

MODERNISATION
OF BRITISH RAILWAYS

**THE SYSTEM
OF
ELECTRIFICATION
FOR
BRITISH
RAILWAYS**



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BRITISH
TRANSPORT COMMISSION
LONDON

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OF BRITISH RAILWAYS

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FOR
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WAY 7

BRITISH
TRANSPORT COMMISSION

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I. INTRODUCTION

1. The British Transport Commission, in presenting their Plan for the modernisation of British Railways, have announced their intention to convert to electric traction within the next fifteen years 1,210 route miles of trunk and suburban lines, as well as to extend by 250 route miles the present network of electrified lines on the Southern Region. Thus will be set in hand a programme of electrification which will continue beyond the limits set by the present Plan, until it has been applied to all lines in Britain upon which it can be economically justified.

2. In 1948, the Commission set up a Committee to review existing methods of electric operation on railways, and to recommend the system or systems to be adopted in future electrification in Britain. The Commission in due course accepted the recommendation of the Committee, that the direct-current system with an overhead conductor wire at 1,500 volts should be adopted, other than upon the greater part of the Southern Region, where the third-rail system was established, and upon the railways operated by London Transport. The Committee did not rule out the possibility of using direct current at 3,000 volts, or single-phase alternating current at 50 cycles or a lower frequency for secondary lines with light traffic.

3. Recognising that the last four years had seen rapid developments in the technique of railway electrification, particularly in the field of alternating-current systems, the Commission recently caused a comparative study to be made of the application of the 1,500V d.c. system and of an a.c. system at 25 kilovolts to certain main lines

to be electrified under the Modernisation Plan.

4. With the results of this study in their possession, the Commission have taken a decision of major consequence affecting the system of electrification to be used as the standard in the work that now confronts them. They were aware that their choice would influence the course of electrification on British Railways for all time, and would be practically irrevocable. They also recognised that the system had not only to be the right one for the immediate needs of the Plan, but had also to be the one which showed the greatest promise of technical development to match the needs of the future.

5. Accordingly, the Commission have decided to depart from the electrification systems hitherto used in this country and to adopt as a standard for future electrification the use of an overhead supply of alternating current at industrial (50-cycle) frequency, generally at a pressure of 25kV. They except from this ruling only those parts of the Southern Region where a change in the existing third-rail system is not practicable. Their decision is taken subject to the approval of the Minister of Transport.

6. The following chapters, after providing a brief historical review of railway electrification in Britain and elsewhere, outline the origin and nature of the technical data upon which the Commission have based their decision. At either end of the book is a map of British Railways, upon which are shown the lines to be electrified as part of the Plan in relation to the remainder of the system.

II. HISTORICAL REVIEW OF RAILWAY ELECTRIFICATION

THE FIRST PHASE (1890–1916)

7. The end of the nineteenth century saw the birth of electric traction. Its first application, to tramway systems which up to then had been predominantly horse-drawn, met with great and immediate success.

8. On railways, however, development was much less rapid. The steam engine was giving satisfactory service; behind it lay years of experience, valuable depots and workshops had been built to serve it—and in Britain there were cheap and plentiful supplies of good coal. Justification for electrifying a railway therefore depended on special conditions. In foreign countries where coal had to be imported, and where hydro-electric power was available, electrification suited the national economy. In Britain, however, the first important application was to London's underground railways, where steam operation on the Metropolitan and District lines was becoming intolerable.

9. In 1890, the opening of the City & South London Tube, using electric locomotives, demonstrated the possibilities of electric traction, not only for cleanliness but for rapid acceleration, and foreshadowed the creation of the London Transport railway system as we know it today. A few years later the Liverpool Overhead electric railway was opened, using passenger coaches equipped with motored axles—the precursors of the modern multiple-unit train.

10. In the years preceding the first World War there was a period of activity on the part of the main-line railway companies, during which suburban lines were electrified with conductor rail on North Tyneside; between Liverpool and Southport and Manchester and Bury; and, most important, the London suburban lines of the London & South Western Railway, which marked the beginning of the present Southern Region electrified system. Two lines were electrified on the overhead contact system—between Lancaster, Morecambe and Heysham and on the London Brighton & South Coast Railway between Lon-

don Bridge and Victoria and Crystal Palace. The last major development in this period was the electrification of the Newport–Shildon line of the North Eastern Railway, which also used an overhead wire contact and was supplied with 1,500V direct current. The line was opened in 1916 but reverted to steam operation in 1935, as the traffic using the line decreased.

TECHNICAL FEATURES OF EARLY SCHEMES

11. Development of railway electrification in Britain had, up to 1914, been based almost entirely on d.c. supply, using a conductor-rail contact and making use of the valuable characteristics of the d.c. traction motor, which by this time had already proved its reliability. The practicability of the third-rail system, using the running rails for the return of current to substations, had been effectively established.

12. Generating stations in the earlier years supplied direct current, but at the turn of the century the country's electricity supply was beginning to assume its present form as turbo-alternators were brought into use for the generation of alternating current. For some years frequency was not standardised, and it was not until 1926 that Parliament took the decision which eventually led to the adoption of a 50-cycle standard frequency throughout the country. Early rotary converters, necessary to convert a.c. to d.c. for traction purposes, required a lower-frequency a.c. current for satisfactory performance. Consequently, the railways built their own power stations independently, or used frequency-changers to provide a low frequency current, generally at 25 cycles, for conversion to direct current.

13. Meanwhile, abroad, railway electrification was developing in other directions. It was recognised that for successful application of electrification to main-line routes, requiring haulage of long trains over great distances, a higher voltage than could be carried by conductor rails was necessary for successful operation. National economic circumstances were such that electrifi-

cation of main lines promised to some foreign railways exceptional advantages. Thus, overhead contact systems were developed, using high voltages such as 1,500V and later 3,000V d.c.; and as a.c. traction motors capable of working with low-frequency current had now been introduced certain railways were electrified on single-phase low-frequency a.c. systems, using voltages between 6 and 15kV.

14. The use of the d.c. overhead system was simply a convenient development of the established d.c. traction technique; but the use of the low-frequency a.c. system, coupled with very high voltage, opened the door to substantial economy in the supply of power to the train. A smaller conductor wire sufficed, overhead structures could be lighter, and fewer substations were required. But the a.c. motor was not yet fully developed and could not be made to operate on industrial frequency, and confidence in the system was not universally established. The electrification of the Lancaster–Morecambe–Heysham line in 1908 and the London, Brighton & South Coast line in 1909, both using 6.6kV 25-cycle a.c., were attempts to obtain for this country the benefits of a.c. electrification, but neither was successfully exploited. Then came the first World War, and the railways turned their thoughts to problems of maintenance rather than to improvements in motive power.

THE SECOND PHASE (1919–1939)

15. With the aftermath of the war and the growth of road competition, the railways' earlier hopes for widespread main-line electrification were not realised, but great progress was achieved by the Southern Railway in their suburban and country electrification. The third-rail network was extended to cover the whole of the London area and eventually reached the coast at Portsmouth, Bognor, Brighton, Eastbourne and Hastings.

16. The former London, Brighton & South Coast suburban lines were converted to the third-rail system in 1925. Other suburban railways electrified were the Manchester–Altrincham line (at 1,500V d.c. with overhead supply) and the Wirral Line (at 650V d.c. with the third rail).

17. In 1935, under the Railways (Agreement

Act which provided for various works in relief of unemployment to be undertaken with the assistance of Government credit, two electrification schemes were started on the L.N.E.R. These were the suburban line from Liverpool Street to Shenfield, and the important cross-country trunk route from Wath and Sheffield to Manchester, which carries a heavy coal traffic over the Pennines. In each case, the system adopted was 1,500V d.c. with overhead supply. Both works were suspended soon after the outbreak of the second World War.

STANDARDISATION OF SYSTEMS

18. Until 1932, the choice of system for Great Britain as a whole remained undetermined. Over the world at large, development of d.c. and a.c. electrification was proceeding simultaneously and there was little difference in the total mileages electrified on either system. Meantime, considerable thought was being given in Britain to future policy. The advantages of main-line electrification were being increasingly recognised, and the need for a standard system was clear. There were, however, differences of opinion within the four independent railway companies on the best system to adopt, and there was thus a possibility that the 'Battle of the Gauges' of the previous century might be repeated in a different form. A Committee was therefore set up under the chairmanship of Sir John Pringle to make recommendations.

19. As a result of this Committee's report the Minister of Transport, using his powers to require standardisation under the Railways Act 1921, made the Standardisation of Electrification Order of 1932. This order, which still stands, permits only the 1,500V d.c. system with overhead current collection and a lower-voltage system of 750V d.c. with conductor rail as general standards for main-line operation in this country (3,000V d.c. is, however, permitted for exceptional conditions). Thus the stage seemed set for electrification of the main lines of Britain on the 1,500V d.c. system, but war once more intervened.

THE THIRD PHASE (1945–1951)

20. The immediate pre-war years had seen the

emergence of the diesel locomotive as the prime successor to the steam locomotive in the United States, and the introduction of diesel-motored trains in Europe. Thus, after the period of immediate post-war reconstruction was over and thoughts were turned to new forms of motive power, electrification had to be compared not only with steam, but also with diesel traction.

21. Two important technical improvements had meanwhile been established in the electrical field, namely the mercury-arc rectifier for conversion of alternating to direct current, and remote control of electricity substations, which reduced the operating costs of electrification by eliminating the necessity for substation attendants.

22. A new system of a.c. electrification was appearing, using a supply of current to the contact wire at a frequency of 50 cycles. In the immediate pre-war years, pioneer installations had been operating on the Hungarian and the German Railways, and shortly after the war the French Railways installed, between Aix-les-Bains and La Roche-sur-Foron, a section 55 miles long using 20kV single-phase 50-cycle a.c. Experiments were carried out with locomotives employing both a.c. and d.c. traction motors.

23. In Britain, it was decided to continue with the electrification of the Liverpool Street–Shenfield and the Manchester–Sheffield–Wath lines, started before the war, using 1,500V d.c. as originally planned.

24. In 1948, shortly after the nationalisation of British Railways and London Transport, the British Transport Commission invited both to appoint a joint Committee, to which reference has already been made, with the object of reviewing the methods of electric operation employed on railways at home and abroad, and making recommendations as to the system or systems to be adopted in future electrification schemes in Britain. In 1951, the Commission accepted the recommendations made by the Committee, which were that the d.c. system, with an overhead line at 1,500V, should be adopted as standard in all future schemes, except for an area to be earmarked for extension of the third-rail system of the former Southern Railway. The only other exception was the areas within which the

fourth-rail contact system might be employed in extensions of the London Transport railway network.

25. Thus the Committee and the Commission did not differ with the recommendation of the Pringle Committee made 19 years previously. The Committee did not, however, rule out the possibility of using d.c. at 3,000V, or single-phase a.c. at 50 cycles or a lower frequency, on secondary lines with light traffic where this might be found to be convenient and economical.

26. In considering the a.c. system, the Committee recognised the advantages it possessed in minimising the cost of fixed installations required for power supply, but on information then available considered that this would be counterbalanced by the greater cost of locomotives and powered trains, and by other drawbacks of a technical nature. They nevertheless recommended that an experimental section should be installed on a suitable line.

27. The Commission, having accepted the report, therefore authorised the restoration of electric services on the Lancaster–Morecambe–Heysham line as an experiment in the single-phase 50-cycle a.c. system, using 6.6kV, with powered coaches fitted with mercury-arc rectifiers and d.c. traction motors. They also authorised further suburban electrification at 1,500V d.c. for the London, Tilbury and Southend line, and for extensions of the Liverpool Street–Shenfield line to Chelmsford and Southend.

THE LAST FIVE YEARS

28. Experience obtained on the experimental section has proved beyond question that standard d.c. motors used in association with mercury-arc rectifiers are entirely satisfactory and reliable in operation. Within the last few months, trials have been carried out with germanium rectifiers which show great promise; the trials are of special interest, for this was the first time such rectifiers had been used for traction purposes anywhere in the world. Their technical significance is discussed in more detail in paragraph 91.

29. Meantime, the French Railways had decided, as a result of the success of their experimental line at Aix-les-Bains, to adopt the 25kV single-phase 50-cycle a.c. system for the important

electrifications of the railways in north-eastern France, which carry the heaviest industrial traffics in the country. This decision was made notwithstanding the success of electrification elsewhere in France on the 1,500V d.c. system, notably on the Paris-Lyon route, which is 320 miles long and has been completed since the War.

30. Operation of a section between Valenciennes and Thionville began in July 1954, and in May 1955 the French Railways invited an international group of railway engineers to a conference at Lille, at which they presented the complete results of their experience after nine months' operation of the new system. They demonstrated that considerable economies had been achieved in the cost of fixed equipment, after taking into account the cost of additional insulation and the alterations to structures required to provide the greater electrical clearances for the overhead wire necessary for the higher voltage. Further, the claim was made that, contrary to earlier expectations, the a.c. locomotives they had introduced were cheaper and lighter than the d.c. counterpart for equivalent duties.

31. In Britain, the Modernisation Plan pub-

lished in December 1954 announced a programme of main-line electrification which has, for its ultimate aim, application to all lines in the country where it can be financially justified, so that full advantage can be taken of the possibilities flowing from the coming introduction of atomic power for the generation of electricity.

32. In view of the importance of the developments which had taken place in the technique of a.c. electrification since their acceptance of their Committee's report in 1951, the Commission recognised the possibility that its scope for further improvement would be greater than appeared likely with the systems already established in Britain. On the recommendation of their Technical Development & Research Committee, therefore, the Commission instructed their officers to carry out a survey of a typical main line, and to obtain estimates of the cost of construction, equipment and operation for electrification by both the 1,500V d.c. and the 25kV 50-cycle a.c. systems. The evidence that was placed before the Commission is described in the following chapters, together with the reasons that led them to their final decision.

III. THE CHOICE OF SYSTEM

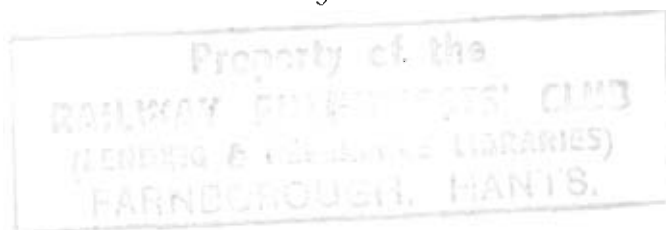
SCOPE OF COMPARATIVE SURVEY

33. The Commission had before them two alternatives. They could continue to pin their faith to the well-established 1,500V d.c. system, already in operation on the Liverpool Street-Shenfield and Manchester-Sheffield-Wath lines, and in course of installation between Shenfield and Chelmsford and Southend. This was the convenient choice, for it presented few technical problems to the railway engineers or to industry, and offered the advantage of continuity of practice and manufacture.

34. The alternative of the 25kV a.c. system presented greater technical problems to be solved and postulated the rapid development of new de-

signs of locomotives and powered stock, and conversion of existing d.c. installations to the a.c. system. But for the future the prospect of great economies and wider scope for technical progress appeared to outweigh the immediate difficulties. Further, the lower cost of a.c. electrification might make possible its application, in years to come, to lines whose electrification on one of the older systems could never have been justified.

35. The line chosen for the comparative survey was the London Midland Region main route from Euston to Manchester and Liverpool. As detailed results became available they were applied to enable comparisons to be made as to the suitability of the a.c. system for the other



works included in the Modernisation Plan. As the survey proceeded there was consultation with the electrical engineering industry, the Central Electricity Authority and other national organisations concerned. Close contact was maintained with the French Railways, who have been at all times generous in their desire to pass on knowledge of the experience they have gained. Railway electrical engineers in a number of other countries have also been consulted.

36. The investigation has therefore been based on the broadest possible field of evidence. It should be emphasised here that it was confined to a comparison between the two systems of electrification. It did not set out to make comparisons with either steam or diesel operation, partly because the decision ultimately to electrify the lines concerned had already been taken.

37. The first step in the survey was to determine the pattern of the traffic that was to be operated. Increases in the average speeds of passenger, mineral and freight trains had to be allowed for, ranging from ten per cent for the fastest trains to well over double for the slowest. It was assumed that the range of train weights would not materially alter.

38. Two types of locomotive would be necessary—one designed for express passenger duties, characterised as 3,000/3,500 h.p., and the other, for mixed-traffic working, as 2,500/3,000 h.p. So far as power supply is concerned, it will be recognised that at periods of peak load, when starting or accelerating, powers greatly in excess of these figures would be developed by the locomotives.

39. It was found that for efficient overall working it would be necessary to electrify approximately 495 route miles of track, including diversionary lines, all of which are shown on the map on the inside cover of this booklet.

40. In presenting the details of the examination, it is convenient to treat power supply and the overhead contact system separately from motive power, and the next sections deal with each in turn.

POWER SUPPLY

(i) Voltage

41. The experience of the French Railways suggested that consideration should first be given

to a voltage of 25kV. It was eventually decided to adopt this voltage for general use in Britain because the survey showed that it would result in an economic balance between the size of the overhead contact wire and structures required to carry it, the spacing and number of substations required, the arrangements for power distribution to sections of the track, and the electrical clearances that would have to be provided for overhead structures, bridges and tunnels. Further, the decision is in the interests of international standardisation and therefore of international trade and British export; for this voltage is not only in use in France, but is already adopted in a number of other countries—for example, Portugal, Turkey, Japan and the Belgian Congo.

(ii) Consultation with the Central Electricity Authority

42. The Central Electricity Authority were consulted on where and how supplies of power could be made available to meet the needs of the London Midland Region lines. At the same time there was a joint investigation to determine whether harmful effects on the C.E.A. three-phase supply system would be caused by the unbalancing effect of a single-phase railway load, or by harmonic disturbances set up by rectifiers in the locomotives and trains.

43. Officers of the Commission and of the C.E.A. visited France together, and discussed with representatives of *Electricité de France* and the French Railways their experience of these effects. It was proved to the British representatives that no difficulties had been found in France, and since the nature of the C.E.A. grid is such that conditions will be more favourable in this regard in Britain the C.E.A. have been able to assure the Commission that the way is clear to use a single-phase supply for railway traction, should they so decide.

(iii) Substations

44. The electrification of the Euston–Manchester–Liverpool lines by the a.c. system is estimated to require 12 transforming substations and to produce a maximum half-hourly sustained load of about 90MW, with an annual consumption of about 550 million units, representing an average load equal to 70 per cent of the maximum sustained load.

45. The substations, which would be the property of the C.E.A., would be supplied direct from their main 132kV grid, duplicate single-phase transformers being used to step down to 25kV. There is already a C.E.A. substation close to each of twelve positions at which it would be convenient to take the railway supply. It is estimated that it would in fact only be necessary for less than 17 miles of feeder cables or overhead lines to be installed for the supply of current from C.E.A. substations to the railway lineside feeding-points for an overhead contact system extending over the whole of the 495 route miles.

46. The C.E.A. have confirmed their agreement to these arrangements, which by direct supply from the main 132kV grid provide the most reliable source of power that is available.

47. By contrast, if the 1,500V d.c. system were used it would be necessary to build and equip approximately 70 substations in order to maintain adequate voltage at the locomotives. Although it was not necessary to attempt to site each of the prospective d.c. substations jointly with the Electricity Boards who would be concerned, discussion with the C.E.A. showed that this would involve the railways in supplying a 33kV cable system for about one half of the route, through which substations, spaced down the line at intervals of approximately seven miles, could be fed from a restricted number of points where adequate supplies of power could be made available. In addition, it would be necessary to instal approximately 300MW of converting plant in the substations for the d.c. scheme, whereas with a.c. it will only be necessary for the C.E.A. to instal transformers having an aggregate capacity of slightly less than 200MW, because the wider spacing of substations will enable better use to be made of spare plant capacity and increase the load factor of plant in commission.

48. Thus it was established that very substantial economy, both to the railways and to the C.E.A., would result from the provision of power supply by the 25kV a.c. system, and further economies would be forthcoming in the maintenance of substation equipment, not only because of the smaller numbers of substations, but also because of the simpler nature of the apparatus within them.

(iv) *Power Distribution and Track Sectioning*

49. In any power distribution system, the spacing of substations must be so adjusted as to enable substation equipment to be taken out of service periodically for maintenance, and the remaining plant must therefore be capable of supplying the whole load. It is also necessary to provide means of shortening the length of track supplied from one substation without overloading those adjacent to it.

50. Current is supplied to the overhead wire by means of feeder cables from the substations, which are provided with switching arrangements to enable these requirements to be met. Switching arrangements must also be provided for the local control of supply to individual tracks and sidings to cater, for example, for the protection of men working on overhead equipment or on the track. With the a.c. system, track sectioning is also necessary to avoid putting one grid substation in parallel with another, which could cause an excessive transfer of load through the railway overhead wires from one substation to the next.

51. Track-sectioning arrangements present no new technical problems for either system, and the result of the survey was to show that the cost of power distribution, with the necessary controls, would be approximately the same whichever system were used.

THE OVERHEAD CONTACT SYSTEM

52. The choice of voltage and the spacing of substations determines the conductivity required of the overhead wires. For the d.c. system a cross-section equivalent to 0.6 sq. in. of copper, increased over parts of the route to 0.75 sq. in., is necessary, whereas with the a.c. system 0.23 sq. in. gives equivalent conductivity. The former requires a compound catenary type of overhead construction, in which a main catenary supports an auxiliary catenary which in turn supports the contact wire. In the case of a.c. a single catenary has been shown to be adequate, even for the high train speeds required.

53. Although insulators cost more, the contact system for the a.c. supply therefore weighs only one-third of that needed for d.c. Thus a considerable reduction in the required strength, and so in the cost, of supporting structures and

their foundations is obtained, after due provision is made for the differing effects of ice and wind loads and pantograph dimensions.

54. Light mast and cantilever overhead equipment can be used with a.c. on two-track sections of line, in favourable contrast to the heavier structures required for d.c. However, many British main lines include four or more tracks over considerable distances, which makes the use of portal-type structures spanning all tracks desirable. Nevertheless, the overhead equipment for a.c. will always be lighter and cheaper to construct. Lightness will facilitate erection, and permit the work to be more easily mechanised. Further, it provides better visibility for drivers and others on the track.

55. In view of the present and prospective high price and shortage of copper and steel, the following approximate comparisons are significant:

WEIGHT OF MATERIALS REQUIRED PER SINGLE-TRACK MILE	25kV a.c.	1,500V d.c.	a.c. as proportion of d.c.
	TONS	TONS	%
Weight of copper for equivalent conductivity	2.9	9.0	32
Weight of steel (average for a section of the railway)	20.0	24.0	83

56. The saving by the use of the a.c. system for all the lines proposed for electrification in the Modernisation Plan will amount to about 27,000 tons of copper and 16,000 tons of steel.

57. Considerably larger insulators will be required for the a.c. system, but they will be free from deterioration by electrolytic action and subject to lower mechanical stresses because of the lighter equipment.

58. Maintenance procedure with overhead line equipment will be affected by the choice of system. The voltages used with a.c. and d.c. systems are equally lethal unless appropriate precautions are taken, and unless rules made for the safety of the railway staff and of the public are rigidly observed. It is considered that all work on the 25kV a.c. lines will have to be done with the line 'dead', whereas on the d.c. lines some work has been done by trained staff with the line alive. The lighter weight of the a.c. contact sys-

tem, will, however, enable independent overhead equipment for adjoining lines to be more easily provided, thus allowing work on one to be carried out while the wire is live on the other. This will simplify maintenance and repair.

59. Significant increases can be expected in the life both of the contact wire and of the pantograph collectors with a.c. as compared with d.c., since the current to be collected for equal duty will be only about one-fifteenth as great, and the pressure of the pantograph on the overhead wire will be only about one-half as great. In both cases automatic tensioning will be required to maintain good current collection at high speeds under differing atmospheric temperatures.

ELECTRICAL CLEARANCES

60. Clearances in Britain are subject to Statutory Order, and in existing systems conform to those laid down in the Railways (Standardisa-

tion of Electrification) Order 1932. Substantially larger clearances to ensure safe working will be required with the high-voltage a.c. than with the lower-voltage d.c. between the live wires and earthed structures, and between the contact wire and the locomotives, rolling stock and wagon contents.

61. Clearances on electrified systems abroad vary for similar systems because of differences in atmospheric conditions and in the degree of air pollution near the wires by steam locomotives. Similarly, clearances in use do not reflect proportionately the difference between the a.c. and d.c. voltages. It is an important characteristic of the d.c. system that when a circuit on which a fault has developed is opened there is a rapid surge or rise in voltage. Clearances in d.c. systems must take this into account; a.c. systems are less subject to this effect.

62. British Railways have now had a consider-

able amount of experience with the clearances required in various conditions for 1,500V d.c. Moreover, apart from experience with the 6.6kV a.c. system on the Lancaster-Morecambe-Heysham line, there is also the satisfactory experience of 19 years of operation of the old Brighton line electrification at the same voltage, under less favourable conditions than may be anticipated in the future as regards pollution by steam locomotives. It therefore seems safe to assume that the 4-in. minimum clearance which is at present stipulated for 1,500V d.c., and which was used for these a.c. electrifications, is enough for 6.6kV a.c. under any conditions in Britain. The importance of this deduction will be seen later in this chapter.

63. After close study of the tests and experience of the French Railways and of other railways using high-voltage a.c. systems, it is proposed at first to use a basic minimum clearance of 11 in. for the 25kV a.c. system, and experiments are in hand to prove that this will be safe in all circumstances and to determine whether it can be safely reduced. There is evidence that this clearance is as safe, relatively, as the existing d.c. clearance.

64. The question of clearance is, of course, particularly acute where there are many overbridges and tunnels. On the main line from Euston to Manchester and Liverpool via Birmingham and Crewe, and branches, there are 904 overbridges. Of these, 478 (53 per cent) would require lifting in order to obtain the 4-in. clearance for 1,500V d.c., and 701 (78 per cent) would require lifting to obtain the 11-in. clearance necessary for 25kV a.c. Out of the total, 97 bridges would present such special difficulties as to make the 11-in. clearance to both rolling stock and structures impracticable, and would require treatment by special measures. The total cost of providing the necessary clearances throughout is estimated to be about £6 million for 1,500V d.c. and £9 million for 25kV a.c.

65. Clearances at low bridges can be provided by lifting the bridge, by lowering the track or by reconstructing the bridge with shallow girders. Tunnels may be enlarged or opened out. Developments are in hand which may enable the underside of bridges or the roofs of tunnels to be efficiently insulated so as to reduce the air clear-

ances required for safe operation.

66. Where none of these courses is practicable, as in the case of long tunnels, or sections near big cities where the numerous overhead structures would prohibit the provision of clearances of 11 inches save at unreasonable expense in time and money, it is proposed to reduce the line voltage from 25kV to 6.6kV, for which it is anticipated that a minimum clearance of 4 inches will be required. Provision can be made in locomotive and powered-stock design to permit satisfactory operation at either 25kV or 6.6kV, and automatic controls will be provided to eliminate the possibility of error by the driver in passing from one voltage to another.

COMPARATIVE COSTS OF POWER SUPPLY

67. The total estimated capital costs of the supply of power for the Euston-Manchester-Liverpool scheme from the C.E.A. 132kV grid to the motive power is shown hereunder for each system:

25kV a.c.	1,500V d.c.
£29.3 million	£38.6 million

Thus the cost for the a.c. supply, at £9.3 million less, is only about three-quarters of that for d.c. The estimates include all fixed electrical equipment, overhead structures and contact systems and the provision of clearances. They also include capitalised sums to cover annual charges which the Commission will be required to pay to the Central Electricity Authority for the use of their equipment.

68. It is necessary to consider whether the comparative costs for power supply for the Euston-Manchester-Liverpool scheme would hold good for other main lines, bearing in mind that the only part of the fixed equipment in which the cost of the a.c. system exceeds that for d.c. is in providing structural clearances. A broad survey has been made of the occurrence of tunnels and overbridges on other typical main lines; from this it is clear that the lines selected for the comparative estimates present more difficulties in this respect than others. On the main line from King's Cross to York, for example, the average number of bridges per mile is less than one half of that on the Euston-Manchester-Liverpool lines.

69. There is no doubt that C.E.A. supplies are as readily available in other parts of the country, and on lines of less dense traffic, where the greater part of the route is limited to double track, there will be additional advantage in favour of a.c. by reason of the lower cost of overhead structures. It may therefore be safely stated that the advantage of the a.c. system that has so far been demonstrated will apply in equal or greater measure to all other lines likely to be electrified in Britain.

EFFECT ON SIGNALLING AND TELECOMMUNICATIONS

70. The effects of the two electrification systems upon signalling and upon railway and Post Office telecommunications have been considered, and consultation with the Post Office Engineering Department has taken place. However carried out, electrification of a railway line will be accompanied by the installation of modern colour-light signalling in place of semaphores, in order to exploit to the full the potential of electric traction for the operation of fast trains on close headways. Provision has been made for such work in the Modernisation Plan.

71. Track-circuiting arrangements will vary according to the system used. With a.c. electrification, a number of arrangements are possible, using a.c. at differing frequencies, impulse systems, or d.c. systems when conditions are suitable.

72. In the estimates prepared it has been taken that the cost of signalling is the same for both systems.

73. The Modernisation Plan also includes an extensive programme for the cabling of open-wire telecommunication circuits. This is essential with any overhead system of electrification under conditions met with in Britain. In any case, it is an improvement necessary to bring railway telecommunications up to modern standards. The work does not therefore affect the comparison between the two electrification systems.

74. Some expense will be necessary with the a.c. system in cabling Post Office circuits that are close to the railway, and in immunising certain of these circuits which have earth connections. No great expense or difficulty is expected in dealing with any troubles that may arise, and the Post Office are in any case themselves cabling many

of their open-wire circuits. The Post Office have notified the Commission provisionally that the a.c. system would, in their opinion, produce no undue difficulties or interference with their telecommunications.

OTHER CONSIDERATIONS

(i) *Safety Factors*

75. Despite the much higher voltage of the a.c. supply, the safety of the public and of railway staff will be in no way diminished. The greater insulation provided and the clearances and protection given to the live wires will enable adequate factors of safety to be retained. The experience of foreign railways affords evidence that the use of such high voltages brings with it no difficulty in the maintenance of safety. Indeed, in some respects, the a.c. system is safer. The comparative freedom of the a.c. system from voltage surges renders failures of insulation less likely. In the event of faults, or accidents giving rise to short-circuits, the extent of arcing and burning of insulation and the risk of fire are less, because of the lower value of fault currents, and because of the greater ease of detection and clearance of faults by the opening of circuit-breakers at the substations.

(ii) *Electrolytic Corrosion*

76. Corrosion of buried metallic structures, pipes and cables may be caused by stray currents from the running rails when used as the return circuit of a d.c. system. Such effects are absent from an a.c. system.

(iii) *Effect on Radio, Radar and Television*

77. It has already been noted that no important difficulties are likely to arise in connection with the effect of a.c. electrification on Post Office telephone services. Consideration must also be given to the possible effect on the public radio and television services, and upon radio and radar used by shipping and aircraft and by the Services. All these matters will have to be cleared with the Government Departments and other authorities concerned. No difficulty in this respect is anticipated, however. In regard to interference, the benefit of the lower currents to be handled by the a.c. system for equal power offsets the disadvantage of the higher voltage.

78. Furthermore, the qualities which the railway requires for efficient current collection—in particular, absence of sparking between pantograph and overhead wire—are the very qualities which are conducive to the absence of interference.

79. The fact that these problems are being resolved in France and in other foreign countries where high-voltage a.c. systems are in operation is sufficient to justify confidence that they will be equally satisfactorily resolved in Britain.

IV. MOTIVE POWER

80. In the previous chapter, it has been demonstrated that for the supply of power to the locomotive the 25kV a.c. system of electrification possesses substantial advantages in comparison with the 1,500V d.c. system in cost of construction, in simplicity and in reliability. From the point of view of safety, or its effect on other railway or public services, the system does not stand at any disadvantage. It remains to compare the qualities of modern a.c. and d.c. locomotives and powered trains to complete the account, before outlining the final conclusions.

81. Comparisons of forms of motive power have therefore been made from three aspects:

- (a) the characteristics of existing designs of a.c. and d.c. locomotives and trains;
- (b) the potential for future development under each system; and
- (c) comparative costs.

82. Reference has already been made in general terms to the performance required from the motive-power units, and to the power of the locomotives that will be necessary. Before reviewing how these requirements can best be met, it will be convenient to compare briefly the main characteristics of electric motive power with other forms, and then to set out the respective merits of electric motive power under the two systems.

ELECTRIC AND OTHER MOTIVE POWER

83. All forms of electric traction enjoy certain advantages as compared with steam or diesel traction. One of the most important is that a well-designed electric locomotive is substantially

free of the power limitations imposed upon all other forms because it can draw on very large amounts of power for short periods from the supply network. The power of steam and diesel engines is limited by dimensional restrictions, but the tractive effort of the electric locomotive is limited only by the adhesion available between wheel and rail, and by the maximum permissible drawbar pull for which the rolling stock is designed. Drawbar pull is determined after consideration of train weights, which depend in turn upon the whole operating policy of the railways. For the present examination a maximum drawbar pull of 60,000 lb. has been taken as normal.

84. The adhesion between the locomotive and the rails is determined by a number of factors which, apart from the condition of the track itself, include the wheel arrangement, bogie design and axle loading of the locomotive; it is also greatly affected by the arrangements for the speed control of the traction motors. Important differences exist between a.c. and d.c. locomotives in respect of adhesion, and these are described in paragraphs 92 to 94.

CHARACTERISTICS OF A.C. AND D.C. TRACTION

85. Both a.c. and d.c. motors can be built in various forms according to the relationship that is desired between speed and torque. The type of d.c. motor which is used for traction is known as the 'series-wound' motor, in which the torque varies inversely to the speed and is proportional to the current. Control of speed is obtained by altering the voltage applied to the motor termi-

nals during acceleration, and finally by reducing the field strength by field taps or shunts. This results in high torque at slow speed, to give powerful acceleration and so make use of the essential characteristics of electricity for traction.

86. In d.c. electrification, as the collector gear receives a steady voltage from the contact wire, it is customary to vary the voltage applied to the motor and limit the current it draws during acceleration by the use of banks of resistances, which are gradually cut out as the speed increases. With the 750V d.c. system the motors are normally wound for the full line voltage, but it is usual on a 1,500V d.c. system to connect two motors permanently in series so as to retain the robust qualities of the 750V motor. In order to make the best use of the essential equipment on d.c. locomotives with four or six motors, the control equipment is arranged to connect the motors, or pairs of motors, in series, in series-parallel, and finally in parallel, during the acceleration period. During this period losses are incurred in the resistances and energy is dispersed as heat, and it is only after the resistances have been cut out that the locomotive works at optimum efficiency. The technique of this method of resistance control has been very fully developed over many years. Equipments built today may include many refinements such as vernier control of notching, air-cooled resistances and innumerable improvements in detail which were unknown to designers at the beginning of the century. No major changes in the principles by which speed and power are controlled seem likely to be economically practicable.

87. A commutator and brushgear are desirable for a.c. motors if the type of speed/torque characteristic just described, which is essential for traction purposes, is to be produced efficiently, unless special arrangements are made to vary the frequency of supply to the motors or to adapt them to respond efficiently to a fixed frequency. Such arrangements are only commercially practicable in a few cases, and nearly all the railways that use a.c. systems employ single-phase commutator motors, to which for the present this appreciation will be confined.

88. A transformer is necessary for each locomotive and motor coach using a c., because the

a.c. system is essentially a high-voltage system, and motors of the size and type required for traction purposes cannot be economically and efficiently wound for the contact-line voltage. With a.c. series motors, advantage is taken of the possibility of varying the output voltage of the transformers over a wide range in order to vary the voltage applied to the motor, and thus to vary its speed and torque. In contrast to the resistance method of control used for d.c. locomotives, with the a.c. system each 'tapping' is an efficient running position which can be maintained for an indefinite time without loss of efficiency or fear of overheating the transformers. This method of speed/load control is one of the main advantages of the a.c. system for traction, and is one of the reasons why that system has been so widely used. It approximates very closely to the speed regulation on steam locomotives.

89. Although in earlier years it was found necessary to use a low-frequency current in order to obtain satisfactory commutation with a.c. traction motors, recent researches have permitted the construction of motors of the size required using a 50-cycle current. Such motors are more complicated, of larger diameter, and more expensive than their d.c. counterparts. It is significant that as their experience of 50-cycle a.c. electrification expands the French Railways tend towards methods which do not require their use.

THE RECTIFIER APPLIED TO LOCOMOTIVES

90. It is possible that some radically new conception will later allow of more effective use being made of the a.c. series motor, and the adoption of high-voltage a.c. transmission would permit of their being used in that event. At the present time it is considered preferable to concentrate British Railways a.c. development on the retention of the well-trusted d.c. series traction motor, powered by the a.c. supply. This requires the interposition of a rectifier or motor generator between the transformers and the motors. The multiphase mercury-arc rectifier has had a profound effect on the design and cost of operation of the static substations in which 50-cycle a.c. power is converted to d.c. for distribution over the contact system to the trains, and several new forms of rectifier have become available in recent

years, all characterised by compactness and high efficiency, which makes them particularly suitable for housing in locomotives or below the floor of motor coaches.

91. Single-phase mercury-arc rectifiers have been known for many years, and two forms have given satisfactory results on the Lancaster-Morecambe-Heysham line. Other forms are in use in France, and still other forms are being developed in this country. In addition we seem to be at the beginning of the development of another form of rectifier of the 'semi-conductor' or transistor type, in which the special properties of very pure germanium and silicon are used for rectification. The first use of this type of rectifier in traction service in the world, as already mentioned, occurred in December 1955, when a 750kW germanium rectifier was brought into trial service in a multiple-unit train on the Lancaster line, with promising results.

ADHESION

92. In motive-power units for the a.c. system employing a transformer and tap-changer to vary the voltage to the motors (and thus their speed and torque), it is economical and convenient to connect all the motors in parallel. On the d.c. system, motors are often connected permanently in series. During acceleration they are placed in series with resistances, when the maximum torque is exerted and the limit of adhesion is most closely approached. The limit of adhesion between a particular wheel and section of rail varies widely and is affected by a variety of general and local conditions. Patches of grease on the rail can have great effect. If the limit of adhesion is exceeded by any wheel, slip occurs and the axle concerned ceases to contribute to the tractive effort of the locomotive. Even with very skilful driving it is difficult in certain circumstances to prevent the trouble spreading to the other axles. It has only recently been fully appreciated to what an extent the series connection of motors and the existence of resistances in series with them renders the conventional d.c. locomotive prone to slip. While adhesion is limited by other than electrical considerations, immediately the instantaneous critical value is reached by one wheel the pair of wheels concerned begins to slip. In doing so, it

upsets the voltage balance of the other motor of the pair. As all pairs of motors are receiving the same voltage from the contact line, the voltage on all the motors of a locomotive is disturbed and, in the absence of instantaneous action by the driver, a state of instability occurs immediately.

93. The maintenance of tractive effort thus depends on the quickness of the reactions of the driver, which varies between individuals. The trouble is most apparent when starting with a heavily loaded train; it is least apparent in sustained high-speed working, when tractive effort is low. In short, the resistance-controlled d.c. locomotive cannot, under all conditions, utilise to full effect the adhesion that is available at any moment between all the wheels and the rails.

94. By contrast, in the transformer-fed a.c. locomotive each motor can develop the maximum torque that wheel and rail conditions allow without any interference caused by the other motors of the locomotive. The tractive effort is proportional to motor current just as in the case of d.c. locomotives, except that, as all motors are in parallel, they must (if of identical design) all exert equal tractive effort, so that if one wheel begins to slip the other motors are not affected. Observation of the performance of these locomotives on bad rails has confirmed this deduction. If very bad conditions affecting all wheels arise, the driver can reduce the tapping, which immediately takes equal effect on all motors. The impedance of the supply system and of the transformer also softens the peak currents which, while reducing the risk of commutator flash-over, also reduces the tendency to wheel-slip during transition from one tap to another. Good bogie design is as important for this type of locomotive as for the d.c. locomotive, and is equally attainable. In contrast to the d.c. locomotive, the a.c. locomotive can use all the adhesion available at any moment between wheel and rail, and less demands are placed upon the driver's skill.

95. After careful investigation, the French Railways now rate a.c. locomotives equipped with d.c. motors supplied by rectifiers as capable of hauling loads 60 per cent in excess of loads permissible for the latest type of d.c. locomotive of the same weight, with a chassis of similar design, so far as adhesion properties are concerned. Al-

though the benefits of better adhesion are more important where heavy trains have to be handled on severe gradients, the improvement in adhesion is useful under all conditions. It will be particularly useful in permitting the construction of lighter and cheaper locomotives. This would react very favourably on the overall cost of the Modernisation Plan, by reducing the wear and tear on the track and the cost of reconditioning it to accept the faster trains now required.

96. It is for these reasons that the a.c. rectifier locomotive with d.c. traction motors was selected as the type to be compared with the conventional d.c. locomotive for the comparative estimates which led to the decision to adopt this a.c. system. Until the results of the experience of the French Railways had been learned, and the benefits which accrued to the a.c. rectifier locomotive through its adhesion characteristics were recognised, it had been anticipated that the a.c. locomotive would be more expensive than its d.c. counterpart. In that event the additional cost of the many locomotives required for a main line with heavy traffic could be a serious offset against the savings for the a.c. system in first cost of fixed equipment. It was largely for this reason that the committee which reported in 1951 did not consider the system likely to be attractive financially for British Railways in general.

LOCOMOTIVES REQUIRED UNDER A.C. AND D.C. SYSTEMS

97. It is now considered, however, that there will be little difference in the total cost of motive-power units as between the two systems. For express services, Bo-Bo locomotives would be satisfactory for either system; the Euston-Manchester-Liverpool scheme may require 150 such locomotives, and these may be more expensive for a.c. than for d.c. For mixed-traffic duties, a Bo-Bo a.c. locomotive would be suitable for hauling loads up to 1,250 tons on gradients of 1 in 100. On past experience, however, it is unwise to expect satisfactory results from a Bo-Bo d.c. locomotive with this load. It would therefore be necessary either to use Co-Co d.c. locomotives capable of hauling loads of this weight or to double-head those trains which fall between 1,000 tons and 1,250 tons with two Bo-Bo loco-

motives. It is estimated that a total of 510 a.c. mixed-traffic locomotives will be required for the London Midland Region scheme, and that with double-heading, if adopted as being the solution more favourable to the d.c. case, 570 d.c. locomotives would be needed.

98. Preliminary enquiries indicate that, while the a.c. rectifier locomotive will cost more than an equivalent d.c. locomotive in Britain in the immediate future, there is reason to believe that as experience is gained the cost of building a.c. locomotives will fall, and that they will at least be no dearer than their d.c. counterparts, whilst yet possessing technical advantages over them. The difference in the estimated costs of the alternative fleets of 720 d.c. locomotives and 660 a.c. locomotives required to operate the Euston-Manchester-Liverpool lines is about £2 million in favour of d.c., in a total cost for d.c. locomotives of £36.3 million.

REGENERATIVE BRAKING

99. It is perhaps appropriate that mention should be made here of regenerative braking, which is a device employed in electric locomotives whereby the traction motors are used as generators for braking purposes, and the current so generated is fed back into the distribution system. It is already in use on the 1,500V d.c. electrified line over the Pennines between Manchester, Sheffield and Wath. The scope for its further effective use in Britain is limited to a few sections of line where dense freight traffic operates on heavy gradients. The device cannot be applied to the a.c. rectifier locomotive, but locomotives equipped with motor-generator sets can be used in such special cases as may arise where regenerative braking is considered to be desirable. It is unlikely that the need will arise in the work proposed in the present Plan.

MULTIPLE-UNIT TRAINS

100. Experience on the Lancaster line has confirmed the suitability of a.c. equipment of the type using rectifier-fed d.c. motors for use on motor coaches. Although the particular stock used did not permit of underframe mounting, some of the electrical equipment was built to dimensions which would permit of its being

mounted on the underframe of standard electric rolling stock. Designs have been prepared for other types of rectifier which can also be arranged in this way. The advantage of the a.c. system can therefore be confidently expected to apply also to multiple-unit train sets. When these are used in suburban services with frequent stops, a considerable saving in energy consumption will result from the elimination of resistance losses, while the better adhesion characteristic will permit higher rates of acceleration, or alternatively the use of a smaller number of larger motors with a consequent saving in cost of electrical equipment. This type of equipment is to be preferred to a.c. commutator motors for this duty, particularly as, with the limited load gauge in Britain, it would be difficult to accommodate the large-diameter motors necessary. The equipment can be arranged to operate at full performance on both 6.6 and 25kV. For the present, the cost of electrical equipment must be assumed to be a little higher than the cost of the conventional 1,500V d.c. equipment, but when designs have been developed to take full advantage of the possibilities of the a.c. equipment the difference of costs may well be

reversed. At present the difference in cost in favour of d.c. for the 220 trains of three and four coaches expected to be required for the suburban and inter-city services on the Euston-Manchester-Liverpool lines is estimated to be of the order of £400,000 in a total cost of about £10 million for d.c. equipment.

TRAIN HEATING AND LIGHTING

101. The system of electrification has an important bearing on the method of heating and lighting passenger trains. Electric heating will become possible for electrically-hauled coaches as well as for electric trains. It may be assumed that the heating system used would be d.c. if the motive power were d.c., and a.c. with a.c. motive power. In the latter case, the ease with which the a.c. could be transformed from one voltage to another would allow it to be used not only for heating, but for lighting and a number of other ancillary services. This would permit the elimination of the axle-driven generators at present used for lighting, and indicates potential savings approaching £1 million in the London Midland Region scheme.

V. COMPARATIVE COSTS AND ADVANTAGES

102. The estimated costs for electrification of the Euston-Manchester-Liverpool scheme by the

25kV a.c. and 1,500V d.c. systems which have resulted from the survey may now be summarised:

	25kV a.c.	1,500V d.c.	Difference in favour of a.c.
Power supply and overhead system (including cost of providing clearances)	£m. 29.3	£m. 38.6	£m. + 9.3
Motive power (including electric trains but excluding hauled stock)	48.6	46.3	— 2.3
Signalling	23.0	24.5	— 0.5
Depots	2.7	2.7	—
Train heating and lighting	6.1	7.1	+ 1.0
Contingencies	6.1	4.4	— 1.7
TOTAL	£117.8m.	£123.6m.	+ £5.8m.

In working out estimated costs, conservative figures have been used for the a.c. system. No account has been taken of possible reductions in the costs of motive power as building proceeds, and a high figure has been included under 'Contingencies.' Omitting the cost of signalling and depots, which is about the same for either system, the direct cost of electrification by the a.c. system is 93 per cent of that by the d.c. system.

103. The lines under consideration are among those which carry the heaviest traffic in British Railways. The motive-power requirements are therefore heavy, and represent a greater proportion of the total cost than would be the case for other lines, and the case for the a.c. system is thus presented at a disadvantage. Further, it has been shown that the density of constructional features affecting expenditure on electrical clearances is higher on these lines than elsewhere. It may therefore be accepted that the proportionate saving in first cost by adopting the a.c. system would be exceeded on other lines to be electrified under the Modernisation Plan.

ANNUAL COSTS

104. A reduction in annual costs estimated at £1 million is anticipated by adopting the a.c. system in preference to the d.c. on the lines considered, as under:

	25kV a.c.	1,500V d.c.
Maintenance and depreciation of fixed equipment, signalling and motive power	£m 4.7	£m 5.2
Cost of current	2.2	2.5
Interest at 4 per cent	4.7	4.9
TOTAL	£11.6m.	£12.6m.

It may be assumed that savings in like proportion may be made on any other line to be electrified under the Modernisation Plan.

SUMMARY OF REASONS ADDUCED FOR PREFERRING THE D.C. SYSTEM IN 1951

105. At this point, it is desirable to consider once more the findings of the Committee whose

recommendations the Commission accepted in 1951, and to refer particularly to the reasons at that time put forward for the preference of the 1,500V d.c. system over the single-phase 50-cycle a.c. system. The Committee recognised the attractive features of the a.c. system in keeping to a minimum the cost of fixed installations. They feared, however, that the cost of motive power would render the total cost of electrification little, if any, lower. They therefore thought that matters other than comparative capital and annual costs should be taken into account. The matters to which they referred were:

- (a) Inter-running between the standard system and the low-voltage d.c. system on the Southern Region.
- (b) The unbalancing effect of a large single-phase load on the three-phase national supply system.
- (c) Interference with railway telecommunications.
- (d) The experimental nature (in 1951) of existing 50-cycle a.c. systems. They felt that proof was still necessary that operation would be satisfactory and that motive power could be built at reasonable cost.

Notwithstanding this, the Committee recommended an experimental installation in Britain, and this was put into effect, as has already been described.

106. The account given in the foregoing chapters has shown that experience gained since 1951 has resolved, in favour of the a.c. system, all but the first question of inter-running between the Southern Region third-rail electrified zone and the rest of the country. Although the Commission are aware that the construction of locomotives and powered stock capable of operation on both the 25kV a.c. system and the 660V d.c. third-rail system will be rather more expensive than of those which would be required for working on d.c. at both 1,500 and 660V, they are nevertheless satisfied that locomotives and stock of the former type can be built if required, and that the extra cost would be trifling in comparison with the wider issues at stake.

107. Thus in changing their policy in regard to the standard form of electrification four years after the Committee's report was accepted the

Commission recognise the foresight of the Committee, which though not then recommending the a.c. system, and for good reasons, nevertheless gave advice that culminated in the experiments on the Lancaster–Morecambe–Heysham line, and so enabled the present decision to be taken with the greater certainty.

SUMMARY OF THE ADVANTAGES
OF THE 25KV A.C. SYSTEM AS COMPARED
WITH THE 1,500V D.C. SYSTEM

108. The following summarises the features described in the previous paragraphs which have led the Commission to their decision to adopt the a.c. system as the standard for future electrification in Britain.

Power Supply: The cost of power supply equipment, substations and feeder cables is less; the cost of power consumed will be less; supply will be more reliable; maintenance costs will be less.

Overhead Equipment: The conductor wire is lighter, requiring less copper; overhead structures are lighter and cheaper and use less steel; they will be easier to erect; alterations to tunnels and bridges to provide clearances are more difficult and costly, but not to such a degree as to counterbalance the greater savings elsewhere.

Motive Power: Better adhesion will permit lighter locomotives to be used, and afford easier control;

no power will be wasted in main resistances for speed control; electric heating and lighting can be supplied more cheaply and conveniently; although, type for type, motive-power units may cost more in the early stages, eventually with bulk production this disadvantage should disappear. *Safety Factors:* Safety factors can be maintained by adequate insulation and clearances; greater freedom from voltage surges renders insulation failures less likely; there will be less risk of fire from short-circuits and arcing because of the low value of fault currents, and greater ease of clearing faulty circuits.

109. Taking an overall view, the Commission are satisfied that the a.c. system offers substantial economies both in first cost and in annual costs of operation. They consider that the system will permit of the electrification in the future of certain secondary lines whose electrification by the d.c. system could not be financially justified.

110. Further, they are convinced that, apart from the technical advantages that are immediately available, the a.c. system possesses much greater potential for development in design and technique than is the case with other systems. The Commission therefore trust that the Minister of Transport will approve their decision, and revoke or amend the Railways (Standardisation of Electrification) Order 1932.

VI. HOW ELECTRIFICATION WILL BE CARRIED OUT

111. The Modernisation Plan for British Railways contains the following major electrification projects:

Electrification of Trunk Routes (820 route miles):
London Midland Region Main Lines: Euston to Birmingham, Crewe, Liverpool and Manchester.
Eastern/North Eastern Region Main Lines: King's Cross to Doncaster, Leeds and (possibly) York.
Eastern Region Main Line (in extension of existing

electrification): Liverpool Street to Ipswich, including Clacton, Harwich and Felixstowe branches.

Suburban Electrification (390 route miles): London, Tilbury and Southend line; Liverpool Street to Enfield and Chingford; Liverpool Street to Hertford and Bishop's Stortford; King's Cross and Moorgate to Hitchin and Letchworth, including the Hertford loop; Glasgow suburban lines.

Extensions of Southern Region Electrification (250 route miles): The geographical situation of the lines to be electrified is shown on the map.

In the Appendix is a list of the lines already electrified, or on which electrification is at present in progress. These lines are also indicated on the map.

112. All lines to be electrified will be equipped on the a.c. system, except for the extensions on the Southern Region system to the Kent coast, where the existing d.c. system will be used. The following paragraphs describe how the Plan will be carried out, and the effect of the Plan on lines already electrified.

113. The Euston-Manchester-Liverpool line was chosen for the investigation not only because it was known that the result would have a decisive bearing on all other electrification work, but also because it was desired to start work on the line as quickly as possible. The investigation provided essential data upon which the working plans are being based. The electrification of the section between Manchester and Crewe will be carried out as the first stage. This section is being given priority because it can be completed quickly in order to enable experience to be gained at the earliest opportunity of the operation of the new equipment under normal service conditions. Meanwhile work on the other schemes, including the remainder of the London Midland main-line scheme, will be going on as fast as the availability of staff and materials will allow.

114. In choosing the a.c. system, the Commission were very conscious of the effect of the choice on existing and authorised electrification schemes, and on the question of inter-running between the areas they cover. Certain of them, such as the Liverpool-Southport, the Wirral and the Tyne-side lines, do not present pressing problems, as they are isolated from the lines forming part of the Plan. The Euston-Watford line is also effectively a separate entity, with its own tracks, and no difficulty will be experienced where these tracks, with their conductor-rail contact system, are jointly used—for example, in Euston Station. There are numerous precedents for dual equipment of lines. In addition there is interworking of London Transport trains over the outer part of this line, and it is therefore convenient to leave it in its present form.

115. Similarly, the Manchester-Altrincham line need not be changed, because it uses separate platforms at Manchester London Road Station. When the necessity arises to renew its equipment, a change to the a.c. system can be made. The position with regard to the Manchester-Sheffield-Wath line is similar. The Plan does not include extensions to this line, but when it is desired to make them, and so bring the line into working contact with the London Midland and Eastern Region main lines, it will be necessary to face conversion to obtain full inter-running.

116. The case of the Southern Region third-rail electrification is a special one. As will be noted from the map, a very high proportion of the mileage of the Eastern and Central sections has already been electrified on the third-rail system, and the cost of changing this to the a.c. system now would be prohibitive. In addition there is only a limited staff available, and, even if it were practicable to face the cost of conversion, to do so would very seriously delay the extensions of electrification in this Region which form part of the Plan. The Commission have therefore supported the decision of all the earlier committees which considered this problem and decided to continue the existing system, with the reservation, however, that the a.c. system might be introduced in the Western part of the Region if and when electrification of that area takes place.

117. The Manchester-Bury line needs special consideration, as its rolling stock requires early renewal, and its side-contact conductor-rail system is nearing the end of its life. It is a short line with numerous overbridges and a tunnel. The cost of obtaining clearance for 25kV would not be warranted, and consideration is being given to conversion to 6.6kV a.c.

118. The East Anglian lines of the Eastern Region, including the Shenfield electrification and its extensions, and the authorised electrifications to Enfield and Chingford from Liverpool Street and to Tilbury and Southend from Fenchurch Street, which is linked to Liverpool Street, presented a more difficult problem. Electrification between Liverpool Street and Shenfield is already on the 1,500V d.c. system, and extensions to Southend and Chelmsford are well advanced.

There must be no delay in the introduction of any of the electrified services mentioned. For efficient working of the line and maintenance of the rolling stock and equipment, all these lines must be electrified on the same system so as to provide flexibility in operation and to make use of the Ilford repair shops; moreover, it would of course be impossible to have two different overhead systems over any one track. On the other hand, a decision to retain 1,500V d.c. would commit to that system the whole of the later extensions of these lines included in the Modernisation Plan, and others likely to follow, comprising all important lines in East Anglia. This would not be an impossible arrangement, but it would lead to considerable operating inconveniences when, at a later date, lines electrified on the a.c. system joined up with 1,500V d.c. lines at the boundaries of the two systems, e.g. at Cambridge and March, and in the London exchanges. Also it would deny to a large block of the Eastern Region the economies and advantages of the a.c. system. After careful thought the Commission have decided to convert the existing 1,500V d.c. lines to a.c., adopting 6.6kV in the inner areas so as to reduce additional civil engineering work to a minimum, and to equip the London, Tilbury and Southend line for a.c. working forthwith. Similarly, the Enfield and Chingford lines will be operated on the a.c. system from the commencement.

119. It is estimated that the cost of making the conversion will be less than the saving by the

adoption of the a.c. system for the lines in this area included in the Plan. There is just time to make the necessary alterations without delay to the authorised works. The taking of this decision will ultimately lead to great economy as other lines in East Anglia are electrified, and will ensure full inter-running between all lines north of the Thames. If it had been otherwise, there would have been two important areas of electrified railways using different systems, neither of them the same as the standard now to be adopted for the rest of the country. Now only one—the Southern Region—will remain.

120. When the electrification of the Glasgow suburban lines proceeds, this also will follow the standard pattern and be done on the a.c. system with a voltage of 6.6kV in the inner zone and of 25kV in the outer areas.

121. In announcing their decision, the Commission are happy to state that they have the full support of the electrical industry, who will be so closely associated with them in the tasks that lie ahead. Both are aware of the urgency to be attached to the development of the new locomotives and other equipment if the Plan is to keep to its timetable. The Commission have faith in the ability of the industry to carry out its part of the Plan, and to deliver the goods within the dates that will be set.

122. The Commission are confident that time will show that the decision they have made has anticipated the needs of the new railway era heralded by the Modernisation Plan.

APPENDIX

British Railways

Electrified Lines in Operation and under Construction

SYSTEM	REGION	ELECTRIFIED LINE	MILEAGE	
			Total Route	Total Track
6.6kV 50-cycle a.c. overhead	L M	Lancaster–Morecambe–Heysham	9	19
1,500V d.c. overhead	E	Manchester–Sheffield–Wath	68	300
”	E	Liverpool Street–Shenfield	24	110
”	E	Extensions from Shenfield to Chelmsford and Southend	31	70
”	L M	Manchester–Altrincham	9	29
1,200V d.c. third-rail	L M	Manchester–Bury	14	29
630/660V d.c. third-rail	L M	Liverpool–Southport	37½	94
”	L M	Wirral and Mersey	16	36
”	N E	Tyneside	42	99
”	S	Suburban and South Coast	720	1,796
630/650V d.c. fourth-rail	L M	Euston/Broad Street–Watford	38	88½
”	W	Paddington area (London Transport lines)	3½	12

BRITISH RAILWAYS
EXISTING AND PROPOSED
ELECTRIFICATION

- Lines at present electrified or being electrified on overhead contact system.
- Lines to be electrified on overhead contact system under Modernisation Plan.
- Lines at present electrified with conductor rail.
- Lines to be electrified with conductor rail under Modernisation Plan.
- Other principal lines.

