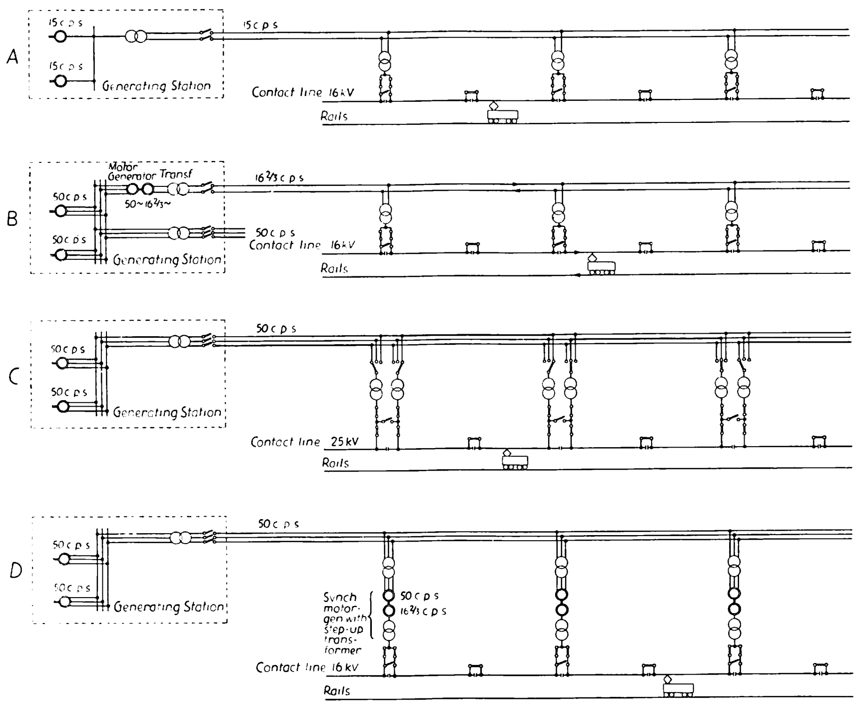



*Fig. 1. Schematic layouts of single-phase A.C. railway traction systems. A. Central generation, separate transmission, frequency 15 c.p.s. B. Central conversion, separate transmission, frequency 16 $^2/_3$ c.p.s. C. Connection to a three-phase A.C. supply system, no conversion or conversion on locomotives, frequency 50 c.p.s. D. Connection to a three-phase A.C. supply system, conversion in substations, frequency 16 $^2/_3$ c.p.s.*

In Sweden, the first single-phase A.C. system took shape in the electrification of the line Luleå—Riksgränsen in 1910 to 1923. The whole layout of this system was typical of its time. Single-phase alternating current was produced in separate generators, and was conveyed to the railway line over separate transmission lines. Aggregation of the railway load and the power demand for other uses was therefore possible only in the utilisation of the water power resources. The voltage was particularly sensitive to load variations since the locomotives were directly affected by the voltage drops not only in the contact lines, but also in the transmission lines. However, this system had a good efficiency in operation, and was entirely independent of the other branches of power supply.

The value of independence in this respect is debatable. It seems to be highly appreciated in German railway circles. At any rate, this appreciation appears to be one of the principal reasons why it was decided in 1954 that the railway electrifications which are now in progress in Germany should be based on the independent single-phase A.C. system, although this decision was made in opposition to the interests and wishes of power producers. All the same, this system will be modified in that three-phase/single-phase converters will be installed in the generating stations. As regards the aggregation of loads, this is a step forward in the right direction, since the three-phase generators will be used in common for the power production in its entirety. For the rest, this system has the same weak points as the original single-phase A.C. system. The high sensitivity of the voltage to load variations and the use of separate transmission lines are the most conspicuous of these drawbacks.

In order to avoid separate transmission lines, a direct-fed power distribution system for railways, which was inspired by previous Hungarian and German designs, has been launched in France. The contact line system is connected through single-phase transformers to the existing three-phase transmission lines. This improves the utilisation of the resources which are normally available in generating stations and in power distribution systems. However, this advantage is bought at the expense of considerable sacrifices, which are briefly indicated in what follows.

First and foremost, it is necessary to put up with unbalanced loads in the three-phase system. Under normal conditions, they are equalised fairly well before they reach the generating stations, but unsymmetrical loads in the transmission and distribution line system are inevitable, and can reach a substantial magnitude. In particular, this is the case when disturbances occur, so that a converting substation has to be taken out of service. On such occasions, heavy unbalanced loads can also be met with in generating stations. It is obvious that the quality of power transmission is impaired by these circumstances, and the resultant drawbacks, which affect the railways as well as the power consumers in general, must influence the power costs of railway operation in some way or another. The direct-fed power distribution system can therefore be regarded as justifiable only in those cases where the amount of power consumed in railway traction is, and may be expected to remain, small in comparison with the amount of power supplied to other users from the three-phase lines utilised for power transmission to railways. In France it is considered that the former power demand may be allowed to amount to 10 per cent of the latter. This is a disputable standard, which can scarcely be supposed to be complied with on all occasions without exception.

The direct-fed single-phase A.C. system makes use of the standard frequency, 50 c.p.s., whereas the before-mentioned separate systems utilise a frequency of 15 or 16 $^2/_3$ c.p.s. Therefore, the direct-fed system, as compared with the latter systems, involves a higher inductive voltage drop in the contact line, produces greater disturbing effects on telecommunication systems, and implies more unfavourable conditions for the design and construction of electric locomotives.

The inductive voltage drop is counteracted by increasing the voltage, in France to 25 kV, as against 16 kV in the low-frequency systems. However, the use of a higher voltage does not eliminate the superiority of the latter systems, for the same increase in voltage, if applied to these systems, would yield a greater profit in respect of transmission. Furthermore, it is in many cases difficult and expensive to provide that space for the contact line which is necessary when the voltage is as high as 25 kV.

Under similar external conditions, the 50 c.p.s. system is more dependent on disturbance-compensating devices than the low-frequency systems, because the disturbances in telecommunication systems increase as the frequency of the railway traction current becomes higher. On the other hand, from an engineering point of view, it is not impossible to prevent interference. Even the use of cables for telecommunication lines is an important improvement in this respect. A still better method is to combine the contact line with negative booster transformers and a return feeder. This method is used in Sweden in conjunction with shielding of telecommunication lines by cables. The voltages induced in the telecommunication system by the railway traction current are thus reduced to values which are, as a rule, less than 0.05 V per 100 A-km.

The table below shows the effects produced by the frequency on the impedance and the induced disturbing voltage. This table represents a special case in so far as it reproduces the results of measurements made on a test line section, which was as short as 35 km and which comprised a part of a large railway yard, where the return feeder was situated in such a manner that it was not able to produce its normal interference-suppressing effect. Nevertheless, the values given in the table are instructive. The disturbing voltages were measured, firstly, on the conductors of a telephone cable laid in the railway embankment, and secondly, on a bare telephone line conductor, which was run along the railway line at an average distance of 390 m from the latter.

| Contact Line System | Impedance Ohms per Kilometre at | | Disturbing Voltage V per 100 A-km in | | | |
|---|---|---|---|---|---|---|
| | | | Cable | | Bare Conductor | |
| | 50 c.p.s. | $16^2/_3$ c.p.s. | 50 c.p.s. | $16^2/_3$ c.p.s. | 50 c.p.s. | $16^2/_3$ c.p.s. |
| Contact line without return feeder and without negative booster transformers | 0.56 | 0.27 | 5.35 | 4.69 | 7.13 | 3.45 |
| Contact line without return feeder but with negative booster transformers | 0.66 | 0.33 | 1.34 | 0.27 | 3.29 | 1.13 |
| Contact line with return feeder and with negative booster transformers | 0.77 | 0.38 | 0.25 | 0.13 | 0.13 | 0.04 |

As is seen from the above table, it is to be expected that the impedance as well as the disturbing voltages induced by the contact line current would be doubled by a change-over from 16 $^2/_3$ to 50 c.p.s. The values given in the table do not include those disturbing voltages which are due to the upsetting of balance in the three-phase supply system by the direct-fed railway power distribution system.

On account of the pulsating magnetic field, the single-phase A.C. commutator motor is exposed to transformer voltages which occur in the armature windings short-circuited by the brushes. This well-known fact is to be regarded as a valid reason for the use of a low-frequency current in railway traction. At any rate, it is more difficult to ensure satisfactory commutation at 50 c.p.s. than at 15 or 16 $^2/_3$ c.p.s. for purely physical reasons. When the French system was first presented for discussion, there was a tendency to abstract from this circumstance. Now it is not disregarded any longer. The advisability of using locomotives equipped with rectifiers on 50 c.p.s. railway systems is attracting attention to an increasing extent. However, objective cost calculations show that such locomotives are more expensive, at least at the present time, than the locomotives designed for low-frequency current operation when they are equivalent in performance. Even if the development of rectifier engineering may be imagined to bring about a change in this respect, such a prospect is too insecure to be counted upon for the time being.

In some French circles it is contended that the above-mentioned difference in price is merely virtual. It is maintained that the rectifier locomotive, whose traction motors run on direct current, possesses such a great qualitative superiority as to afford ample compensation for the difference in price. However, in order to arrive at this conclusion, it is assumed that the low-frequency locomotives are not able to withstand accelerations which are lower than about 8 cm per sec$^2$ under heavy starting conditions, whereas Swedish experience shows that these locomotives are in reality easily capable of withstanding an acceleration which is as low as one-eighth of the above value, i.e. about 1 cm per sec$^2$. In other words, the French argumentation is based on an assumption which is at variance with reality in Swedish practice.

This circumstance may largely be attributed to the development of the single-phase A.C. motor, which has attained a high standard of excellence in Sweden. This work was primarily accomplished by the late Gustaf Thielers, Former Chief Designer of Traction Motors, Asea, a prominent pioneer in this field. To illustrate what he and his co-workers have achieved, it may be mentioned that the total distance which a heavily strained Swedish single-phase locomotive is able to cover before it becomes necessary to re-grind the commutators has been increased in the course of several years from about 50,000 to nearly 800,000 km. It is evident that a comparison of various types of locomotives will lead to different results according as the comparison is referred to different points of this development curve.

The Swedish single-phase A.C. railway traction system has been based since the 1920ies on three-phase/single-phase motor generators, which are installed in railway substations and which are connected to the three-phase supply system. Consequently, the three-phase system is submitted to balanced railway loads. Furthermore, the Swedish system ensures a stable voltage in all feeding points of the contact line system. Moreover, the voltage on the three-phase side is also stabilised because the synchronous motors of the motor generators are over-excited in operation. The integration of loads due to railway traction and to other consumers is ideal. This circumstance has a favourable influence on the power costs.

The leading experts in the German railway administration are of the opinion that the motor generators in the Swedish system result in an unduly low efficiency, that they are not sufficiently reliable in operation, that they constitute an obstacle to the use of non-sectionalised contact lines, i.e. to the parallel connection of the feeding substations on the single-phase side, and that this system is better suited for low-load railway traction than for heavy-load operation. These objections need not remain uncontradicted.

The efficiency of the motor generators has been steadily increasing as a consequence of new and improved designs. When defined within the limits from the three-phase terminals of the motor to the high-voltage terminal of the step-up transformer which forms part of each motor-generator unit, the guaranteed over-all efficiency of the most recent motor generator type used on the Swedish State Railways amounts to about 92 per cent in a wide load range (see Fig. 2). The mean annual efficiency of converting substations operating at a normal utilisation factor is nowadays 85 to 87 per cent. If the reactive power fed to the three-phase supply system is taken into account, then the total efficiency is still higher.

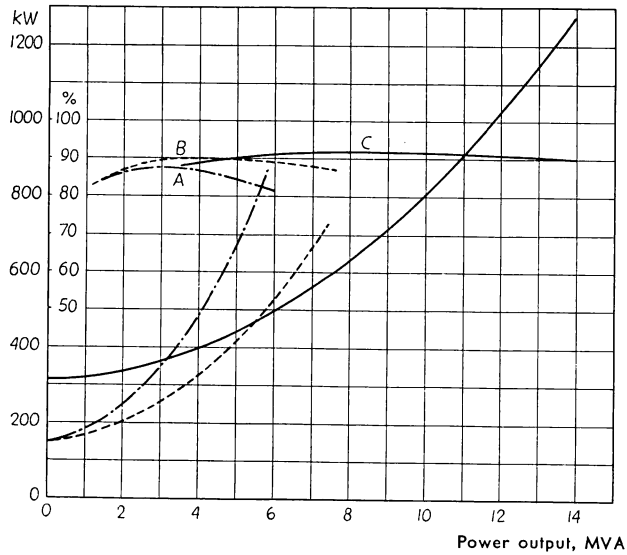



*Fig. 2. Efficiency, in per cent, and losses, in kW, of three-phase/single-phase motor generators, including the single-phase transformers comprised in the units.*
*Ratings: A = 3,300 kVA, B = 5,800 kVA, C = 10,000 kVA.*

The motor generators are dependable in service. Troublesome faults have not occurred more frequently than once in 10 to 15 years per motor-generator set. Furthermore, if the railway power distribution system is connected to an extensively interconnected power supply system which is fed from many generating stations, then, as has been demonstrated by Swedish experience, the railway operation is more reliable than in those cases where the traction current is supplied by an independent single-phase transmission line system, whose resources are more limited.

The converting substations of the Swedish State Railways are normally operated in parallel on the single-phase side as well as on the three-phase side. The operating results are excellent, although the motor-generator sets are equipped with fixed stators. It is to be noted that the phase displacements arising on the three-phase side between the converting substations are reduced to one-third owing to frequency conversion before they reach the single-phase side. Therefore, the phase displacements on the single-phase side are in practice so small that they cannot give rise to any troublesome equalising currents in the non-sectionalised contact line.

Railways are in operation day and night, on workdays and on holidays. The integrated power demand in an extensive railway system is therefore subject to relatively slight variations. As a rule, these variations decrease as the load becomes greater, since an increase in load is usually due to an expansion of the train schedule. Consequently, the motor generators are utilised

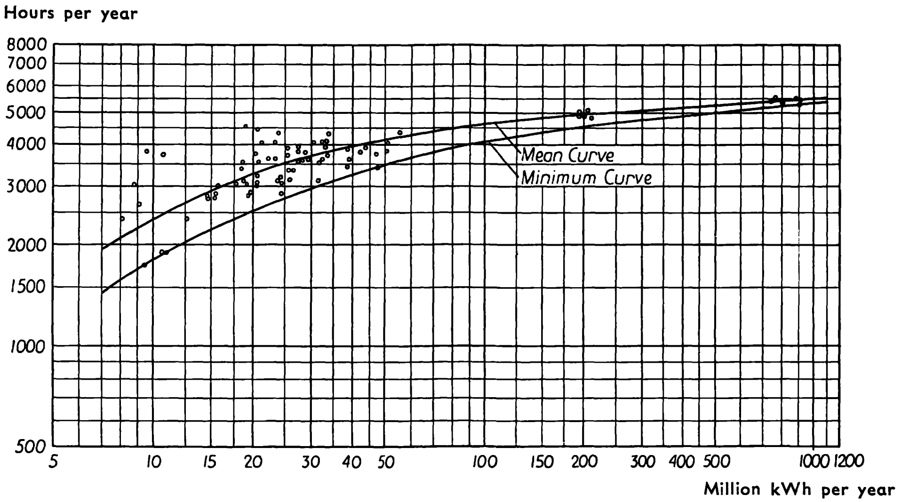



*Fig. 3. Utilisation time of the maximum load, i.e. the annual energy consumption divided by the annual quarter-hour maximum load, on motor-generator sets in converting substations (energy consumption less than 60 million kWh per year) and in substation groups of the Swedish State Railways. The small circles mark observed values, while the curves represent the values used in forecast calculations.*

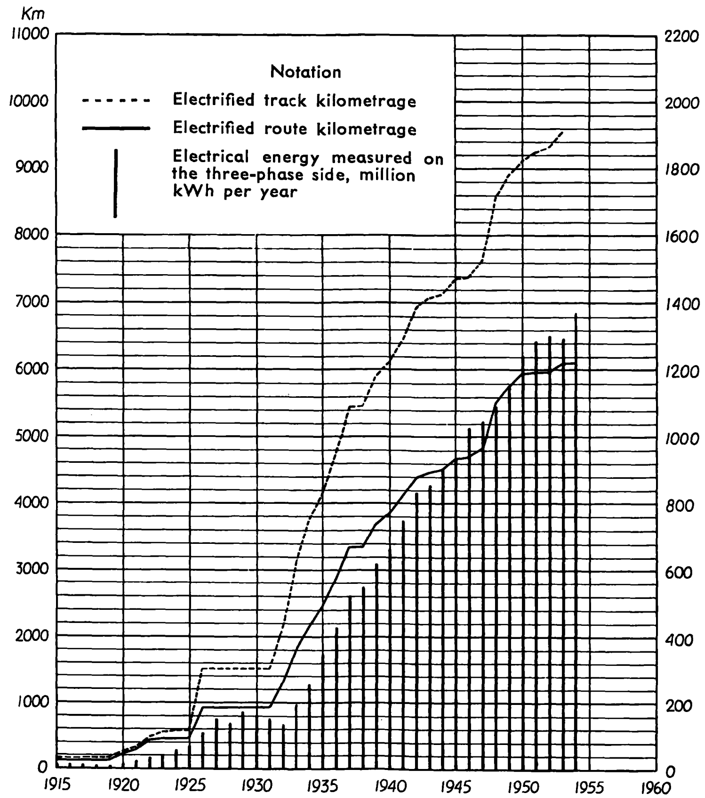



*Fig. 4. Development of the electrified track and route kilometrage and increase in the annual consumption of electrical energy on the Swedish State Railways during the years 1915 to 1954.*

better and better, and the operation becomes more and more economical, as the railway load increases. This circumstance is reflected in the curve representing the utilisation time of the maximum load in individual converting substations and groups of substations on the Swedish State Railways (see Fig. 3). Nowadays, this utilisation time, i.e. the total annual energy consumption divided by the annual quarter-hour maximum load, amounts to about 5,600 hours per year. The development of the annual energy consumption in railway traction is shown in Fig. 4.

*The Swedish single-phase A.C. power distribution system, which is based on motor generators installed in converting substations, is to be regarded as such a good solution of the railway traction problems that it may be justifiable to use this system as a frame of reference in the following comparisons between electric and diesel operation. If some other electric traction system should prove to be more economical, then this would affect the present comparisons only in so far as the competitive power of electric railway operation would be greater than it is demonstrated to be in what follows.*

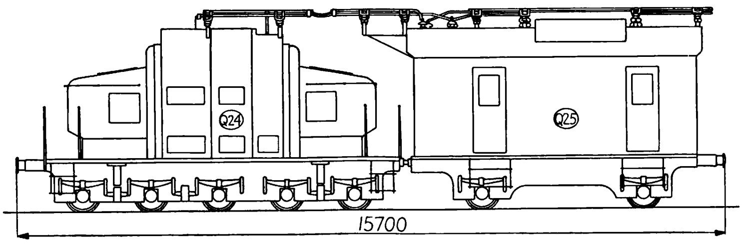
### b. Power Costs

On account of the structure of the power tariff, the progressive load equalisation on the Swedish State Railways has led to a gradual reduction in the average cost of the three-phase A.C. energy purchased by the railways. This trend continued for a series of years, but was interrupted during the Second World War. Irregularities of many kinds were met with in the course of the war years, and the average energy cost varied within relatively narrow limits about the bottom price of the prewar period, which was about 2 Swedish öre per kWh. The power tariff was revised in 1950 in view of the general rise of prices. As a consequence of this revision, the average energy cost during the past few years was about 2.5 Swedish öre per kWh[1].

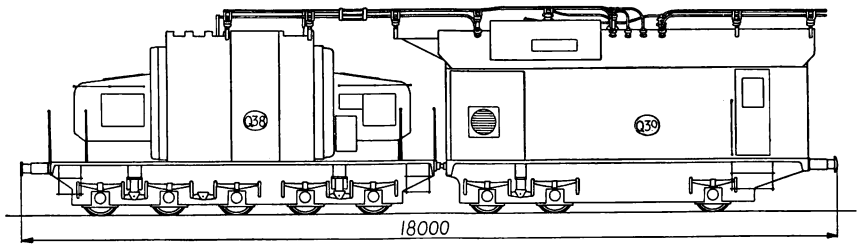
The costs of conversion were largely influenced by the design of the motor-generator sets. Originally, the sets had been built for permanent installation, but a radical change took place in the 1930ies, when mobile motor-generator units were introduced as a standard. Nowadays, they are manufactured in three sizes, which are designed for continuous ratings of 3,300, 5,800, and 10,000 kVA (see Fig. 5). They have an ample overload capacity, and are sufficiently safe against short circuits.

The use of mobile motor-generator units has saved space, facilitated maintenance, and improved the utilisation of reserves. The saving in space is illustrated in Fig. 6 and in the following tables, which also show the influence of the saving in space on the capital expenditure.

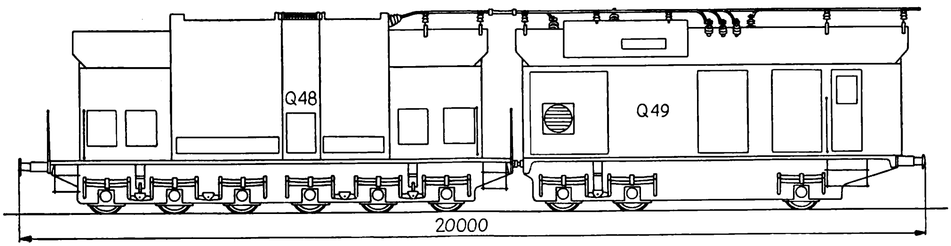
[1] Exchange rate in 1953: 1 £ = 14.50 Swedish kronor, i.e., in round numbers, 1 d $\approx$ 6 Swedish öre.




Rated output 3,300 kVA. Weight 121.8 metric tons




Rated output 5,800 kVA. Weight 144.4 metric tons




Rated output 10,000 kVA. Weight 196.5 metric tons

*Fig. 5. Mobile synchronous/synchronous motor generators coupled with transformer and switchgear cars so as to form self-contained units, 50/16 $^2/_3$ c.p.s., 6/16 kV. Swedish State Railways.*

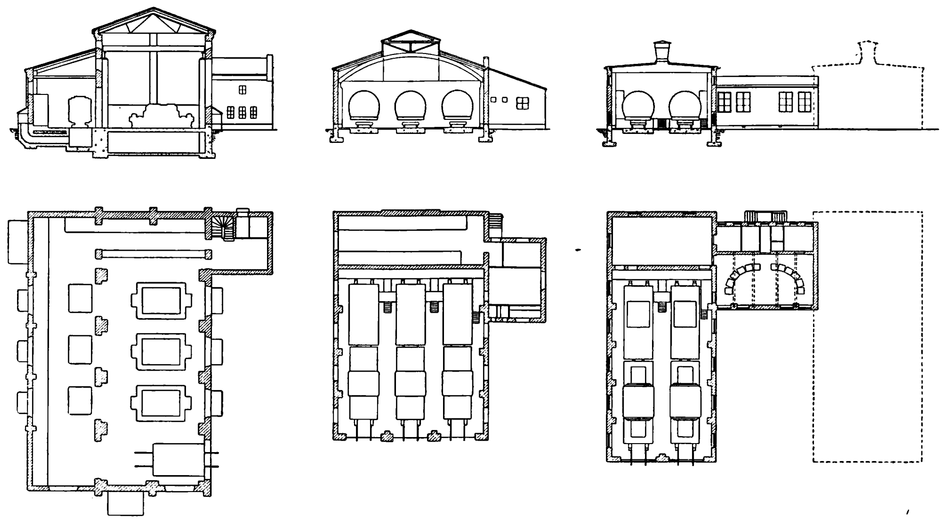


*Fig. 6. Development of converting substations on the Swedish State Railways. Owing to the adoption of mobile motor generators, the building volume was reduced from 660 to 110 m$^3$ per 1,000 kVA.*

*Development of Motor-Generator Sets and Its Effect on Space Requirements.*

| Year | Type of Motor Generator | Continuous Rated Output per Motor-Generator Set kVA | Cost of Motor-Generator Set per kVA | | General Index of Costs (Cost Index in 1936 = 100) | Building Volume per 1 000 kVA $m^3$ |
|---|---|---|---|---|---|---|
| | | | Swedish Kronor | Per Cent of Cost in 1936 | | |
| 1926 | Stationary | 2,900 | 69 | 90 | 109 | 660 |
| 1936 | Mobile | 3,300 | 77 | 100 | 100 | 290 |
| 1946 | Mobile | 5,800 | 95 | 123 | 149 | 175 |
| 1955 | Mobile | 10,000 | 150 | 195 | 211 | 110 |

*Capital Expenditure on Standard-Type Converting Substations.*

| Year | Electrical Equipment | | | | | Buildings | | | Other Capital Expenditure Items Thousand Swedish Kronor | Total Costs | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Motor-Generator Sets | Rated Output per Motor-Generator Set kVA | Costs of Motor-Generator Sets | | Other Costs Thousand Swedish Kronor | Building Volume $m^3$ | Building Costs | | | Thousand Swedish Kronor | Swedish Kronor per kVA |
| | | | Swedish Kronor per kVA | Total Cost Thousand Swedish Kronor | | | Swedish Kronor per $m^3$ | Total Cost Thousand Swedish Kronor | | | |
| 1926 | 3 | 2,900 | 69 | 600 | 160 | 5,740 | 40 | 230 | 70 | 1,060 | 122 |
| 1936 | 3 | 3,300 | 77 | 762 | 150 | 2,854 | 26 | 75 | 40 | 1,027 | 104 |
| 1946 | 2 | 5,800 | 95 | 1,104 | 260 | 2,043 | 61 | 125 | 75 | 1,564 | 135 |
| 1955 | 2 | 10,000 | 150 | 3,000 | 420 | 2,160 | 116 | 250 | 110 | 3,780 | 189 |

The savings effected in this way and the increase in efficiency have caused such a great reduction in costs of conversion that—if all the equipment in operation were modern—the real cost per kWh of single-phase A.C. energy used for electric traction on the Swedish State Railways would now be lower than ever before. This circumstance can be inferred from the data tabulated in what follows.

*Capacity of Standard-Type Converting Substation, Exclusive of 20 Per Cent Stand-By Capacity.*

| Capacity and Turnover | 1926 | 1936 | 1946 | 1955 |
|---|---|---|---|---|
| Regular available power output, exclusive of stand-by, kVA | 7,000 | 7,900 | 9,300 | 16,000 |
| Converted three-phase A.C. energy, million kWh per year | 24 | 29 | 36 | 68 |

*Annual Cost of Standard-Type Converting Substation.*

| Cost Items | 1926 | 1936 | 1946 | 1955 |
|---|---|---|---|---|
| 1. *Interest and depreciation:* | | | | |
| Electrical equipment, Swedish kronor | 41,300 | 49,600 | 74,200 | 186,000 |
| Buildings, Swedish kronor | 12,800 | 4,900 | 8,500 | 15,300 |
| 2. *Operating costs:* | | | | |
| Supervision, Swedish kronor | 15,000 | 15,000 | 20,000 | 55,000 |
| Maintenance, Swedish kronor | 5,000 | 5,000 | 8,000 | 20,000 |
| Total, Swedish kronor per year | 74,100 | 74,500 | 110,700 | 276,300 |
| Total, Swedish öre per kWh three-phase A.C. | 0.31 | 0.26 | 0.31 | 0.41 |

*Mean Annual Efficiency of Conversion and Total Energy Costs.*

| Cost Items and Efficiency | 1926 | 1936 | 1946 | 1955 |
|---|---|---|---|---|
| Mean cost of purchased three-phase A.C. energy, Swedish öre per kWh | 2.90 | 2.08 | 1.90 | 2.50 |
| Cost of conversion, Swedish öre per kWh | 0.31 | 0.26 | 0.31 | 0.41 |
| Total, Swedish öre per kWh three-phase A.C. | 3.21 | 2.34 | 2.21 | 2.91 |
| Mean annual efficiency, per cent, about | 84 | 85 | 86 | 87 |
| Cost of single-phase A.C. energy, Swedish öre per kWh | 3.82 | 2.75 | 2.57 | 3.34 |
| Cost of single-phase A.C. energy reduced to the purchasing power of money in 1936 by means of the general index of costs, Swedish öre per kWh | 3.50 | 2.75 | 1.72 | 1.58 |

In order to simplify the following treatment of the subject, all costs of power purchase and conversion will be referred to the three-phase side, on which the energy consumption is metered. Reduced to the price level in 1953, to which the comparisons of costs made below are referred, the total cost of energy determined in this manner was less than 3 Swedish öre per kWh of consumed three-phase A.C. energy.

### c. Contact Lines

There would be much to say about contact lines if they were allowed to occupy that position in this survey which they deserve. This is obvious since the cost of contact lines is always an important item in the total costs of railway electrification. For this reason, the methods used in the design and construction of contact lines attract well-justified attention.

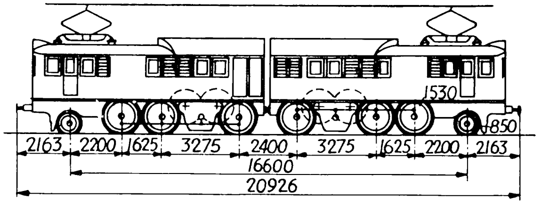
However, for the sake of concentration, we shall abstain from dealing with contact line problems in this study. In what follows, we shall content ourselves with using those contact line costs which are representative of Swedish conditions. For this reason, our calculations are based on the assumption that the capital cost of a complete contact line, including negative booster transformers and a return feeder, is 40,000 Swedish kronor per km and that the annual maintenance and supervision cost is 310 Swedish kronor per km. Both these figures are referred to the price level in 1953. Furthermore, our cost estimates are made on the supposition that the rate of interest is 5 per cent and that the depreciation period on the contact line side is 40 years.

## III. LOCOMOTIVES

### a. Development of Locomotive Types

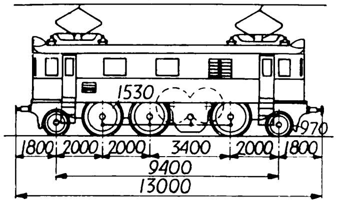
The development of electric motive power on the Swedish State Railways has been concentrated through many years, first, on locomotives, which are either provided with individual axle drive or equipped with coupling rods, Coupling rod drive

1924 - 1944



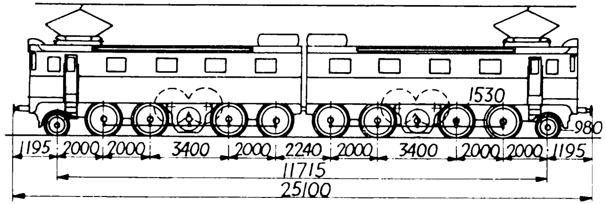

Class Of, 2,800 H.P., 60 km per hour
Weight 134 metric tons. Draw-bar pull 35 metric tons

1925 - 1943



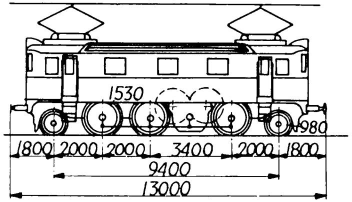

Class D, 1,660 H.P., 75 to 100 km per hour
Weight 80 metric tons. Draw-bar pull 17 metric tons

1953 -




Class Dm, 5,000 H.P., 75 km per hour
Weight 162 metric tons. Draw-bar pull 50 metric tons

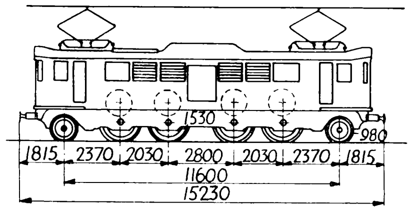
1952 -




Class Da, 2,500 H.P., 100 to 135 km per hour. Weight 75 metric tons. Draw-bar pull 18 metric tons

Single-truck locomotives

1942 - 1948



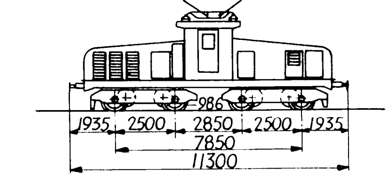

Class F, 3,500 H.P., 135 km per hour
Weight 102 metric tons. Draw-bar pull 18 metric tons

1936 - 1939

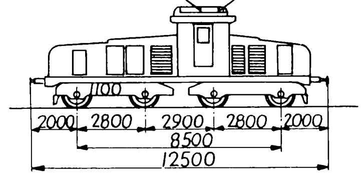
1947 - 1954

Individual axle drive

Double-truck locomotives

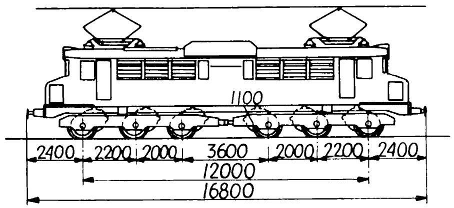



Class Ha, 1,600 H.P., 70 km per hour
Weight 49 metric tons. Draw-bar pull 11 metric tons



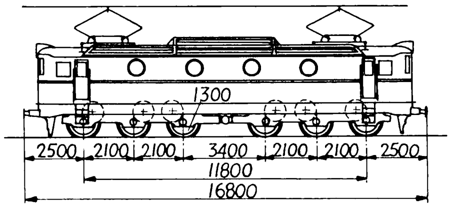

Class Hg, 1,760 H.P., 80 km per hour
Weight 64 metric tons. Draw-bar pull 16 metric tons

1944 - 1945



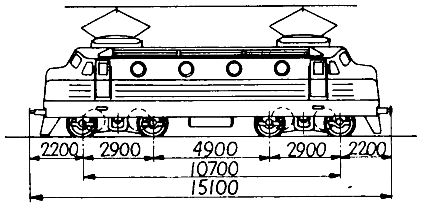

Class M, 3,600 H.P., 80 km per hour
Weight 102 metric tons. Draw-bar pull 30 metric tons

1953 - 1955




Class Ma, 4,500 H.P. 100 km per hour
Weight 104 metric tons. Draw-bar pull 33 tons

1955 -




Class Ra, 3,300 H.P., 150 km per hour
Weight 61 metric tons. Draw-bar pull 15 metric tons

*Fig. 7. Park of electric locomotives on the Swedish State Railways. Main features of development during the years 1924 to 1955. This development was concentrated on locomotives equipped with coupling rods as well as on those provided with individual axle drive.*

and second, on motor coaches. If we confine ourselves to locomotives, then we find that the main features of development can be represented by the data given in the following table and in Fig. 7.

*Main Types of Electric Locomotives*
*Used on the Swedish State Railways in 1955.*

| Class of Locomotive | First Delivered in | Wheel Arrangement | Weight Metric Tons | Driving Axle Load Metric Tons | One-Hour Rating H.P. | Maximum Normal Speed Kilometres per Hour | Normal Maximum Weight of Cars on 10 per Mil Grade Metric Tons | Uses |
|---|---|---|---|---|---|---|---|---|
| Dg | 1925 | 1'C1' | 80 | 17.0 | 1,660 | 75 | 900 | Goods trains |
| Ds | 1925 | 1'C1' | 80 | 17.0 | 1,660 | 100 | 550 | Passenger and express trains |
| Dk | 1934 | 1'C1' | 80 | 17.0 | 2,000 | 100 | 600 | Express trains |
| Da | 1952 | 1'C1' | 75 | 17.0 | 2,500 | 100 | 650<br>900 | Express trains<br>High-speed goods trains |
| | | | | 15.0 | 2,500 | 135 | 450 | High-speed express trains |
| Ha | 1936 | Bo'Bo' | 48 | 12.0 | 1,600 | 70 | 650 | Suburban goods trains |
| Hb | 1939 | Bo'Bo' | 52 | 13.0 | 1,600 | 80 | 650 | Suburban goods trains |
| Hg | 1947 | Bo'Bo' | 64 | 16.0 | 1,760 | 80 | 800 | Suburban goods trains |
| Ra | 1955 | Bo'Bo' | 61 | 15.5 | 3,300 | 150 | 450 | High-speed express trains |
| F | 1942 | 1'Do1' | 102 | 17.0 | 3 500 | 135 | 600 | Heavy express trains |
| M | 1944 | Co'Co' | 102 | 17.0 | 3,600 | 80 | 1,400 | Heavy goods and passenger trains |
| Ma | 1953 | Co'Co' | 104 | 17.3 | 4,500 | 100 | 1,500 | |
| Of | 1924 | 1'C+C1' | 130 | 17.0 | 2,800 | 60 | 2,200 | Iron ore trains |
| Dm | 1953 | 1'D+D1' | 162 | 17.0 | 5,000 | 75 | 3,000—3,500 | Iron ore trains |

As early as in 1924, a very serviceable type of electric locomotive was evolved in Sweden. This was the iron ore train locomotive, Class Of, which has since been used during three decades for hauling heavy ore trains on the line Kiruna—Riksgränsen.

The Class D locomotive, which was derived from Class Of, is an all-service locomotive, which constitutes the backbone of the park of locomotives on the Swedish State Railways. The Class D locomotive exists in four models. The most recent of them, Class Da, has a one-hour rating of 2,500 H.P.

The Da locomotive has served as a basis for the design of the most powerful locomotive that has so far been constructed in Sweden, namely, the new ore train locomotive, Class Dm, which has a one-hour rating of 5,000 H.P. Owing to the introduction of this locomotive, the weight of the cars hauled in loaded ore trains has been increased from 2,000 to 3,000 metric tons, and the maximum speed was at the same time raised from 60 to 75 km per hour.

All above-mentioned locomotives are driven by means of coupling rods via a jack shaft, which is mounted in the main frame. This implies that the number of motors and gears has been reduced to a minimum, that the adhesive weight has been utilised to the greatest possible degree, and that power is transmitted to the driving wheels by the aid of a simple, rugged, and well-balanced device, which enables the main frame and the cab, together with the whole equipment housed in them, including the motors, to be spring-borne in relation to the wheels.

Individual axle drive is based either on motors which are suspended on the axles, or on motors which are completely spring-borne on the wheels.

The use of nose suspenison drive simplifies the design, but has the drawback that the motors are exposed to harmful shocks and vibrations, which become more strongly marked as the speed increases. Furthermore, the nose-suspended motors increase the mass of the unsprung structural parts of the locomotive, with the result that the stresses on the track, which always become heavier as the speed becomes higher, increase at a progressively greater rate. Nose-suspended motors are therefore not recommendable in the cases where high speeds are required.

The use of those types of individual axle drive in which the whole weight of the motor is spring-borne leads to designs which are intricate, and hence expensive, but these types of drive subject the motors to smaller strains and, if rationally utilised, result in a maximum reduction of the weight which is unsprung with reference to the track. Individual axle drive with entirely spring-borne motors is therefore well adapted for locomotives running at extremely high speeds.

Coupling rod drive can be used on single-truck locomotives only, whereas individual axle drive can be employed both on single-truck and on double-truck locomotives.

Individual axle drive was introduced on the Swedish State Railways at the same time as the first electric locomotive, which was delivered on June 9th, 1905. For several concurrent reasons, the individual axle drive was subsequently thrown into the background. Not until the 1930ies did it come into more extensive use on the Swedish State Railways. At that time, it was required to design a light-weight electric locomotive suited for line sections having a weak superstructure. This problem was successfully solved by choosing the Class H locomotive, a double-truck locomotive of the type Bo' Bo'. The first model of this locomotive, Class Ha, had a one-hour rating of 1,600 H.P. and a weight of only 48 metric tons. The Class H locomotive is nowadays built in many variant models, all of which are heavier than the prototype. Most Class H locomotives are equipped with nose suspension drive. This is in conformity with the regular practice, since Class H locomotives are used in suburban goods trains and in passenger trains whose speeds do not exceed about 80 km per hour.

A more powerful double-truck locomotive went into service in 1944, when the Swedish State Railways adopted the Class M locomotive of the type Co' Co', which is designed for heavy mixed train service. This locomotive has subsequently served as a prototype in developing a variant model, Class Ma. Both Class M and Class Ma locomotives are provided with individual axle drive, and the whole weight of each motor is spring-borne. The respective motor ratings are 3,600 and 4,500 H.P.; the respective maximum speeds are 80 and 100 km per hour.

The most recent type of double-truck locomotive acquired by the Swedish State Railways is the high-speed express train locomotive, Class Ra, whose maximum speed is 150 km per hour. This is a locomotive that is specially built for extremely high speeds. Its design is adapted to this use. The weights of the motors in both two-axle trucks are entirely spring-borne. The total motor rating is 3,300 H.P.

The Class F express train locomotive is an intermediate type, which comes between the single-truck locomotives equipped with coupling rod drive and the double-truck locomotives provided with individual axle drive. This is a single-truck locomotive with individual axle drive, in which the entire weight of each motor is supported by springs. It is used in heavy express train service. The rating is 3,500 H.P., and the maximum speed is 135 km per hour.

On the whole, the development of the electric locomotives outlined in the above is characterised by a progressive increase in the rated power output per unit of locomotive weight (see Fig. 8). This trend has in some measure counteracted the effect produced by the general rise of prices on the first cost of motive power, and has improved the performance of the locomotives.

### b. First Cost and Performance

The price of a locomotive should be brought into relation with its performance. If such a relation is correctly established, then it is found that there is a difference in kind between electric locomotives and other locomotives.

The first cost of a Class Da electric locomotive was in 1953, when the Swedish State Railways placed their most recent order for locomotives of this type, 750,000 Swedish kronor, that is 300 Swedish kronor per horse-power. Special attention is called to the fact that the latter figure is obtained if the power output of this locomotive is expressed in terms of its one-hour rating, which amounts to 2,500 H.P. On the other hand, if the normally utilised overload capacity, which is about 40 per cent for Swedish electric locomotives, is taken into account, then it is found that the price of a Class Da locomotive in 1953 was as low as about 200 Swedish kronor per horse-power.

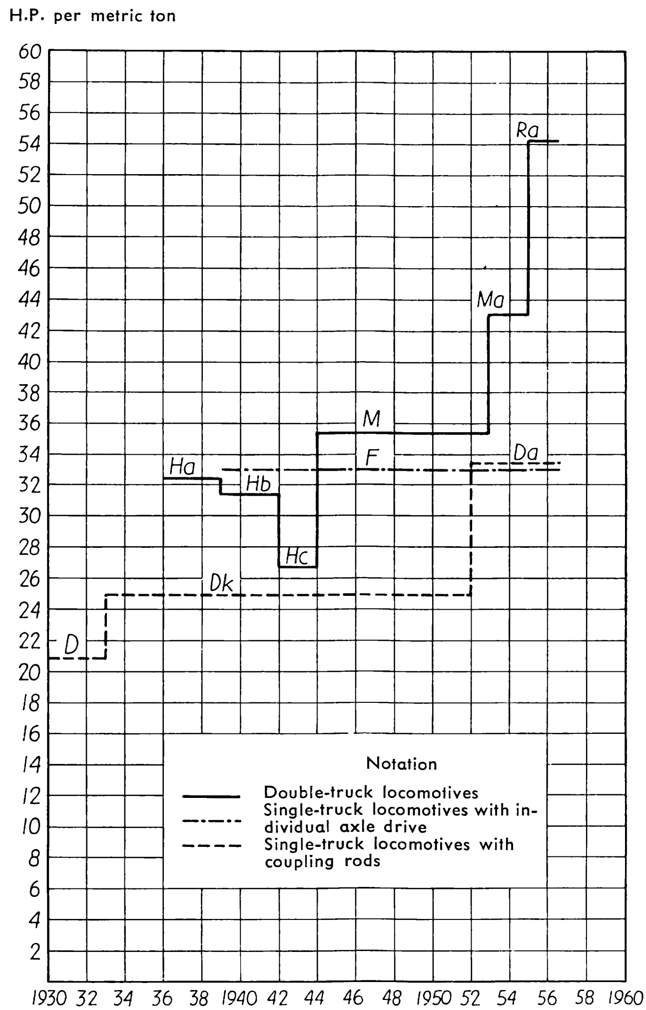



*Fig. 8. Rated power output, in H.P. per metric ton of locomotive weight, of Swedish electric locomotives. Development during the years 1930 to 1955.*

At the same time, a 1,500 H.P. diesel-electric locomotive designed in accordance with American practice and built in Sweden cost about 1,100,000 Swedish kronor, i.e. 735 Swedish kronor per horse-power. If the overload capacity of this locomotive is estimated at 15 per cent, a value which could probably not be exceeded, then the cost of diesel-electric motive power is reduced to about 600 Swedish kronor per horse-power.

It is seen from this example that the capital expenditure per diesel-electric horse-power is 2 to 3 times as great as that per electric horse-power. But this is not the end of the story. In fact, what is of interest in this connection is not the rating of the locomotive—it is the useful power output available at the draw-bar of the locomotive.

The electric locomotive is relatively light. Its weight per horse-power is only about half that of a diesel-electric locomotive. That part of the available power resources which is expended in unproductive work—in propelling the locomotive itself—in diesel-electric traction is therefore considerably greater than in electric operation.

The easiest way to form a concrete idea of the difference between these kinds of haulage is to compare curves which represent the draw-bar pull *available* at the draw-bar of electric and diesel-electric locomotives with curves which express the draw-bar pull *required* for hauling a given weight of cars. The draw-bar pull is expressed in both cases by a function of two variables, viz., first, the speed, and second, the slope of the grade to be ascended.

Such a comparison is reproduced in Fig. 9, from which the values given in the following table were taken as an example. These values refer to the two locomotives mentioned in the above, i.e. the 1,500 H.P. diesel-electric locomotive and the Class Da electric locomotive. Neither of these locomotives represents any culminating point in design. As a matter of fact, the weight of the diesel-electric locomotive might be reduced by 10 or 15 per cent without diminishing the power output, and the weight of the electric locomotive might be cut down still more. All the same, each of these locomotives is such a good representative of the type of traction in question that the tabulated values express a relation which is generally applicable.

*Comparison of Diesel-Electric and Electric Locomotives.*

| Upgrade Per Mil | Balancing Speed km per Hour | Weight of Locomotive Metric Tons | | Weight of Cars Metric Tons | | Weight of Locomotive in Per Cent of Total Weight of Train | |
|---|---|---|---|---|---|---|---|
| | | Diesel-Electric Traction | Electric Traction | Diesel-Electric Traction | Electric Traction | Diesel-Electric Traction | Electric Traction |
| 5 | 50 | 108 | 75 | 675 | 1,450 | 13.8 | 4.9 |
| 10 | 50 | 108 | 75 | 400 | 850 | 21.2 | 8.1 |
| 17 | 50 | 108 | 75 | 250 | 550 | 30.0 | 12.2 |
| 5 | 80 | 108 | 75 | 400 | 1,100 | 21.4 | 6.4 |
| 10 | 80 | 108 | 75 | 200 | 600 | 35.1 | 11.1 |
| 17 | 80 | 108 | 75 | 100 | 450 | 52.0 | 14.6 |

As is seen from this table, if the slope of the grade increases from 5 to 17 per mil, and if the balancing speed is raised from 50 to 80 km per hour, then the weight of cars that can be hauled must be reduced to such a degree that the share of the weight of the locomotive in the total weight of the train varies from about 5 to 15 per cent in electric operation and from about 14 to 52 per cent in diesel-electric traction. Hence it follows, first, that the weight of the locomotives required to haul a given weight of cars increases

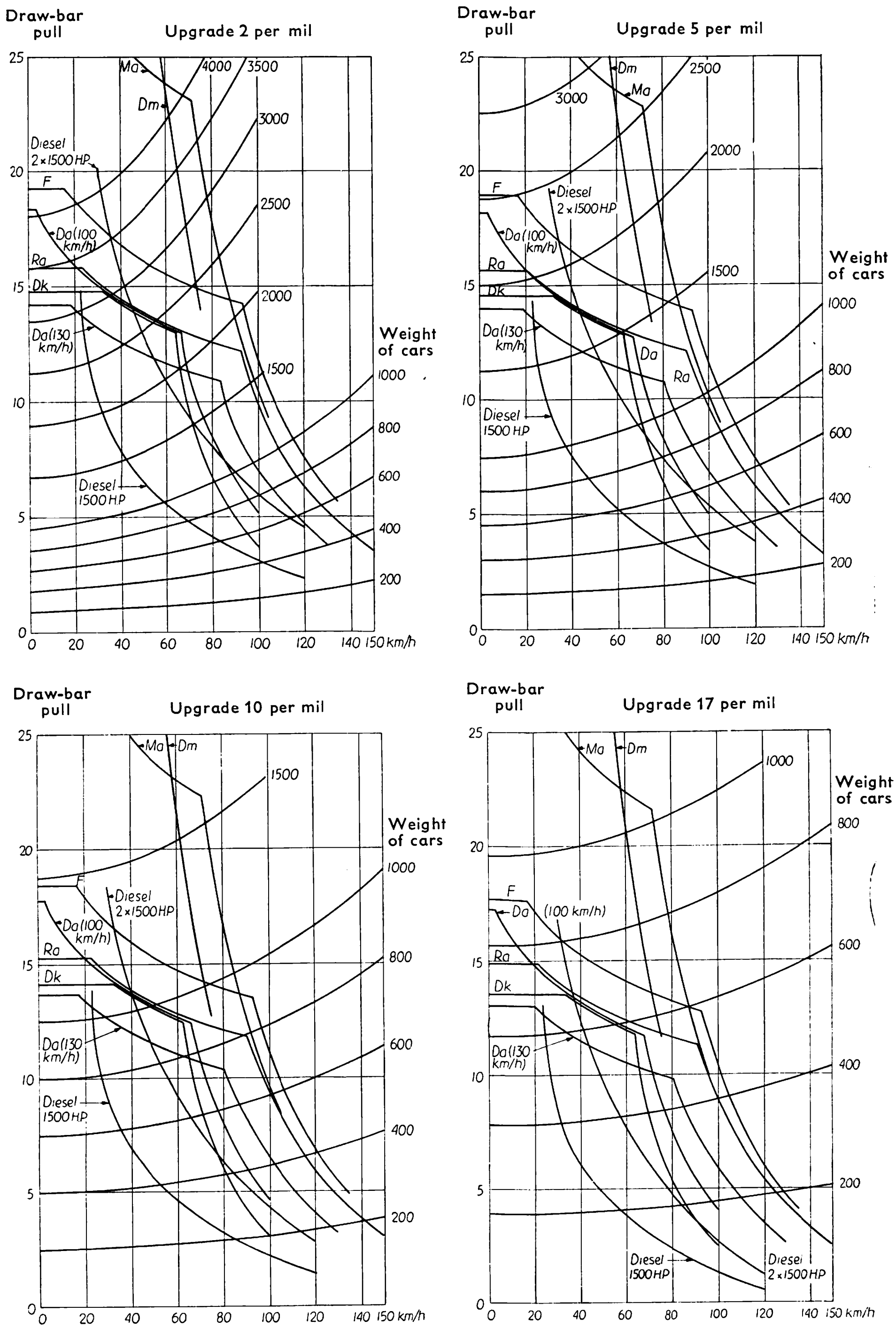



*Fig. 9. The draw-bar pull which is* a v a i l a b l e *at the draw-bar of some types of locomotives and the draw-bar pull which is* r e q u i r e d *at the draw-bar in order to haul a given weight of cars on upgrades of 2, 5, 10, and 17 per mil. The available draw-bar pull curves of the electric locomotives include the overload margins which are normally utilised on the Swedish State Railways. The draw-bar pull and the weight of cars are expressed in metric tons.*

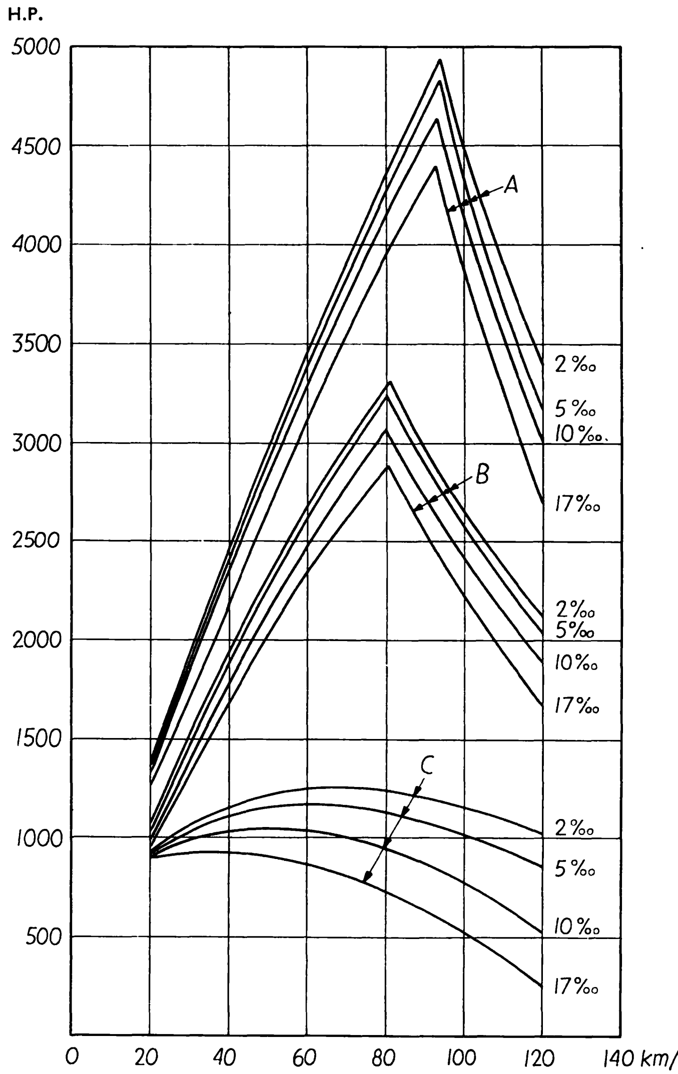



*Fig. 10. The power output, in H.P., available at the draw-bar of the electric locomotives, Classes F (Curves A) and Da (Curves B), and a 1,500 H.P. diesel-electric locomotive (Curves C) at various speeds on upgrades of 2, 5, 10, and 17 per mil. The electric locomotives are able to develop a power output that is considerably greater than their rated power output within a wide range of speeds, whereas the diesel-electric locomotive does not possess this ability.*

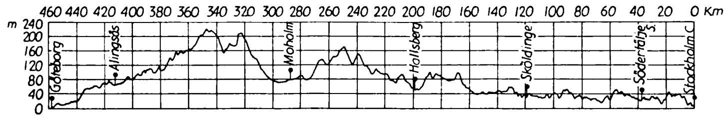
as the speed becomes higher and as the grades to be ascended become steeper, and second, that the rate of this increase in diesel-electric traction is far greater than in electric operation. Consequently, it is in the nature of diesel-electric traction to involve locomotive costs which produce a strongly marked impeding effect on the improvement of the traffic engineering standard. The above table shows that this effect is particularly pronounced in regions of accidented topography. This statement is further corroborated by Fig. 10.

In this connection it should be observed that the extensive use of diesel-electric traction in the United States is in a not inconsiderable degree to be attributed to the topography of that country. In the inland, the trains perform daylong runs extending over broad tracts of flat, open country, which are practically free from difficult upgrades. In the mountainous regions of the East and the West, on the other hand, the character of railway traffic is different. In these regions, the railway men make a virtue of necessity. They utilise the ability of diesel-electric locomotives to develop a great draw-bar pull at a low speed as the trains are slowly hauled up the steep grades. This causes great losses of time, but they are of little importance since they are largely made up for on the wide-stretching plains.

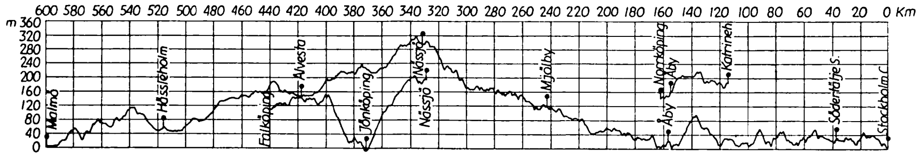
In spite of the circumstance that the train schedules are thus adapted to the topography, the unproductive locomotive weight in the United States often amounts to such a substantial part of the total train weight that the economic aspect of American diesel-electric traction appears to be debatable. Contrary to what one is sometimes led to believe, this statement holds true regardless of the structure of the train service, which is characterised by a large proportion of very heavy trains in the United States. In fact, the draw-bar pull required at the draw-bar of the locomotive per ton of weight of cars remains unchanged irrespective of whether the trains are heavy or light, and is dependent only on the speed and on the lay of the land. Therefore, it seems as if the widespread use of diesel-electric traction in the United States were determined by financial factors rather than by engineering and economic considerations.

If we take this broader view of American diesel-electric traction, then we discover several noteworthy circumstances. We find that very large industrial resources which had been tied up in the manufacture of diesel-electric generating sets for submarines during the Second World War were turned to account by using such sets in railway traction. Furthermore, we realise that diesel-electric traction has enabled the railways to make full use of the production and the distribution of fuel oil, which are well developed in the United States. Moreover, it is possible that some commercial banks which are interested both in railways and in industries tend to favour diesel-electric traction as a business link which induces the former to become important customers of the latter. Finally, it may be presumed that those engaged in high finance prefer to keep their capital in the form of liquid or floating assets, which are readily available for speculation, rather than convert a large part of the capital into permanent or fixed assets. The whole constitutes an intricate and peculiar pattern, which might deserve a detailed analysis. But this subject lies beyond the scope of the present survey.

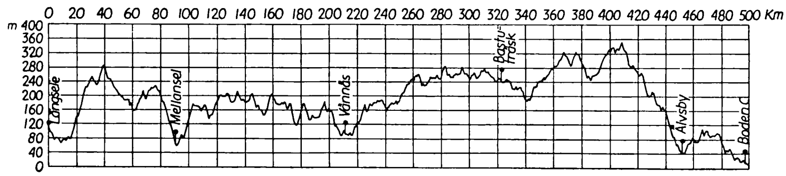
The topographic conditions in Sweden are not similar to those prevailing in North America, as may be seen from Fig. 11. Grades are met with practically everywhere in Sweden. The differences in altitude are not particularly great



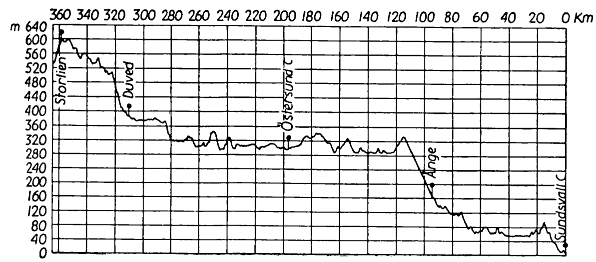

Stockholm—Gothenburg (456 km). Maximum difference in altitude 215 m




Stockholm—Malmö (599 km) and Nässjö—Falköping (113 km). Maximum difference in altitude 315 m.




Långsele—Boden (498 km). Maximum difference in altitude 340 m




Sundsvall—Storlien (359 km). Maximum difference in altitude 600 m

*Fig. 11. Some typical railway line profiles in Sweden.*

—they vary from 200 to 600 m on the main lines—but the inclines are sufficiently frequent, long, and steep to render ample motive power indispensable if a high average speed is to be maintained, and this is indeed the object of all rational railway operation, which aims at short times of travel. Sporadic extreme speed peaks are of small value in this connection. They save little time, whereas they involve great, economically burdensome requirements in respect of the permanent way, the safety devices, and the rolling stock.

### c. Quality of Traction Work

The character of traction work is not only a deciding factor in determining the requisite amount of motive power, which varies according to the kind of railway operation. It also produces marked economic effects on transportation in several other ways, as will be shown in what follows. It is therefore meaningless and erroneous to compare different types of haulage without referring them to adequate performances. This self-evident fact is often overlooked, and here lies the origin of the vague conceptions and the mutually incompatible statements concerning the competitive relations between different kinds of railway traction which now and then appear in specialist papers and discussions.

Consequently, in order to make possible a fair comparison, e. g. between diesel-electric and electric traction, it is first and foremost necessary to determine a certain definite performance level which shall be maintained in both these types of traction. This is a problem in itself, since this level determines the competitive power of the railways and their ability to fulfil their functions in a satisfactory manner. The determination of the performance level is a ticklish task, but it must inevitably be tackled, and this should be done in a progressive spirit.

The performance level, as understood in this connection, that is, as an expression of the quality of traction work, is defined in practice as the time interval in which trains of a given kind shall be able to make a run from one end of a given line to the other, i.e. the total running time. Assume, for instance, that the total running time of express trains on the line Stockholm—Gothenburg (456 km) shall not exceed—according to requirements—4, 5, or 6 hours, alternatively, and that the running times shall be kept within these limits with due regard to the speed restrictions and the duration of stops on this line. Then the total running time in each of these alternatives is a quality-fixing and standardising factor, for this time determines unambiguously the weight of cars which can be hauled when the draw-bar pull is given or, vice versa, the draw-bar pull which is required to haul a given weight of cars. For trains of other kinds, the quality of traction work is specified in an analogous manner.

This method is correct, but its practical application necessitates calculations which involve so much labour that they should preferably be made by some kind of data processing equipment. For lack of such equipment, it is desirable to find simpler methods for determining the quality of traction work. Besides, such methods are indispensable in a general survey, which is not based on any individual line.

Now it is to be remembered that the total running times of trains, particularly in regions of accidented topography, are strongly influenced by upgrades. The speed which can be maintained on upgrades is therefore an expression of the performance level. This expression may be used when it is desired to determine the performance level in a simple manner. Accordingly, the quality of traction work, as understood in what follows, will be indicated by a *quality number*, defined as that balancing speed, in km per hour, which is required to be maintained on a certain definite upgrade in each individual case.

The quality of traction work, as defined in the above, can be either specified, and then it is referred to each separate kind of train, or generalised, and then it expresses an average value for all trains operated on the line or the railway in question. Both these methods will be used in this study. In view of the topographic conditions prevailing in Sweden, the quality numbers will be referred to an upgrade of 10 per mil.

It is obvious that this method of determining the quality of traction work is not so accurate as a method based on the total running time, but the method that we have chosen is sufficiently reliable to elucidate the statement of the problem and to demonstrate the trend of adequate comparisons between various kinds of traction. It is imperative that such comparisons should be made, for without them we grope in the dark, and we may commit fatal mistakes in good faith.

### d. Consumption of Energy, Fuel, and Lubricants

The specific consumption of electrical energy or fuel, that is, the total consumption of energy or fuel divided by the total useful work of transportation, in gross metric ton kilometres (exclusive of locomotives), increases as the requisite quality of traffic becomes higher, i.e. as the quality number becomes greater. The cause of this increase lies in the fact that the train resistance grows higher with the speed, but the rate of this increase varies according to kind of traction. The latter circumstance is partly due to differences in the shape of the efficiency curves. However, it is primarily to be attributed to the above-mentioned variations in the weight of the locomotives required to haul a given weight of cars (cf. p. 26). Consequently, the ratio of the specific consumption of diesel fuel in diesel-electric operation to that of electrical energy in electric traction is a variable equivalent. As a rough estimate, we assume that this equivalent increases from 0.24 to 0.30 kg of diesel fuel oil per kWh of three-phase A.C. energy when the quality number increases from 40 to 100.

The specific energy consumption in electric traction on the Swedish State Railways at a quality number of 70 may be taken to be about 40 Wh of three-phase A.C. energy per gross metric ton kilometre. If this consumption figure is used as a point of departure, and if the above-mentioned variable equivalent is taken into account, then the train resistance curves can serve as a basis for an approximate determination of the specific consumption of energy in electric traction and diesel fuel in diesel-electric traction at various quality numbers. If this determination is made, and if the comparison is extended so that it also includes steam operation, then it is possible to plot curves (see Fig. 12) which represent the probable costs of energy or fuel in these three traction systems.

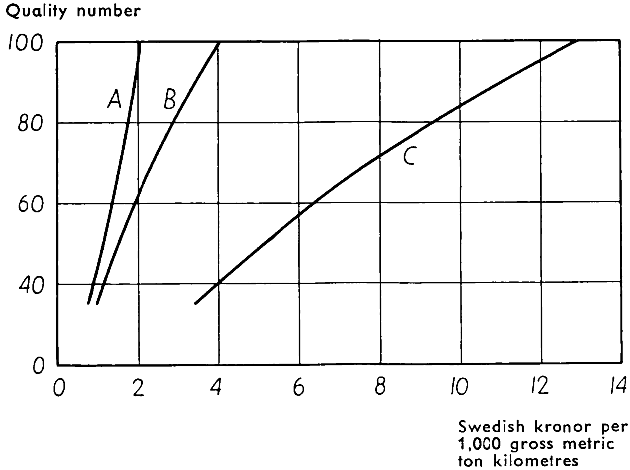



*Fig. 12. Relative costs of electrical energy in electric traction (Curve A), diesel fuel oil in diesel-electric traction (Curve B), and locomotive coal in steam traction (Curve C). Price level: electrical energy, 2.5 Swedish öre per kWh measured on the three-phase side; diesel fuel oil, 15 Swedish öre per kg; and locomotive coal, 80 Swedish kronor per metric ton.*

The curves obtained in this manner are instructive. They verify the above statement that comparisons between different kinds of railway traction are misleading if they are not referred to adequate performances. Furthermore, these curves show that the cost of coal per metric ton kilometre is substantially higher than the corresponding costs of electrical energy and diesel fuel, so that a large saving in costs can be effected by changing from steam operation to electric or diesel-electric traction, whereas the difference between the respective costs of energy and diesel fuel for the latter two kinds of haulage is smaller. Finally, these curves corroborate the assumption that the costs of energy in electric operation and fuel in diesel-electric traction are sufficiently low to ensure that an estimate of these costs which is incorrect within reasonable limits can scarcely be supposed to have any marked influence on a comparison between the total costs of electric and diesel-electric traction. This assumption, whose correctness has been confirmed by some investigations, is noteworthy not least because we may conclude from it that a more detailed study of the diesel fuel equivalent of electrical energy is not to be regarded as called for in connection with this survey.

Electric and diesel-electric locomotives exhibit great differences in the consumption of lubricants. In diesel-electric traction, the consumption of lubricants is usually high; it amounts to about 2 per cent of the diesel fuel oil consumption. On the other hand, electric locomotives equipped with roller bearings require only about 1.5 g of roller bearing grease per locomotive kilometre. The costs of lubrication are of course proportional to these values.



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## e. Maintenance of Locomotives, Wages of Locomotive Crews, and Numbers of Locomotive Kilometres per Year

The maintenance costs of different kinds of locomotives are statistically known, but they are seldom directly comparable, because a type of railway traction which supersedes another kind of haulage is as a rule designed for a greater transportation capacity. It is furthermore to be noted that the available data for comparison of maintenance costs which have been collected in diesel-electric traction in Sweden are hardly adequate, and that our comparisons cannot be directly based on experiences relating to other countries. The reason is that these experiences frequently refer to conditions which do not exist in Sweden. It is therefore necessary to be very cautious in using the available data in order to form an estimate of the comparative costs of maintenance.

Diesel-electric traction in the United States has taken the place of steam operation, while the latter kind of haulage has been superseded by electric traction in Sweden. This circumstance can be used to pave the way for a comparison of maintenance costs in electric and diesel-electric traction—nota bene, on condition that this comparison is based on data collected during periods when both kinds of haulage, i.e. that which was superseded and that which was adopted in its place, were in use side by side. In order to find such data, it is necessary to look back on experiences which are several years old.

In 1946 I got an opportunity to study diesel-electric traction in the United States for the first time. I found that it was easy to obtain statistical data on the economics of diesel-electric traction from the leading manufacturer of diesel-electric locomotives, the General Motors Corporation, while it proved difficult to verify these data in a satisfactory manner by means of comparisons. Not until after having travelled for a few months did I achieve my purpose when I came to Barstow and met one of the top executives in the diesel-electric division of the Santa Fe Railroad. A few days after our first meeting I visited him in his New York office, and he kindly supplied me with the data that I needed. On that occasion, he expressed the wish that the detailed numerical data should not be reproduced in print. Of course, I still respect his wish, but I feel nevertheless at liberty to give here a brief summary of the conclusions which may be drawn from these data.

At the time in question, the Santa Fe Railroad had to a large extent replaced steam operation by diesel-electric traction, and owned a considerable number of multiple unit locomotives rated at 4 × 1,350, i.e. 5,400 H.P., each. These diesel-electric locomotives were 2 to 5 years old. The railroad still had some 30 steam locomotives in operation, which were able to develop approximately the same draw-bar pull as the diesel-electric locomotives, as was demonstrated by draw-bar pull curves. The costs of maintenance varied within wide limits, but the average maintenance costs of the new diesel-electric locomotives were not lower than those of the old steam locomotives. Yet the maintenance of the diesel-electric locomotives was rationalised in a high degree. For this purpose, the overhaul which the locomotives had to undergo after having covered certain definite distances was carefully systematised. Moreover, the workshop operations were facilitated by first-rate equipment, and were very well organised.

Now let us consider Sweden. In this country, electric traction began to take the place of steam operation on a large scale about 1930. The oldest steam locomotives were discarded first. On the other hand, the more recent and more efficient types of steam locomotives remained in service for many years to come. They included, among others, Class B locomotives, all-round locomotives, which are still used in relatively large numbers to-day. The draw-bar pull curve of the Class B locomotive resembles that of the above-mentioned 1,500 H.P. diesel-electric locomotive, and the design of the former is similar to that of the Class D electric locomotive. The Class B locomotive, just as the Class D locomotive, has three coupled pairs of wheels. A comparison of the Class B and Class D locomotives has led to the results which are tabulated below.

*Comparison of Class B Steam Locomotive and Class D Electric Locomotive.*

| Year | Average Distance Covered per Locomotive per Year Thousand Kilometres | | Average Maintenance Cost Swedish Öre per Kilometre | | Cost Ratio B:D |
|---|---|---|---|---|---|
| | Steam Locomotive Class B | Electric Locomotive Class D | Steam Locomotive Class B | Electric Locomotive Class D | |
| 1930 | 68.7 | 107.6 | 22.4 | 9.8 | 2.3 |
| 1932 | 68.1 | 102.0 | 22.5 | 9.9 | 2.3 |
| 1934 | 66.9 | 109.4 | 17.6 | 8.1 | 2.2 |
| 1936 | 70.7 | 113.4 | 18.4 | 8.9 | 2.1 |
| 1938 | 76.9 | 125.1 | 24.0 | 9.7 | 2.5 |
| 1940 | 70.1 | 125.3 | 21.6 | 11.9 | 1.8 |
| 1942 | 42.7 | 139.4 | 32.3 | 13.2 | 2.4 |
| 1944 | 42.2 | 139.0 | 41.2 | 14.2 | 2.9 |
| 1946 | 54.4 | 143.0 | 35.7 | 14.9 | 2.3 |
| 1948 | 49.7 | 146.6 | 48.7 | 14.6 | 3.3 |
| 1950 | 44.2 | 148.3 | 48.4 | 15.1 | 3.2 |

As may be seen from this table, the maintenance cost of the Class B locomotive has been 2 to 3 times as high as that of the Class D locomotive during the whole twenty-year period under consideration. However, this cost ratio is misleading in so far as the Class D locomotive is capable of being at least twice as efficient in operation as the Class B locomotive. This potential superiority has also been put to use in practice. Properly speaking, the Class B locomotive should therefore be replaced in this comparison by a steam locomotive which is more powerful, and hence more expensive in maintenance. That type of Class D locomotive which is cheapest in maintenance, viz., the Class Da locomotive, was taken into service as late as in 1952, and has therefore not influenced the costs given in the above table.

The maintenance costs of both Class B and Class D locomotives have continuously increased in the course of the period in question. This was due to the general rise of prices. The obsolescence of the locomotives has had a smaller effect on the cost of maintenance because this effect was counteracted by progressive rationalisation of maintenance work. The importance of rationalisation may be illustrated by mentioning the fact that the time required for general overhaul of a Class D locomotive has been gradually reduced from 24 to 9 days. This result has been obtained by means of reforms which bring honour in the first place to Mr. S. Nyblin, Head of Electric Locomotive Division, Swedish State Railways. It was he who laid down the fundamental principles for these reforms in the 1930ies. This is pointed out in order to emphasise the fact that not only the upkeep of American diesel-electric locomotives but also the maintenance of Swedish electric locomotives has met with special attention.

If we examine the above data, which relate, on the one hand, to diesel-electric locomotives and, on the other hand, to electric locomotives, both considered in relation to older steam locomotives, and which have been collected in the United States and in Sweden, then we may conclude, without committing any excessively great error, that the steady-state maintenance costs of diesel-electric locomotives are probably 2 to 3 times as high as those of electric locomotives used in a similar manner. Thus, a steady-state cost of about 20 Swedish öre per locomotive kilometre, which is representative of the Class D locomotive in 1953, would correspond to a cost of about 50 Swedish öre per locomotive kilometre in diesel-electric traction.

The wages of locomotive crews in electric and diesel-electric traction are approximately equal, on condition that one-man operation can be used to the same extent for both these kinds of haulage. As a rule, this may be presumed to be the case so long as it is not required to use multiple unit articulated diesel-electric locomotives, which have no counterpart in electric traction. On the Swedish State Railways, the wages of locomotive crews in electric traction amounted in 1953 on an average to about 0.50 Swedish kronor per locomotive kilometre.

Electric and diesel-electric locomotives do not differ to any appreciable degree in respect of service conditions. The need for time out of service for electric locomotives is slightly shorter. Therefore, the number of kilometres per year covered by an electric locomotive is usually some 10 per cent greater than that covered by a diesel-electric locomotive. However, whether this additional performance can actually be utilised or not, depends on the train schedules. Steam locomotives lag far behind in this respect.

# IV. COMPETITIVE RELATIONS BETWEEN RAILWAY TRACTION SYSTEMS

The competitive relations between different kinds of railway traction are elucidated by means of comparisons. It has been demonstrated in the above that these comparisons must be referred to identical performances in order to be equitable. The term "identical performances", as used in this connection, denotes identity in respect of the scope and the quality of traction work. This identity can briefly be expressed by the term *tractive parity.*

Tractive parity has an important economic consequence. If two kinds of traction stand at tractive parity, then they give the railway the same ability to utilise its resources and to derive an income from traffic. On the other hand, tractive parity does not necessarily imply identical expenses. However, since the costs of traction work in different kinds of haulage increase at unequal rates as the requirements become greater, it must as a rule be possible —for any given volume of traffic—to find such a quality level that two kinds of traction operating on this level entail equal costs. In that case, the parity is both tractive and economic, and may therefore be described as *complete parity.*

## a. Complete Parity

If two kinds of traction stand at complete parity, then—and then only—one of them is as good as the other. Consequently, complete parity defines the lines of demarcation which separate the natural fields of use of different kinds of traction from each other, and which are therefore of great importance. The determination and utilisation of these lines of demarcation, or parity curves, is the main problem dealt with in the present publication.

A theoretical and generally applicable solution of this problem is given in what follows. This solution is illustrated by examples which concern the competitive relation between electric operation and diesel-electric operation.

The examples are based on the numerical data given in the preceding chapters. These data have been intentionally referred to an earlier price level. This was done in order to avoid a fruitless discussion of more or less fluctuating market prices, and for the purpose of anchoring the comparisons in price relations which are known in a dependable manner, and which may be expected to result in a reliable picture of the above-mentioned competitive relation.

Complete parity of two kinds of railway traction is determined on the basis of several transportation characteristics, which relate to the length of route, the volume and the density of traffic, the means of traction, and the performance level. This determination can be systematised. The method used for this purpose is illustrated in the following table, which deals with the case where the traffic is handled by means of standard unit locomotives and where the solution of the problem is based on the average quality of the traction work performed by all trains on a given railway line. The procedure remains unchanged in principle if the problem involves certain definite types of trains and a heterogeneous park of locomotives.

| Assumptions and Method of Calculation | Symbol | 1. Electric Traction | 2. Diesel-Electric Traction |
|---|---|---|---|
| Total length of track, in kilometres .... | $A$ | $A$ | $A$ |
| Total length of route, in per cent of $A$ .. | $b$ | $b$ | $b$ |
| Total length of route, in kilometres .... | $a$ | $A \cdot b$ | $A \cdot b$ |
| Density of traffic, in gross metric ton kilometres per route kilometre per year (exclusive of locomotives) .......... | $B$ | $B$ | $B$ |
| Total volume of traffic, in gross metric ton kilometres per year (exclusive of locomotives) ...................... | | $B \cdot a$ | $B \cdot a$ |
| Quality of traffic, expressed in terms of the balancing speed, computed in this case as a mean value for all trains in service on a given line or railway and referred to a certain definite upgrade, in kilometres per hour .............. | $c$ | $c$ | $c$ |
| Mean weight of cars per locomotive, determined for the value of $c$ taken from the draw-bar pull curve of the locomotive type in question[1]), in metric tons .............................. | $Q$ | $Q_1$ | $Q_2$ |
| Number of train kilometres per year, $Ba:Q$ ............................ | $T$ | $B \cdot a : Q_1$ | $B \cdot a : Q_2$ |
| Number of locomotive kilometres per year (exceeds $T$ by a certain definite amount, e.g. 10 per cent) .......... | $L$ | $1.1\ B \cdot a : Q_1$ | $1.1\ B \cdot a : Q_2$ |
| Number of kilometres per locomotive per year, statistical mean value referred to $c$ ........................ | $f$ | $f_1$ | $f_2$ |
| Number of requisite locomotives, $L:f$ .. | $m$ | $1.1\ B \cdot a : Q_1 \cdot f_1$ | $1.1 B \cdot a : Q_2 \cdot f_2$ |
| Unit first cost of locomotives, in Swedish kronor per locomotive .............. | $n$ | $n_1$ | $n_2$ |
| Total first cost of locomotives $m \cdot n$, in Swedish kronor .................... | $N$ | $1.1\ B \cdot a \cdot n_1 : Q_1 \cdot f_1$ | $1.1\ B \cdot a \cdot n_2 : Q_2 \cdot f_2$ |
| Capital charges, in per cent of $N$, calculated on the assumption that the depreciation period is 30 years for electric locomotives and 25 years for diesel-electric locomotives, and that the rate of interest is, say, 5 per cent .... | $g$ | 6.51 | 7.26 |
| Total capital charges for the whole park of locomotives, $g \cdot N$, in Swedish kronor per year .................. | $K$ | $0.072 B \cdot a \cdot n_1 : Q_1 \cdot f_1$ | $0.081 B \cdot a \cdot n_2 : Q_2 \cdot f_2$ |

[1]) A certain definite percentage may possibly be deducted from this value, see p. 41.

| Assumptions and Method of Calculation | Symbol | 1. Electric Traction | 2. Diesel-Electric Traction |
|---|---|---|---|
| Cost of maintenance, statistically determined, in Swedish kronor per locomotive kilometre .................... | $u$ | $u_1$ | $u_2$ |
| Total cost of maintenance of the whole park of locomotives, $u \cdot L$, in Swedish kronor per year .................... | $U$ | $1.1\ B \cdot a \cdot u_1 : Q_1$ | $1.1\ B \cdot a \cdot u_2 : Q_2$ |
| Consumption of energy in electric traction at an assumed quality of traction, in kilowatt-hours per gross metric ton kilometre .................... | $w$ | $w$ | — |
| Diesel fuel oil equivalent of electrical energy at the quality value $c$, expressed in kilogrammes of diesel fuel oil per kilowatt-hour of three-phase A.C. energy .................... | $e$ | — | $e$ |
| Consumption of energy in electric traction, in kilowatt-hours of three-phase A.C. energy per year, or consumption of diesel fuel oil in diesel-electric traction, in kilogrammes per year .................... | $d$ | $B \cdot a \cdot w$ | $B \cdot a \cdot e \cdot w$ |
| Unit cost of electrical energy, including all costs of conversion, in Swedish kronor per kilowatt-hour of three-phase A.C. energy, or unit cost of diesel fuel oil, in Swedish kronor per kilogramme .................... | $k$ | $k_1$ | $k_2$ |
| Total annual cost of electrical energy or diesel fuel oil, $d \cdot k$, in Swedish kronor per year .................... | $D$ | $B \cdot a \cdot w \cdot k_1$ | $B \cdot a \cdot e \cdot w \cdot k_2$ |
| Consumption of lubricants in electric traction, ball bearing grease, in kilogrammes per locomotive kilometre, e.g. | | 0.0015 | — |
| Consumption of lubricants in diesel-electric traction, lubricating oil, in per cent of the diesel fuel oil consumption, e.g. .................... | | — | 2 |
| Total annual consumption of lubricants, $L \cdot 0.0015$ or $0.02 \cdot d_2$, in kilogrammes per year .................... | | $0.00165 \cdot B \cdot a : Q_1$ | $0.02 \cdot B \cdot a \cdot e \cdot w$ |
| Unit cost of ball bearing grease or lubricating oil, in Swedish kronor per kilogramme, e.g. .................... | | 2,00 | 0,70 |
| Total annual cost of lubricants, in Swedish kronor per year .................... | $S$ | $0.0033\, B \cdot a : Q_1$ | $0.014 \cdot B \cdot a \cdot e \cdot w$ |
| Wages of locomotive crews in Swedish kronor per locomotive kilometre .... | $p$ | $p_1$ | $p_2$ |
| Total annual wages of locomotive crews, $p \cdot L$, in Swedish kronor per year .... | $P$ | $1.1\ B \cdot a \cdot p_1 : Q_1$ | $1.1\ B \cdot a \cdot p_2 : Q_2$ |

| Assumptions and Method of Calculation | Symbol | 1. Electric Traction | 2. Diesel-Electric Traction |
|---|---|---|---|
| Capital expenditure on contact lines, in Swedish kronor per track kilometre . . | $r$ | $r$ | — |
| Total capital expenditure on the contact line system, in Swedish kronor . . . . . . | $R$ | $Ar$ | — |
| Capital charges, in per cent of $R$, calculated on the assumption that the depreciation period is, say, 30 years and that the rate of interest is 5 per cent . . . . . . . . . . . . . . . . . . . . . . . . . . . . . | | 5,83 | — |
| Total capital charges for the contact line system, in Swedish kronor per year . . | $t$ | $0.0583\, A \cdot r$ | — |
| Cost of maintenance of contact lines, in Swedish kronor per kilometre per year | $h$ | $h$ | — |
| Total cost of maintenance of contact lines, in Swedish kronor per year . . . . | $v$ | $A \cdot h$ | — |
| Total annual cost of the contact line system, $(t + v) = 0.0583 \cdot A \cdot r + A \cdot h = A \cdot (0.0583 \cdot r + h)$, where $A = a : b$, in Swedish kronor per year . . . . . . . . . . | $E$ | $\frac{a}{b}(0.0583\, r + h)$ | — |

The condition for complete parity of electric traction and diesel-electric traction is
$(K_1 + U_1 + D_1 + S_1 + P_1) + E = (K_2 + U_2 + D_2 + S_2 + P_2)$
or $E = (K_2 + U_2 + D_2 + S_2 + P_2) - (K_1 + U_1 + D_1 + S_1 + P_1)$

In this expression, $a$ enters as a factor into all terms, and $B$ enters as a factor into all terms except $E$. The equation can therefore be reduced by dividing both members by $a$. After that, the equation is solved for $B$ by substituting various corresponding values for the other variables.

This table shows that the capital charges for electric and diesel-electric locomotives, just as the total annual costs of locomotive maintenance, locomotive crews, electrical energy, diesel fuel oil, and lubricants, can be expressed by functions of the traffic density. If the sum of all these costs in diesel-electric traction is equal to the corresponding sum of costs in electric traction, with the addition of the total annual cost of the contact line system, then these two kinds of traction stand at complete parity, on condition that all costs of frequency conversion, which shall be debited to electric traction, are included in the costs of electrical energy, as has been done in the present case. Hence it follows that we can deduce a set of equations, each of which corresponds to a certain definite performance level. These equations are used for calculating that density of traffic which results in complete parity of electric traction and diesel-electric traction. In each individual case, the performance level is expressed in terms of a quality number, which is identical for both kinds of haulage. A point of parity is calculated for each of these quality numbers. The detailed application of the method outlined in the above is explained in the table.

This method is simple. It is obviously nothing but a natural consequence of logical reasoning. All the same, it seems to be new.

The method in question is generally applicable. It is equally well suited for any type of locomotive. It is equally reliable, irrespective of whether it is based on an average quality number calculated for all trains operated on a given line or railway, or on individual quality numbers referred to the various kinds of trains in service. Furthermore, it does not matter whether the quality number is defined in the same way as in the above or in any other manner, provided that it expresses a single-valued relation between the speed and the maximum weight of cars. Moreover, if required, a calculation based on this method can easily be corrected so as to allow for incomplete utilisation of motive power, on condition that equivalent corrections are applied to both kinds of traction to be compared. As has already been indicated in the table, all that is needed for this purpose is to deduct a certain definite percentage, which shall be identical for both kinds of traction, from the weight of cars determined from the draw-bar pull curves. Finally, this method paves the way for solutions of problems involving the determination of the difference in costs between various kinds of traction in those cases where they operate on the same performance level, but where this level is such that their parity is only tractive, i.e. not complete.

The application of the method outlined in the above is illustrated by the following example, which is based on the before-mentioned assumptions. Thus, we start from the price level in 1953 and from the numerical data given in Chapter II and III. We compare, on the one hand, electric traction based on Class Da locomotives and, on the other hand, diesel-electric traction based on locomotive units having an individual rating of 1,500 H.P. We assume, furthermore, that the weight of cars per train is equal on an average to 80 per cent of that weight which each locomotive is able to haul. We suppose, finally, that the price of diesel fuel oil varies from 15 to 20 Swedish öre per kg, and that the length of route is alternatively equal to 50, 60, 70, or 80 per cent of the total length of track. On these assumptions, we obtain the parity curves, i.e. lines of demarcation separating the natural fields of use of electric traction and diesel-electric traction, which are shown in Fig. 13.

These curves are to be regarded as symbolic since they do not relate to any definite line or railway, and therefore express conditions which have no exact counterpart in reality. For example, the tractive power of the locomotives may rather seldom be expected to be utilised as well as it has been assumed to be in this case. However, this need not imply that the curves assign an unduly wide range to electric traction. In fact, if the locomotives are inadequately utilised, then greater waste and losses may be caused in diesel-electric traction, in which locomotive power is more expensive per horse-power than in electric operation.

Furthermore, the relations between the prices and between the performances which have served as a basis for these curves are not unchangeable. Nevertheless, so long as the trends of prices and engineering improvements in

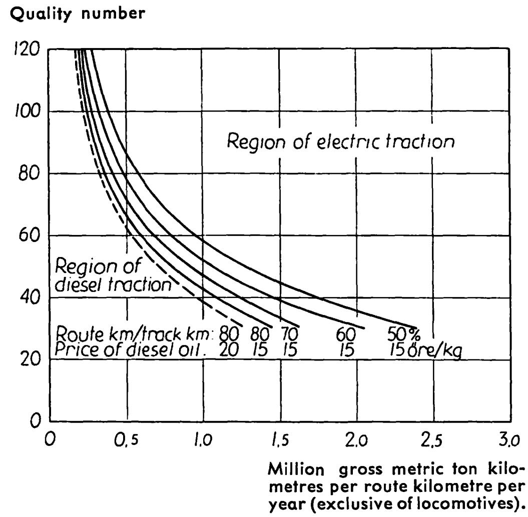


*Fig. 13. Symbolic curves representing theoretical complete parity of electric traction and diesel-electric traction on Swedish railways. These curves are based on the following assumptions: (1) Both kinds of traction are well utilised. (2) The number of route kilometres is alternatively equal to 50, 60, 70, or 80 per cent of the number of track kilometres. (3) The price level is equal to that in 1953. (4) The rate of interest is 5 per cent.*

electric traction are more or less parallel to those in diesel-electric traction, the results calculated in the above will not undergo any appreciable change.

Special stress should once more be put on the fact that equivalence, as represented by the parity curves, is a concept which has a wide scope. This concept implies that the performances in transportation and the costs of traction are adequate, but it goes farther than that. If the transportation is maintained on a certain definite performance level, then the ability of the railway to derive an income from traffic and to utilise its aggregate resources, such as permanent way, rolling stock, traffic and line staff, etc., remains on the whole unchanged, irrespective of whether use is made of the one or the other kind of traction to be compared. Consequently, each point of the parity curve represents a state in which the parity is complete.

## b. Tractive Parity

The regions situated outside the parity curve are characterised by different conditions. The difference in costs between the kinds of traction which stand at tractive parity, but not at economic parity, comes to the front in these regions. This is easily understood from the simple reasoning below.

Assume that the traffic density on a railway line is 1.5 million gross metric ton kilometres per route kilometre per year. Suppose furthermore that the transportation shall be maintained on a performance level which is characterised by a quality number of 60. Then it is to be expected that electric operation of this line will involve considerably lower costs than diesel-electric traction, since the abscissa and the ordinate corresponding to the above-mentioned values of the traffic density and the quality number (see Fig. 13) intersect at a point which is situated far in the interior of the region of electric traction. How shall we determine the difference in cost between these two kinds of traction?.

If the parity curve which is applicable to the above example shows that complete equivalence of diesel-electric operation and electric operation is impossible unless the quality of transportation is reduced to the level characterised by a quality number of 40, then the difference between the quality numbers 40 and 60 gives an idea of the superiority of electric traction. However, it would evidently be incorrect to compare the costs of diesel-electric operation on a performance level of 40 with the costs of electric operation on a performance level of 60, since, as has been demonstrated in the above, the costs of traction of any kind, not least those of diesel-electric traction, increase as the quality of transportation service becomes higher. Furthermore, as a rule, an improvement of quality gives rise to an incalculable gain which consists in an increase of the receipts from traffic and in an improvement of the utilisation of railway resources.

It follows from the above that the changes which an improvement in the quality of transportation service causes not only in the debit items of railway operation, but also in its credit items, have such an effect that the economic comparisons must be made on that performance level which is to be maintained, that is, on the level characterised by a quality number of 60 in the present reasoning. This is a more precise statement of the general condition that the performances in transportation corresponding to different kinds of traction must at least stand at tractive parity in order that these kinds of traction may be comparable.

So long as this condition is satisfied, the problem under consideration can be solved, as is explained in what follows. In that case, the incalculable credit items indicated in the above always remain approximately unchanged, irrespective of the kind of traction. Therefore, these items do not influence the difference in cost to be determined. Consequently, the solution of the problem can be confined to an investigation of the costs of traction, which are relatively easy to determine. However, it is to be observed that identity in respect of performance also implies identity in respect of *capacity* of performance. This follows from the requirement that the amounts of non-utilised motive power corresponding to different kinds of traction must be equal in order that a fair comparison may be possible.

To show how a numerical comparison can turn out when it deals with two kinds of traction which stand at tractive parity, but not at complete parity, is the purpose of the following example, which has been schematised so as to be clear in presentation.

This example is based on a railway line of the same type as the line Stockholm—Gothenburg. The length of the line is assumed to be 500 km. The traffic handled by the line is supposed to be characterised by the data stated in the table below.

| Type of Train | Mean Weight of Cars per Train Metric Tons | Thousand Train Kilometres per Year | Million Gross Metric Ton Kilometres per Year |
|---|---|---|---|
| Express trains | 500 | 3,000 | 1,500 |
| Passenger trains | 300 | 4,500 | 1,350 |
| High-speed goods trains | 700 | 3,500 | 2,450 |
| Suburban goods trains | 350 | 500 | 175 |
| | Total | 11,500 | 5,475 |

The total length of track is assumed to be 1,250 km. It is supposed that all tracks shall be equipped with contact lines in connection with the introduction of electric traction.

The topography of the line and the time table are assumed to be such that the express trains must be able to reach a balancing speed of 80 km per hour on an upgrade of 10 per mil in order to comply with the stipulated running times. The corresponding speeds of the passenger trains and goods trains are supposed to be 70 and 50 km per hour, respectively.

The traffic is assumed to be handled by standard unit locomotives. If it is supposed that the line permits a maximum axle load of 17 to 18 metric tons and a maximum speed of 120 km per hour, then the above-mentioned Class Da, 2,500-H.P. locomotive (weight 75 metric tons) in electric traction and the above-cited 1,500-H.P. locomotive (weight 108 metric tons) in diesel-electric traction can be chosen as standard unit locomotives. The use of standard unit locomotives necessitates the application of the multiple unit system in those cases where the power output that can be developed by a *single* locomotive unit is not sufficient for the execution of the stipulated traction programme.

The requisite draw-bar pull is determined by the stipulated speed and by the *maximum* weight of cars that shall be *capable* of being hauled in each individual train in conformity with the prescribed train schedule. The *scheduled maximum* weight of cars in the present example is assumed to be distributed among the trains of various types in accordance with the table below. If this distribution and the stipulated speeds are taken as a point of departure, then the numbers of locomotive units required for the trains can be determined with the help of the draw-bar pull curves of the locomotives chosen in the above (see p. 27).

The table shows that the requirements assumed in the present example can be fulfilled without resorting to multiple unit locomotives in electric traction, whereas they are to a certain extent necessary in diesel-electric traction. It is furthermore seen from the table that the motive power cannot be exactly adapted to the demands. Margins are available in the form of non-utilised motive power, and these margins in electric traction are in some cases greater than those in diesel-electric traction, while the opposite is true in some other cases. This implies an approximate equivalence in *capacity of performance*, which is a prerequisite to a fair and correct comparison. It is to be observed, however, that, owing to the properties of diesel-electric locomotives, an increase in quality causes the available motive power surplus to be used up in diesel-electric operation much more rapidly than in electric traction. In reality, the margins on the electric side, as compared with those on the diesel-electric side, are therefore greater than the corresponding figures given in the table.

| Train Service Data | Express Trains | | Passenger Trains | | | | | High-Speed Goods Trains | | Suburban Goods Trains | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum weight of cars per train, in metric tons | 650 | 600 | 550 | 400 | 300 | 250 | 200 | 900 | 550 | 900 | 500 | |
| Per cent of the number of train kilometres per year | 80 | 20 | 30 | 10 | 30 | 20 | 10 | 70 | 30 | 25 | 75 | |
| Number of train kilometres per year, thousands.. | 2,400 | 600 | 1,350 | 450 | 1,350 | 900 | 450 | 2,450 | 1,050 | 125 | 375 | 11,500 |
| Number of locomotive units per train: | | | | | | | | | | | | |
| Electric traction........ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| Diesel-electric traction .. | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | |
| Non-utilised capacity of transportation, in metric tons of weight of cars: | | | | | | | | | | | | |
| Electric traction........ | 75 | 125 | 200 | 350 | 450 | 500 | 550 | 100 | 450 | 100 | 500 | |
| Diesel-electric traction .. | 25 | 75 | 0 | 150 | 250 | 25 | 75 | 375 | 300 | 375 | 350 | |
| Number of locomotive kilometres, thousands, in train service per year: | | | | | | | | | | | | |
| Electric traction ........ | 2,400 | 600 | 1,350 | 450 | 1,350 | 900 | 450 | 2,450 | 1,050 | 125 | 375 | 11,500 |
| Diesel-electric traction .. | 7,200 | 1,800 | 2,700 | 900 | 2,700 | 900 | 450 | 7 350 | 2,100 | 375 | 750 | 27,225 |

Number of electric locomotives 11,500,000 : 150,000 = 77
Number of diesel-electric locomotives 27,225,000 : 135,000 = 202

When the scope and the distribution of the train service are known, and when the motive power requirements for the various trains have been determined, we can calculate the total number of locomotive kilometres in train service per year. As is seen from the above table, this number is 11,500,000 in electric traction and 27,225,000 in diesel-electric traction.

On a line of such a length as that in the present case, the average annual number of kilometres per locomotive unit in train service may be supposed not to exceed some 150,000 in electric traction and some 135,000 in diesel-electric traction. Consequently, as may be seen from the table, the requisite numbers of electric and diesel-electric locomotives in this example are 77 and 202, respectively.

Now it remains to calculate the total annual costs of electric and diesel-electric traction. In the present case, the cost calculation is based on the data given in Chapters II and III, which are referred to the price level in 1953.

The capital and depreciation charges for the locomotives are determined on the basis of their number, while the costs of locomotive maintenance are determined on the basis of the total number of locomotive kilometres, which may be assumed to exceed the number of locomotive kilometres in train service by 5 per cent in electric traction and only by 3 per cent in diesel-electric traction on account of the greater number of locomotive units in the latter kind of operation.

The total wages of the locomotive crews are dependent on the rules which fix the number of engine drivers. We assume the rules in diesel-electric traction to be the same as the normal rules in electric traction. Furthermore, we suppose that the crew of each multiple unit locomotive always consists of two men, regardless of the number of units entering into the locomotive. Then we find that the total wages of the locomotive crews in diesel-electric operation are higher than in electric traction. When this difference in wages, which seems to be in agreement with American experiences, is calculated on the assumptions made in the present example, it figures out at about 1.7 million Swedish kronor per year.

The average consumption of electrical energy is estimated on the basis of experience at 41 Wh of three-phase A.C. energy per metric ton kilometre. The energy cost, including all costs of conversion, is supposed to amount to 3 Swedish öre per kWh of three-phase A.C. energy. It is assumed that 1 kWh in electric traction corresponds on an average to 0.27 kg of diesel fuel oil, which costs 20 Swedish öre per kg, in diesel-electric traction. We can thus determine the respective annual costs of electrical energy and diesel fuel oil. The annual costs of lubricants just as those of the contact line system are directly determined from the data given in the respective chapters. In this case, however, the rate of interest is assumed to be $3^1/_2$ per cent.

The annual costs of electric traction and diesel-electric traction are tabulated below.

| Kind of Traction | Annual Costs, Million Swedish Kronor | | | | | | Total Million Swedish Kronor per Year |
|---|---|---|---|---|---|---|---|
| | Park of Locomotives | | Wages of Extra Locomotive Crews | Energy or Fuel and Lubricants | Contact Lines | | |
| | Interest and Depreciation | Maintenance | | | Interest and Depreciation | Supervision and Maintenance | |
| Electric traction.... | 3.14 | 2.42 | — | 6.77 | 2.28 | 0.39 | 15.00 |
| Diesel-electric traction.... | 13.49 | 14.00 | 1.68 | 13.00 | — | — | 42.17 |
| Net difference on the credit side of electric traction ...................... | | | | | | | 27.17 |

This table does not comprise any costs which are chargeable to the converting stations, since these costs have been included in the costs of the electrical energy required for electric traction, as has been indicated in the above.

It is seen from the table that the savings due to electric traction as compared with diesel-electric operation in the present example would be sufficient to pay off the capital cost of the contact line system, which amounts to about 50 million Swedish kronor, in less than two years.

Since the calculation reproduced in the above refers to a schematised example, it does not concretise any definite case. Nevertheless, this calculation is realistic as it is based on assumptions concerning the character of the train service, the volume of traffic, and the extent of the contact line system which are in relatively close agreement with the actual conditions met with in 1953 on the line Stockholm—Gothenburg. Consequently, this comparison may be supposed to give a fairly correct idea of the effects produced by various factors on the competitive power of electric traction in relation to diesel-electric operation. In particular, it is to be observed that the costs of diesel-electric locomotives become predominant when the volume of traffic is great and the quality of traction work is high. The competitive power of electric traction in the present example is therefore increased when the rate of interest becomes higher. On the other hand, it is obvious that an increase in the rate of interest has the opposite effect on cost comparisons dealing with light traffic.

### c. Comments and Conclusions

A competitive power which rapidly increases as the demands on performance in transportation become greater is a distinctive feature of electric traction, as may directly be seen from the parity curves in Fig. 13. This competitive power would also be brought out clearly enough in the last-cited example if the speed requirements were varied, while the other basic assumptions were unchanged.

The same trend of the competitive power of electric traction is illustrated in a different way in Fig. 14. This diagram shows how the competitive relation between electric traction and diesel-electric traction can turn out on Swedish railway lines which handle such a low traffic load that the choice of the kind of traction can be debatable. The horizontal rectangles represent the traffic loads expressed in terms of traffic density. The vertical dash lines mark those limit values of the traffic density at which it may be expected that electric traction and diesel-electric traction will stand at complete parity. This is evident if we note that these limit values were taken from that parity curve in Fig. 13 which may be considered to be most closely applicable to the lines included in Fig. 14. The limit values show that as the demands on the quality of traction work progressively grow greater, a larger number

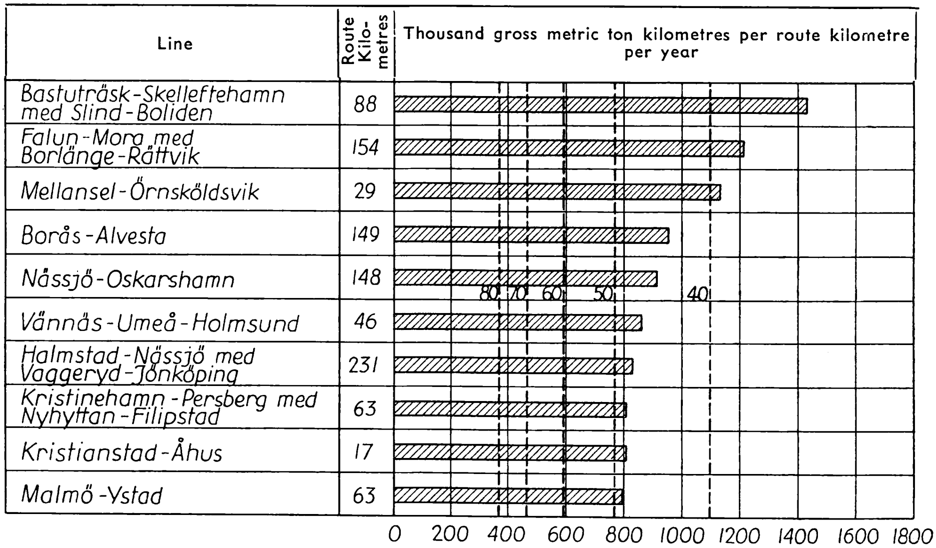


*Fig. 14. Competitive relation between electric traction and diesel-electric traction schematically represented on the basis of the principle of parity. This diagram refers to some Swedish railway lines on which the traffic density is so low that the choice of the kind of traction can be problematical. The thick vertical dash lines mark those values of the traffic density which must be exceeded in order that electric traction in the quality number range from 40 to 80 may be expected to entail lower costs than diesel-electric traction.*

of the lines in question become suitable for electrification, and that the demands need not be particularly great in order that it may be advantageous to electrify all these lines. When the parity curves are utilised in this manner or in a similar way, they may be regarded as a general guiding principle, and they serve as a reminder of the fact that railway electrification in Sweden, just as in most other countries, has not yet reached that extent which it should have. How far, then, should railway electrification be expanded?

This question in each individual case can be answered unambiguously in engineering and economic terms by means of the methods of calculation advanced in the above. It is to be noted, however, that the boundary between the natural fields of use of different kinds of traction can never be fixed definitively. This is due to several causes, which will be touched upon in what follows.

The parity of various kinds of traction is liable to oscillations caused, first, by changes connected with engineering progress and by variations in price level, and second, by fluctuations in the rate of interest, which reflect the state of the capital market and the tendency of financial policy. Apart from these oscillations, however, electric traction is especially advantageous because it is remarkably economical when great demands are made on the efficiency of railway operation. Of course this statement applies in particular to those railway undertakings which direct their energies towards meeting the demands of the users for a *progressive* reduction of the time required for travel and transportation in order to gain and to maintain their competitive power.

The development in the field of energy supply also tends to cause electric traction to come to the front. As the power requirements of human society increase, it becomes more and more imperative that the power resources should be adequately utilised. This object is achieved in the simplest and the best possible manner when the power supply is based on generation, distribution, and consumption of electrical energy. Electric railway operation fits in well with this development programme, whose importance is emphasised by the advent of the atomic age. In fact, electric power is not often utilised better than in traction.

Considered in this connection, the questions relating to the type of current in electric traction are subordinate. It is self-evident that the conditions of equivalence in performance and in capacity of performance, which are prerequisite to comparisons between electric traction and diesel-electric operation, must also be satisfied in the cases where different electric traction systems are to be compared with one another. In such cases, however, it is particularly to be observed that the comparisons should not be confined to the sphere of interest of the railway itself. The general utilisation of the power supply system and the effects of railway traction on telecommunication should also be taken into account. Furthermore, due regard should be paid to desirable uniformity. Development has shown that continued large-scale expansion of D.C. traction systems operating at 1,500 and 3,000 V is scarcely to be expected. Accordingly, the $16^2/_3$ c.p.s. single-phase A.C. systems have become so predominant that their expansion appears to be natural (see the table on p. 51). Moreover, standardisation on this basis offers considerable engineering and economic advantages.

To sum up, we can state that each kind of traction has its own natural field of use, which can be determined by means of accurate calculations. All the same, there is no doubt that electric traction has the future before it. As has been demonstrated in the above, this prognostic rests on two arguments. First, electric traction enables the railways to fulfil their function in an ideal manner. Second, electric traction is in harmony with the general development in the field of power supply. Electric railway operation holds an exceptionally advantageous position in both these respects.

The connection between railway operation and the general power supply shows that the choice of the kind of traction can be influenced by circumstances over which the railway management has no control. Similar observations can be made in the financial sphere, where the railways, which have to compete with other undertakings for capital resources, can find themselves in such a predicament that the requisite capital is not placed at their disposal, or is offered to them on terms which interfere with their freedom of action.

Although the choice of the kind of traction may thus happen to be affected by conditions which are extraneous to railway operation as such, it is nevertheless to be remembered that this choice must be guided by an estimate of the engineering and economic factors met with in each individual case, and that such an estimate must be based on the above-given principles in order to be fair. If the elucidation of these principles can stimulate the interest in a rational determination of the boundaries between the various kinds of traction, and if it can contribute to the promotion of fruitful competition between them, then the present study will have served its purpose.

Stockholm December 1st, 1956.

*Electrified Standard-Gauge Railways in Western Europe.*

(Extract from Eisenbahn-Technische Rundschau, No. 7, 1955.)

| Country | Route Kilometrage | | | D.C. Route Kilometrage | | | Single-Phase A.C. Route Kilometrage | | | | | Three-Phase A.C. Route Kilomet-rage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Electri-fied | Electri-fied in Per Cent of Total | 1.5 kV and Lower | 3 kV | Total | 16 $^2/_3$ c.p.s. | 25 c.p.s. | Total | 50 c.p.s. | Total | |
| Belgium, SNCB.... | 4,973 | 191 | 3.9 | — | 191 | 191 | — | — | — | — | — | — |
| Denmark, DSB.... | 2,643 | 52 | 2.0 | 52 | — | 52 | — | — | — | — | — | — |
| Germany, DB .... | 30,510 | 1,808 | 5.9 | 21 | — | 21 | 1,693 | 38 | 1,731 | 56 | 1,787 | — |
| France, SNCF .... | 41,426 | 4,409 | 10.7 | 4,284 | — | 4,284 | 47 | — | 47 | 78 | 125 | — |
| England, BR...... | 30,968 | 1,508 | 4.9 | 1,508 | — | 1,508 | — | — | — | — | — | — |
| Italy, FS.......... | 16,872 | 5,834 | 34.6 | 15 | 4,490 | 4,505 | 20 | — | 20 | — | 20 | 1,309 |
| Netherlands, NS .. | 3,186 | 1,343 | 42.2 | 1,343 | — | 1,343 | — | — | — | — | — | — |
| Norway, NSB .... | 4,390 | 1,131 | 25.8 | — | — | — | 1,131 | — | 1,131 | — | 1,131 | — |
| Austria, ÖBB...... | 6,005 | 1,360 | 22.7 | — | — | — | 1,295 | 65 | 1,360 | — | 1,360 | — |
| Portugal .......... | 3,589 | 27 | 0.7 | 27 | — | 27 | — | — | — | — | — | — |
| Sweden, SJ........ | 15,078 | 6,089 | 40.4 | — | — | — | 6,089 | — | 6,089 | — | 6,089 | — |
| Switzerland, SBB .. | 2,927 | 2,824 | 96.5 | — | — | — | 2,824 | — | 2,824 | — | 2,824 | — |
| Spain, RENFE .... | 12,992 | 723 | 5.6 | 606 | 86 | 692 | — | — | — | — | — | 31 |
| Total | 175,559 | 27,299 | 15,5 | 7,856 | 4,767 | 12,623 | 13,099 | 103 | 13,202 | 134 | 13,336 | 1,340 |
| | | (100) | — | (28.8) | (17.4) | (46.2) | (48.0) | (0.4) | (48.4) | (0.5) | (48.9) | (4.9) |

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