ANALYSIS OF THE OPERATIONS OF THE RAILWAY NETWORK BETWEEN SYDNEY - MELBOURNE - ADELAIDE

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ABSTRACT: *The paper illustrates the application of an analytical tool, namely linear programming, to railway operational and project evaluation problems. Two illustrative examples are presented relating to the Sydney - Melbourne - Adelaide railway network. Firstly, the scope for better use of existing facilities is investigated, and secondly, the proposal to standardise the Melbourne - Adelaide - Crystal Brook link is evaluated. The paper concludes that, although rail standardisation cannot be justified on economic grounds at present, the scope for operational savings, obtained by making improved use of existing facilities, ranges from $360,000 to $1.35m per annum.*

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1. INTRODUCTION

This paper illustrates the application of an analytical tool, namely linear programming (LP), to railway operational and project evaluation problems. The results of the analyses indicate the scope for improved use of existing facilities. Furthermore, it is envisaged that this type of analysis could be used to assist decision makers in determining priorities for various policy options.

Australia's non-urban railway system is largely structured with branch lines feeding into the main intercapital trunk routes. Within this structure is the triangular intercapital network linking Sydney, Melbourne and Adelaide, which forms the subject of this paper. At present, the links of the network are broad gauge between Melbourne, Adelaide and Peterborough and standard gauge between Peterborough, Sydney and Melbourne (Fig 1a). The network is operated by three separate authorities each apparently pursuing its own objectives, which will not, in general, produce an optimum for the total system.

Firstly, the paper investigates the possibility of making better use of existing facilities by considering the network as a whole. It attempts to determine the scope for more efficient use of resources involved in providing current rail services by reallocating traffic to the various links so that empty wagon and locomotive movements are reduced. Although it is recognised that passengers always prefer to choose their travelling path between origin and destination, there is room for reallocation of the intercapital freight traffic tasks between the various links of the network.[1]

Secondly, the effect of standardising the Melbourne-Adelaide-Crystal Brook link is investigated. Minimum cost

(1) Non-intercapital freight as well as Perth-Eastern-States traffic, are not included in the analysis since there is little or no scope for reallocating this traffic to other links of the network.

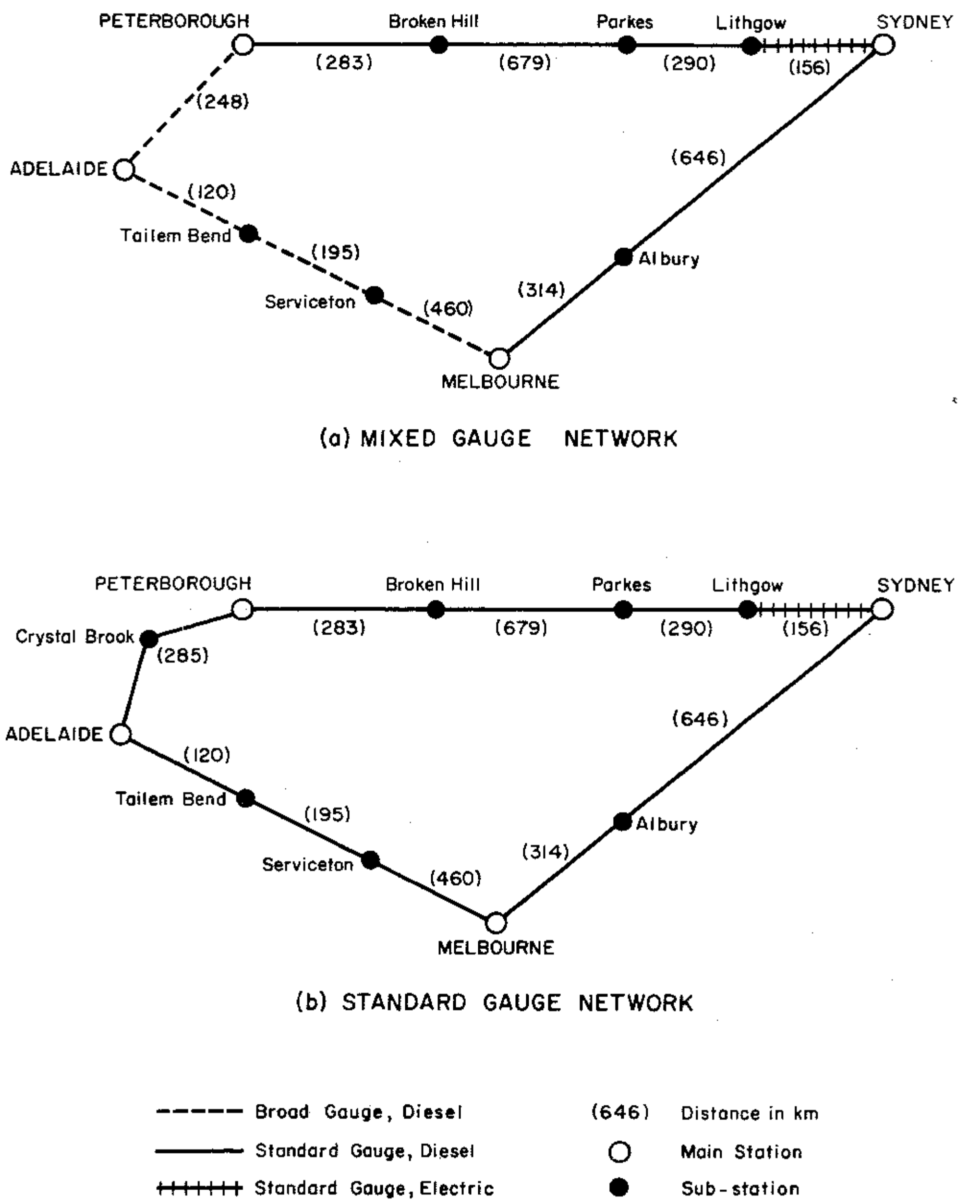

FIGURE 1
BASIC RAIL INFRASTRUCTURE CONFIGURATIONS

operations of this completely standard gauge network are compared to the cost of operating the existing mixed gauge network (Fig 1).

Both of the above applications are considered over the 20 year period from 1975-76 to 1994-95.

Although the application of the LP model to the analysis of these rail networks requires considerable simplification of reality, the results give a useful indication of the order of magnitude of the gains possible from the improved operation of existing facilities and the merits of the Melbourne-Adelaide-Crystal Brook rail standardisation proposal.

2. ANALYTICAL TOOL AND MAIN ASSUMPTIONS

The tool used in the network analysis was developed by Demoulin (1976) while he was seconded to the Bureau of Transport Economics. It is basically a linear programming model which optimises the operation of railway system resources by minimising total operating costs, including the cost of running and waiting times.(1) The LP takes as input a set of parameters describing a given rail infrastructure. This feature allows the model to be used as the basis for the economic evaluation of alternative rail configurations.

In practice, the optimising process amounts to rearranging the present allocation of the intercapital freight traffic task along the links of the network with a view to reducing the movements of:

(i) full wagons,

(ii) empty wagons,

(1) The savings due to the reduction in the cost of the inventory-in-transit are not included in the analysis since they are small compared to other savings. See BUREAU OF TRANSPORT ECONOMICS (1975). Mainline Upgrading - Evaluation of a range of options for the Melbourne-Sydney Rail Link. (p.158)

(iii) locomotives,

(iv) spare bogies.

Such a process should lead to a decrease in operating costs. It is implicitly assumed here that suitable revenue sharing arrangements - corresponding to improved traffic allocation - could be negotiated between the various railway authorities involved. Alternatively, the possibility should not be forgotten that in the long run, the operation of the network might be controlled by a single authority.

2.1 RAILWAY SYSTEM COMPONENTS

For the purposes of analysing the operation of the railway system, the following components are identified in the model:

(a) *Railway Line Network:*

(i) set of main stations where goods are loaded and unloaded, trains are marshalled and bogies are exchanged,

(ii) set of sub-stations where locomotives are changed,

(iii) links between two main stations and sub-links between two stations,

(iv) electrified and non-electrified links,

(v) gauge specifications.

Fig 1 describes the network infrastructure in terms of the above parameters for both the mixed and standard gauge cases.

(b) *Intercapital Goods Traffic:*

(i) divided into broad classes for which standard wagons can be used interchangeably within a given class,

(ii) flows of goods originating and ending at main stations only.

(c) *Locomotives:*

(d) *Wagons:*

(i) except for bogies, wagons are assumed to be interchangeable throughout the network,

(ii) when loaded, wagons are assumed to carry an average net load, depending on the class of goods and the type of wagon.

(e) *Trains:*

(i) trains are loaded, unloaded and remarshalled only at main stations,

(ii) at any station, trains can be modified by the addition, withdrawal or change of one or more locomotives,

(iii) due to track characteristics on any main link, trains are subject to maximum length and maximum load constraints.

(f) *Bogies:*

(i) bogie exchange for locomotives is not considered on the basis that it is costly and creates excessive delays in the system,

(ii) bogie exchange for wagons is allowed at main stations situated at the break of gauge points. In the case of the present mixed gauge network, bogie exchange takes place in Melbourne and Peterborough.

Basic data on the system components listed above are provided in Annex A.

2.2 TIME DIMENSION

Since the LP model is essentially spatial and static it should be used in conjunction with a scheduling model. This scheduling model would derive train running times over each link, reflecting congestion levels (or delays) for a given traffic volume. In this paper, however, it is assumed that the rail links will be upgraded so that delays over the twenty year period of the study will remain close to their present levels. The Bureau of Transport Economics[(1)(2)] has shown that such upgradings are

(1) BUREAU OF TRANSPORT ECONOMICS (1975). Mainline Upgrading - Evaluation of a range of options for the Melbourne-Sydney Rail Link. (Australian Government Publishing Service: Canberra).

(2) BUREAU OF TRANSPORT ECONOMICS (1975). Mainline Upgrading - Evaluation of a range of options for the Melbourne-Serviceton Rail Link. (Australian Government Publishing Service: Canberra).

economically justifiable and can be implemented at relatively low cost. On this basis, the above assumption appears reasonable and present train running times over each link are taken as an input by the model.

As a first approximation, it is assumed that locomotives and wagons are available when they are required and no time-table restrictions are made on that account. To compensate for this simplification, utilisation coefficients for locomotives and wagons are introduced in the model. The utilisation coefficient of an item of rolling stock or motive power is a measure of its long-term utilisation level and is defined as the fraction of time spent moving, including delays incurred while travelling. It is an attempt to account for routine and unscheduled maintenance, waiting times for connection to the next train, loading and unloading times for wagons. These coefficients are exogenous to the model.

2.3 THE MATHEMATICAL MODEL

The model minimises the operating cost of accomplishing a given freight task subject to operational constraints.

(a) Costs included in the model:

- (i) crew costs, which are assumed proportional to total train travelling time,
- (ii) fuel and track maintenance costs, which are assumed proportional to total gross-tonne-km,
- (iii) locomotive and rolling stock maintenance costs, which are assumed proportional to total distance travelled,
- (iv) direct bogie exchange costs which are assumed proportional to the total number of bogies exchanged,
- (v) capital costs for locomotives, wagons and spare bogies. The numbers of these items of capital equipment required to carry out a given freight task depend on:
  - (a) the size of the freight task and the network operational characteristics,
  - (b) the line haul times,
  - (c) long term utilisation levels.

(b) Constraints

The sum of the above costs is minimised subject to the following constraints:

- (i) conservation laws and transshipment laws for locomotives, full and empty wagons,
- (ii) system operational restrictions which include lengths of trains, line capacities, locomotive requirements etc.

(c) The model outputs:

- (i) full wagon flows,
- (ii) empty wagon flows,
- (iii) number of trains to run daily on each link,
- (iv) locomotives running on each link,
- (v) number of spare bogies transported around the network.

A more comprehensive mathematical description of the model is provided in Annex B.

2.4 USE OF THE MODEL IN EVALUATING THE ALTERNATIVES

In the analysis, the model is applied to the network in both the existing and improved cases, to determine operating costs for each year of the 20 year period 1975-76 to 1994-95. Since the LP uses traffic levels as an input parameter, the model has to be run separately for each year of the study period in a situation where traffic is projected to increase over that period. A discussion of the freight projections is given in Annex C.

Because the model considers the average daily performance of the system, the projected annual freight figures need to be converted to daily tonnages. This is achieved by assuming that there are 312 working days (6 days per week) in a year.

The model, amongst other things, outputs the average number of trains per day for each link. Although, from a strict point of view, it does not make sense to talk about fractions of trains, locomotives or wagons, it must be emphasised that a measure of the average daily performance of the system is sought. If for example, the model indicates that 2.5 trains are to be scheduled each day between stations A and B, it could be arranged that 2 trains travel on every second day and 3 trains move on the remaining days. In practice, given the usual build up of traffic towards the end of the week, the scheduling could be arranged so that 2 trains run on Mondays, Tuesdays and Wednesdays and 3 on the rest of the 6 day week.

The costs output by the model are then discounted over the study period to compare the alternatives under consideration.

3. RESULTS

After having applied the model to the existing system, it was used to examine, firstly, the possibility of improving the operations of the existing mixed gauge network and secondly, the merits of the Melbourne-Adelaide-Crystal Brook standardisation proposal.

Owing to the critical nature of the value of certain input parameters, namely:

- (i) fuel costs,
- (ii) wagon capital costs,
- (iii) wagon maintenance costs,
- (iv) locomotive maintenance costs,
- (v) track maintenance costs,
- (v) locomotive utilisation coefficient,

the sensitivity of the results to variations in these data was tested. Runs of the model using lowest cost estimates for items (i)-(v) above, combined with the highest estimate of the locomotive utilisation coefficient (item (vi) above), produced the lowest operating costs. This lead to the lowest estimates of benefits accruing from operating cost savings. These runs are referred to as the "pessimistic cases" in the text. Similarly, runs of the model using the highest cost estimates and the lowest estimate for the locomotive utilisation coefficient are referred to as the "optimistic cases" because they give rise to the highest operating costs and consequently the highest benefits from operating cost savings.

3.1 EXISTING MIXED GAUGE NETWORK

On application of the model to the existing mixed gauge network illustrated in Fig. 1a, the results indicated that total operating costs are reduced if all of the Adelaide-Sydney traffic, presently travelling via Broken Hill, is rerouted via Melbourne. The traffic flows are shown in Table 3.1, and Table 3.2 shows the breakdown of the operating costs for each of the cases analysed. By considering the results of the "pessimistic cases", it can be seen that these changes in the traffic flow pattern would lead to minimum cost savings of $360,000 in 1975-76 and $740,000 in 1994-95. Table 3.3 displays the locomotive and wagon requirements for the two methods of operating the network. The figures in Table 3.3 indicate that the savings in operating costs are due to:

(i) a reduction in empty wagon movements at both the beginning and the end of the study period leading to a decrease of slightly more than 1% in total wagon requirements,

(ii) better locomotive deployment, resulting in a reduction of 4% in total locomotive requirements.

3.2 STANDARD GAUGE NETWORK

The second application of the model investigated the effect of standardising the Melbourne-Adelaide-Crystal Brook link. This new network, shown in Fig 1b, is slightly different to the existing one. Keeping the present traffic allocation, the application compared the operation of the completely standard gauge network with the operation of the existing mixed gauge system.

The potential benefits of standardisation would be twofold:

(i) the costs and delays of bogie exchanging wagons would be eliminated,

TABLE 3.1

EXISTING TRACK - COMPARISON OF THE NUMBER OF TRAINS RUNNING GIVEN EXISTING OPERATING PRACTICES WITH THE NUMBER RUNNING IF NETWORK OPERATING COSTS WERE MINIMISED.

Origin	Destination	Number of Trains/Day (1)(2)			
		Existing Practice		Improved Practice (3)	
		1975-76	1994-95	1975-76	1994-95
Sydney	Melbourne	5.7	12.0	6.6	13.9
Melbourne	Sydney	5.0	10.5	5.8	12.3
Melbourne	Adelaide	2.2	4.6	2.8	5.9
Adelaide	Melbourne	2.2	4.6	2.8	6.0
Adelaide	Peterborough	1.3	2.7	-	-
Peterborough	Adelaide	1.2	2.6	-	-
Peterborough	Sydney	0.9	1.8	-	-
Sydney	Peterborough	0.8	1.7	-	-

(1) This table represents both "optimistic" and "pessimistic" cases since the number of trains running in both cases is the same. This is because the relative magnitudes of the sensitive parameters did not change. See the introducion to Section 3 for more details.

(2) See Section 2.4 for a comment on fractional trains.

(3) Note that more trains are running under the improved practice than under the existing practice because the wagons which used to travel Sydney-Adelaide via Broken Hill now travel via Melbourne.

TABLE 3.2

EXISTING TRACK - COMPARISON OF THE ANNUAL OPERATING COST
OF THE EXISTING AND THE IMPROVED OPERATING PRACTICES

($m)

Direct Operating Costs	Existing Practice				Improved Practice			
	Pessimistic Case		Optimistic Case		Pessimistic Case		Optimistic Case	
	1975-76	1994-95	1975-76	1994-95	1975-76	1994-95	1975-76	1994-95
Capital	9.63	20.30	17.22	36.29	9.48	19.98	16.94	35.68
Crew	3.11	6.56	3.11	6.56	3.03	6.39	3.03	6.39
Fuel and Maintenance(1)	5.93	12.49	15.77	33.23	5.86	12.35	15.57	32.81
Track Maintenance	2.14	4.51	4.99	10.52	2.13	4.50	4.98	10.49
Bogie Exchange	0.41	0.86	0.42	0.88	0.36	0.76	0.36	0.76
TOTAL	21.22	44.72	41.51	87.48	20.86	43.98	40.88	86.13

(1) This term covers the fuel and maintenance costs for motive power and rolling stock.

TABLE 3.3

EXISTING TRACK - DAILY ROLLING STOCK AND MOTIVE POWER REQUIREMENTS FOR THE TWO METHODS OF OPERATING THE NETWORK.

Type of Vehicle (2)	Rolling Stock and Motive Power Requirements (1) (No. Vehicles)			
	Existing Practice Pessimistic Case		Improved Practice Pessimistic Case	
	1975-76	1994-95	1975-76	1994-95
No. full vans	-	-	-	-
No. empty vans	-	-	-	-
No. full opens	121.5	256.0	121.5	256.0
No. empty opens	20.4	43.0	20.4	43.0
No. full flats	246.9	520.3	246.9	520.3
No. empty flats	15.4	32.4	15.4	32.4
No. full car carriers	34.8	73.4	34.8	73.4
No. empty car carriers	32.6	68.7	27.4	57.7
Total No. full wagons	403.2	849.7	403.2	849.7
Total No. empty wagons	68.4	144.1	63.2	133.1
TOTAL NO. WAGONS	471.6	993.8	466.4	982.8
No. electric locos	3.3	6.9	-	-
No. small standard locos (3)	6.9	14.5	-	-
No. large standard locos	37.7	79.4	39.6	83.4
No. small broad locos (3)	20.1	42.4	22.7	47.8
No. large broad locos	8.8	18.5	11.3	23.9
TOTAL NO. LOCOS	76.8	161.7	73.6	155.1

(1) Rolling stock and motive power requirements give the number of vehicles required to carry out the given freight task.
(2) See Annex A. for a comment on wagon and locomotive types.
(3) "Standard" or "broad" refers to the gauge on which the locomotive runs.

(ii) locomotives could be scheduled to operate around the whole network to improve their deployment.

Table 3.4 illustrates the traffic flows for the two different networks. It should be noted that the differences in the numbers of trains running in the two cases are due to the basic network differences. The corresponding differences in the compositions of the locomotive and rolling stock fleets are shown in Table 3.5 which displays the wagon and locomotive requirements for the "pessimistic cases". More detailed examination of the results indicates that there are no circular movements of locomotives but, in general, an increased number of wagons circulated in the standardised case. Table 3.6 shows the breakdown of the operating costs for each of the cases examined. By considering the results of the "pessimistic cases", it can be seen that operating the standardised network leads to savings of about $400,000 in 1975-76 and $880,000 in 1994-95. From Table 3.6, it can be seen that these savings are mainly due to the elimination of bogie exchange costs.

3.3 EVALUATION OF THE STANDARDISATION PROPOSAL

The results of the analysis of Section 3.2 can be used to give some indication of the benefit to cost (B/C) ratio of the proposal to standardise the Melbourne-Adelaide-Crystal Brook link in 1975/76. The standardisation option is compared to the existing network operating under the existing traffic allocation.

To obtain an upper limit for the B/C ratio for the proposal, calculations were based on estimates of the maximum benefits combined with estimates of the minimum likely capital cost of the proposal.

The minimum capital cost was estimated to be $70m for building a standard gauge link from Adelaide to Crystal Brook plus $70m for standardising from Adelaide to Melbourne by using a third rail. More detailed investigation, however, may show that a third rail option between Melbourne and Adelaide is technically infeasible and, consequently, the total capital cost of the proposal is likely to be considerably higher than $140m.

TABLE 3.4

EXISTING OPERATING PRACTICE-COMPARISON OF THE NUMBER OF TRAINS RUNNING ON THE EXISTING NETWORK WITH THE NUMBER RUNNING ON THE STANDARDISED NETWORK.

Origin	Destination	Number of Trains/Day (1)(2)(3)			
		Existing Track Existing Practice		Standardised Track Existing Practice	
		1975-76	1994-95	1975-76	1994-95
Sydney	Melbourne	5.7	12.0	5.8	12.3
Melbourne	Sydney	5.0	10.5	4.9	10.4
Melbourne	Adelaide	2.2	4.6	2.2	4.6
Adelaide	Melbourne	2.2	4.6	2.1	4.4
Adelaide	Peterborough	1.3	2.7	1.3	2.7
Peterborough	Adelaide	1.2	2.6	1.1	2.2
Peterborough	Sydney	0.9	1.8	0.8	1.8
Sydney	Peterborough	0.8	1.7	0.7	1.5

(1) This table represents both "optimistic" and "pessimistic" cases since the number of trains running in both cases is the same. This is because the relative magnitude of the sensitive parameters did not change. See the introduction to Section 3 for more details.

(2) See Section 2.4 for a comment on fractional trains.

(3) It should be noted that differences in the numbers of trains running in the two cases are due to basic network differences (see Fig 1).

TABLE 3.5

DAILY ROLLING STOCK AND MOTIVE POWER REQUIREMENTS FOR OPERATING THE EXISTING NETWORK AND THE STANDARDISED NETWORK UNDER EXISTING OPERATING PRACTICES.

Type of Vehicle(2)	Rolling Stock and Motive Power Requirements(1) (No. Vehicles)			
	Existing Track Existing Practice Pessimistic Case		Standardised Track Existing Practice Pessimistic Case	
	1975-76	1994-95	1975-76	1994-95
No. full vans	-	-	-	-
No. empty vans	-	-	-	-
No. full opens	121.5	256.0	100.3	211.3
No. empty opens	20.4	43.0	30.9	65.2
No. full flats	246.9	520.3	270.0	568.8
No. empty flats	15.4	32.4	4.0	8.4
No. full car carriers	34.8	73.4	34.8	73.4
No. empty car carriers	32.6	68.7	27.4	57.7
Total No. full wagons	403.2	849.7	405.1	853.5
Total No. empty wagons	68.4	144.1	62.3	131.3
TOTAL NO. WAGONS	471.6	993.8	467.4	984.8
No. electric locos	3.3	6.9	2.8	6.0
No. small standard locos(3)	6.9	14.5	26.8	56.4
No. large standard locos	37.7	79.4	47.1	99.2
No. small broad locos(3)	20.1	42.4	-	-
No. large broad locos	8.8	18.5	-	-
TOTAL NO. LOCOS	76.8	161.7	76.7	161.2

(1) Rolling stock and motive power requirements give the number of vehicles required to carry out the given freight task.
(2) See Annex A for a comment on wagon and locomotive types.
(3) "Standard" or "broad" refers to the gauge on which the locomotive runs.

TABLE 3.6

EXISTING OPERATING PRACTICE - COMPARISON OF THE ANNUAL OPERATING COSTS OF EXISTING NETWORK WITH THOSE OF THE STANDARDISED NETWORK.

($m)

Direct Operating Costs	Existing Track, Existing Practice				Standardised Track, Existing Practice			
	Pessimistic Case		Optimistic Case		Pessimistic Case		Optimistic Case	
	1975/76	1994/95	1975/76	1994/95	1975/76	1994/95	1975/76	1994/95
Capital	9.63	20.30	17.22	36.29	9.67	20.36	17.29	36.42
Crew	3.11	6.56	3.11	6.56	3.09	6.51	3.09	6.51
Fuel and Maintenance(1)	5.93	12.49	15.77	33.23	5.93	12.48	15.79	33.26
Track Maintenance	2.14	4.51	4.99	10.52	2.13	4.49	4.97	10.47
Bogie Exchange	0.41	0.86	0.42	0.88	-	-	-	-
TOTAL	21.22	44.72	41.51	87.48	20.82	43.84	41.14	86.66

(1) This term covers the fuel and maintenance costs for motive power and rolling stock.

Benefits of standardisation arose from:

(i) direct bogie exchange cost savings for the internal network traffic; these led to benefits having a present value (P.V.) of $4.26m (accumulated over 20 years at 10% discount rate)

(ii) elimination of direct bogie exchange costs for the traffic entering and leaving the network (e.g. Perth-Melbourne traffic) lead to benefits with a P.V. of $12.24m,[1][2]

(iii) elimination of Port Pirie and Peterborough bogie exchange delay costs lead to benefits having a P.V. of $10.77m.[2]

Therefore,

$$B/C = \frac{\text{P.V. total benefits}}{\text{P.V. total capital costs}} = \frac{27.27}{140} = 0.19$$

This result indicates that, even under the most favourable conditions, the Melbourne-Adelaide-Crystal Brook rail standardisation proposal was not economically justifiable in 1975-76.

4. CONCLUSIONS

This paper has attempted to demonstrate the usefulness of an analytical tool applied to operational and project evaluation problems.

In the two illustrative examples provided, use was made of upper and lower estimates of input variables to determine the likely boundaries of the results of the analysis. This technique

(1) Originally, Perth-Eastern States traffic was excluded from the analysis since there was little or no scope for reallocation of this traffic.

(2) Relevant costs required for the calculation of the B/C ratio were obtained from: BUREAU OF TRANSPORT ECONOMICS, Study on the East-West Rail Link (to be published).

proved suitable for determining that, without doubt, rail standardisation cannot be justified on economic grounds at present, and for predicting the order of magnitude of gains possible from better operational use of existing facilities. The analysis shows that savings ranging from $360,000 to $1.35m per annum can be achieved by rerouting the Adelaide-Sydney traffic via Melbourne. These savings are a direct consequence of improved locomotive and wagon deployment.

Operational analysis, however, only represents a first step in the evaluation procedure, since, to actually realise the potential savings, the railways would need to initiate administrative and possibly organisational changes. The cost of these changes would need to be taken into account for a more complete evaluation of the possibility of rerouting the Adelaide-Sydney traffic via Melbourne.

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ANNEX A
BASIC DATA(1)

In some particular areas, e.g. capital costs and utilisation coefficients, there is considerable disagreement about the values to be used. This difficulty has been circumvented to some extent by placing upper and lower bounds on the values of these contentious quantities. In the actual running of the model, these bounds give rise to the optimistic and pessimistic cases e.g. low locomotive utilisation coefficients contribute to higher capital costs and so increased direct operating costs.

A.1 CAPITAL COSTS (1975-76)

(a) *Locomotives*

1491 kw diesel	$640,000
2237 kw diesel	$750,000
2684 kw electric	$750,000
Lifetime	20 years

(b) *Wagons*

	Lower Bound	Upper Bound
Van	$31,000	$52,000
Car Carrier	$26,000	$43,000
Open Wagon	$25,000	$40,000
Flat Wagon	$23,000	$38,000
Lifetime	20 years	

(c) *Bogies*

Capital	$5,000
Lifetime	20 Years

(1) The data are BTE estimates mainly based on information received from the various railway authorities in conjunction with BTE's mainline upgrading studies.

A.2 MAINTENANCE COSTS (1975-76)

(a) *Track Maintenance*

Lower Bound	Upper Bound
0.03c/gtk	0.07c/gtk

Note: gtk ≡ gross-tonne-kilometre.

(b) *Locomotive Maintenance*

Lower Bound	Upper Bound
$0.219/km	$0.745/km

(c) *Wagon Maintenance*

Lower Bound	Upper Bound
1.27c/km	3.76c/km

A.3 FUEL COSTS (1975-76)

Lower Bound	Upper Bound
0.0286c/km	0.04689c/km

A.4 BOGIE EXCHANGE COSTS (1975-76)

Cost of bogie exchanging a wagon = $24.12

A.5 CREW COSTS (1975-76)

$26.0/hour

A.6 UTILISATION COEFFICIENTS

The utilisation coefficient is defined as the fraction of time spent moving, including delays incurred while travelling. It is an attempt to account for routine and unscheduled maintenance, waiting times for connection to the next train, loading and unloading times for wagons as well as the general inefficient use of capital equipment.

(a) *Locomotives*

	Lower Bound	Upper Bound
	0.28[1]	0.6

(b) *Wagons*[2]

Van	0.23
Car Carrier	0.44
Flat	0.15
Open	0.16

(c) *Bogies*

0.25

A.7 TRANSIT TIMES

Table A.I provides the transit times for the various links and sublinks of the network obtained from current railway timetables.

A.8 TRAIN DETAILS INCLUDING LOCOMOTIVE REQUIREMENTS

Table A.II provides Train details including locomotive requirements.

A.9 WAGON DETAILS

Table A.III provides wagon information. At this stage a comment needs to be made on the selection of wagons types. From an analysis of the results of the BTE Wagon Study[2] it was calculated that the four types of wagons considered here i.e. vans, flats, opens and car-carriers made up nearly 75% of wagons considered in that study for intercapital movement. On these grounds, it was considered reasonable to construct the wagon fleet for the purposes of this exercise from these four wagons types, thus avoiding a complicating proliferation of wagons types.

(1) Obtained from the South Australian State Transport Authority, Rail Division.

(2) BUREAU OF TRANSPORT ECONOMICS. Railway Freight Operations, A Survey of Wagon Usage (to be published).

TABLE A.I

TRANSIT TIMES FOR THE LINKS AND SUB-LINKS OF THE NETWORKS
(days)

	Origin	Destination	Transit Time
Main Links			
	Sydney	Melbourne	0.96
	Melbourne	Sydney	0.93
	Melbourne	Adelaide	0.67
	Adelaide	Melbourne	0.68
	Adelaide	Peterborough(1)	0.23
	Adelaide	Peterborough(2)	0.26
	Peterborough	Adelaide(1)	0.20
	Peterborough	Adelaide(2)	0.23
	Peterborough	Sydney	1.54
	Sydney	Peterborough	1.26
Sub-Links			
	Sydney	Albury	0.49
	Albury	Sydney	0.53
	Albury	Melbourne	0.29
	Melbourne	Albury	0.34
	Melbourne	Serviceton	0.34
	Serviceton	Melbourne	0.32
	Serviceton	Tailem Bend	0.17
	Tailem Bend	Serviceton	0.11
	Tailem Bend	Adelaide	0.13
	Adelaide	Tailem Bend	0.14
	Adelaide	Peterborough(1)	0.23
	Adelaide	Peterborough(2)	0.26
	Peterborough	Adelaide(1)	0.20
	Peterborough	Adelaide(2)	0.23
	Peterborough	Broken Hill	0.23
	Broken Hill	Peterborough	0.22
	Broken Hill	Parkes	0.72
	Parkes	Broken Hill	0.65
	Parkes	Lithgow	0.34
	Lithgow	Parkes	0.26
	Lithgow	Sydney	0.14
	Sydney	Lithgow	0.14

(1) For the broad gauge link.
(2) For the standard gauge link via Crystal Brook.

TABLE A.II

TRAIN DETAILS INCLUDING LOCOMOTIVE REQUIREMENTS

Sub-Link Origin	Destination	Locomotive Requirements	No. of Wagons/ Train	Train Weight (tonnes)
Sydney	Albury	2x2237kw	28	1100
Albury	Sydney	2x2237kw	28	1100
Albury	Melbourne	1x2237kw	28	1100
Melbourne	Albury	1x2237kw	28	1100
Melbourne	Serviceton	2x2237kw	35	1400
Serviceton	Melbourne	2x2237kw	35	1400
Serviceton	Tailem Bend	1x1491kw	35	1400
Tailem Bend	Serviceton	1x1491kw	35	1400
Tailem Bend	Adelaide	3x1491kw	35	1400
Adelaide	Tailem Bend	3x1491kw	35	1400
Adelaide	Peterborough	1x1491kw	20	800
Peterborough	Adelaide	1x1491kw	20	800
Peterborough	Broken Hill	2x2237kw	30	1200
Broken Hill	Peterborough	2x2237kw	30	1200
Broken Hill	Parkes	2x1491kw	30	1200
Parkes	Broken Hill	2x1491kw	30	1200
Parkes	Lithgow	2x1491kw	30	1200
Lithgow	Parkes	2x1491kw	30	1200
Lithgow	Sydney	1x2684kw	30	1200
Sydney	Lithgow	2x2684kw	30	1200

TABLE A.III

WAGON INFORMATION

Wagon Type	Weight of Empty Wagon (tonnes)	Average Tonnage of Good Type Carried/Wagon: Foodstuff	Iron and Steel	Motor Cars	General Freight	Containers
Van	21.0	21.0	0.0	0.0	21.0	0.0
Open	22.0	26.0	26.0	0.0	26.0	0.0
Flat	19.0	0.0	35.0	0.0	24.0	24.0
Car Carrier	20.0	0.0	0.0	11.0	0.0	0.0

Table A.III also indicates the relationship between wagons and goods classes.

A.10 LOCOMOTIVE WEIGHTS

Weight of 1491 kw locomotive	114 tonnes
Weight of 2237 kw locomotive	130 tonnes

A.11 DISCOUNT RATE

On the grounds of simplicity, only one discount rate, namely 10%, has been used.

ANNEX B
ASSUMPTIONS AND MATHEMATICAL DESCRIPTION OF THE MODEL

The model of the daily performance of the rail network is formulated as a linear program which minimises an objective function representing a sum of direct operating costs subject to constraints derived from a consideration of the operating conditions.

B.1 NOTATION

IMS	=	index set of main stations
ISS	=	index set of sub-stations
IML	=	set of direct main-links (i,j) joining two main stations i and j without going through any other main station
ISL	=	set of all links between any two stations
IBE	=	set of bogie exchange stations
IS(i,j)	=	set of all possible link chains (without loops) between main station i (origin) and main station j (destination)
	=	$\{S_{ij}\}$
B	=	number of types of bogies
K	=	number of classes of goods
L	=	number of types of wagons
M	=	number of types of locomotives
$BOG_{(i,j)}^{(b)}$	=	number of bogies of type b sent from station i to station j
CCPD	=	crew cost per day per crew
CEB	=	cost of exchanging a bogie
DCCB	=	daily capital cost per bogie
DCCL(m)	=	daily capital cost per locomotive of type m
DCCW(l)	=	daily capital cost per wagon of type l
d(i,j)	=	distance of link (i,j)
dd(s)	=	distance of route s
$EW_{(i,j)}^{(l)}$	=	number of empty wagons of type l sent daily through the direct link $(i,j) \varepsilon IML$

FKG = fuel cost per kilometre per gross tonne

$FW^{(l,k)}_{(i,j,s)}$ = number of full wagons of type l, carrying goods of class k shipped daily from origin i to destination j along chain $s \varepsilon IS(i,j)$

$GOOD^{(k)}_{(i,j)}$ = daily tonnage of goods of class k originating at main station i for delivery at main station j through any chain $s \varepsilon IS(i,j)$

$loc^{(m)}_{(i,j)}$ = number of locomotives of type m actually running daily on sublink (i,j)

$MAXTR(i,j)$ = maximum number of trains per day on link (i,j)

$MCL(m)$ = maintenance cost per locomotive of type m per kilometre travelled

$MCW(l)$ = maintenance cost per wagon of type l per kilometre travelled

$NB(l)$ = number of bogies for wagon of type l

$NBEW(l)$ = maximum number of bogies transported on an empty wagon of type l

$NT(l,k)$ = net tonnage of goods of type k carried on a wagon of type l

$NTR(i,j)$ = number of trains to run daily on link (i,j)

$t(i,j)$ = journey time on main link or sub-link (i,j)

$TMC(i,j)$ = track maintenance cost per kilometre per gross tonne on sub-link (i,j) for each $(i,j) \varepsilon ISL$

$TRLOAD(i,j)$ = nominal average load of train on link (i,j)

U_{bog} = utilisation coefficient of spare bogies

$U(m)_{loc}$ = utilisation coefficient of wagon of type m

$U(l)_{wag}$ = utilisation coefficient of wagon of type l

$WB(b)$ = weight of a bogie of type b

$WE(l)$ = weight of an empty wagon of type l

$WL(m)$ = weight of locomotive of type m

Indices i and j are used exclusively to denote stations and as a pair (i,j) to denote a directed link.

Indices b, k, l, m, s are used exclusively to denote a bogie type, a class of goods, a type of wagon, a type of locomotive and a link chain respectively.

B.2 OBJECTIVE FUNCTION

The objective function is the sum of capital costs, crew costs, fuel and maintenance costs for motive power and rolling stock, track maintenance costs and bogie exchange costs.

(a) Capital Costs

Only capital costs which depend on the utilisation of resources are considered.

The numbers of locomotives, wagons and spare bogies required to operate the system depend on their total usage on a given day and also on their long run utilisation levels. In an attempt to account for routine and unscheduled maintenance, waiting time for connection to next train, loading and unloading times for wagons and general inefficient use of capital equipment, the concept of a utilisation coefficient is introduced. It is defined as the fraction of time spent moving including delays incurred while travelling. Utilisation coefficients are considered as exogenous and given.

The daily capital costs are determined from the purchase price under the assumption of an expected lifetime and a certain discount rate.

(i) The daily utilisation of wagons of type l, is given by

$$\sum_{\substack{(i,j)\\ \varepsilon IML}} t(i,j)(EW^{(l)}_{(i,j)} + \sum_{k} \sum_{(\bar{i},\bar{j})} \sum_{S*} FW^{(l,k)}_{(\bar{i},\bar{j},s*)})$$

where s* denotes a chain from $\bar{i}$ to $\bar{j}$ going through (i,j).

The total daily capital costs for all wagons, taking into account their utilisation levels are:

$$C_{wag} = \sum_{l=1}^{L} \frac{DCCW(l)}{U_{wag}^{(l)}} \left(\sum_{\substack{(i,j) \\ \varepsilon IML}} t(i,j) \left(EW_{(i,j)}^{(l)} + \sum_{k} \sum_{(\bar{i},\bar{j})} \sum_{s*} FW_{(\bar{i},\bar{j},s*)}^{(l,k)} \right) \right)$$

(ii) Similarly, the total daily capital cost for all locomotives is given by

$$C_{loc} = \sum_{m=1}^{M} \frac{DCCL(m)}{U_{loc}^{(m)}} \left(\sum_{\substack{(i,j) \\ \varepsilon ISL}} t(i,j)\ loc_{(i,j)}^{(m)} \right)$$

(iii) Similarly, the total daily capital cost for spare bogies is given by

$$C_{bog} = \sum_{b=1}^{B} \frac{DCCB}{U_{bog}} \left\{ \sum_{\substack{(i,j) \\ \varepsilon ISL}} t(i,j)\ BOG_{(i,j)}^{(b)} \right\}$$

(iv) Therefore, the capital cost contribution to the objective function (CAPCOST) is given by

$$CAPCOST = C_{wag} + C_{loc} + C_{bog}$$

(b) Crew Costs

Since the number of crew-days required per day is determined by the total travelling time of the trains, the crew cost contribution to the objective function (CREWCOST) is given by

$$CREWCOST = CCPD \left(\sum_{\substack{(i,j) \\ \varepsilon IML}} t(i,j)\ NTR\ (i,j) \right)$$

(c) Fuel and Maintenance Costs

While fuel costs are assumed to be proportional to the total gross-tonne-km travelled daily, maintenance costs of the motive power and rolling stock are assumed to be proportional to the total distance travelled.

(i) For empty wagons (possibly carrying spare bogies) the fuel and maintenance costs are given by

$$FM_{ewag} = \sum_{l=1}^{L} (FKG*WE(l) + MCW(l)) \sum_{\substack{(i,j)\\ \varepsilon IML}} EW^{(l)}_{(i,j)} \; d(i,j)$$
$$+ \; FKG \left(\sum_{b=1}^{B} WB(b)\left(\sum_{\substack{(i,j)\\ \varepsilon IML}} BOG^{(b)}_{(i,j)} \; d(i,j)\right)\right)$$

(ii) Similarly, the fuel and maintenance costs of full wagons are given by

$$FM_{fwag} = \sum_{l=1}^{L} \sum_{k=1}^{K} (FKG*(WE(l) + NT(l,k)) + MCW(l)) \times$$
$$\left(\sum_{\substack{(i,j)\\ \varepsilon IML}} \sum_{S} FW^{(l,k)}_{(i,j,s)} \; dd(s)\right)$$

(iii) Similarly, the fuel and maintenance costs of locomotives are given by

$$FM_{loc} = \sum_{m=1}^{M} (FKG*WL(m) + MCL(m)) \sum_{\substack{(i,j)\\ \varepsilon ISL}} d(i,j) \; loc^{(m)}_{(i,j)}$$

(iv) Therefore, the fuel and maintenance cost contribution to the objective function (FMCOST) is given by

$$FMCOST = FM_{ewag} + FM_{fwag} + FM_{loc}$$

(d) Track Maintenance Costs

For a particular track on any sublink, the maintenance costs are assumed to be proportional to the gross-tonne-km travelled.

(i) For empty wagons (possibly carrying spare bogies), the track-maintenance cost is given by

$$TM_{ewag} = \sum_{\substack{(i,j)\\ \varepsilon ISL}} TMC(i,j) \; d(i,j)\left(\sum_{l} WE(l) \; EW^{(l)}_{(i*,j*)} + \sum_{b} WB(b) BOG^{(b)}_{(i*,j*)}\right)$$

(ii) Similarly, the track-maintenance cost for full wagons is given by

$$TM_{fwag} = \sum_{\substack{(i,j)\\ \in ISL}} TMC(i,j)d(i,j) \left(\sum_{l}\left(\sum_{k}(WE(l)+NT(l,k))\left(\sum_{(\bar{i},\bar{j})}\sum_{S*} FW^{(l,k)}_{(\bar{i},\bar{j},s*)}\right)\right)\right)$$

(iii) Similarly, the track maintenance cost for locomotives is given by

$$TM_{loc} = \sum_{\substack{(i,j)\\ \in ISL}} TMC(i,j)\ d(i,j)\ \left(\sum_{m} WL(m)\ loc^{(m)}_{(i,j)}\right)$$

(iv) Therefore, the track maintenance cost contribution to the objective function (TMCOST) is given by

$$TMCOST = TM_{ewag} + TM_{fwag} + TM_{loc}$$

(e) Bogie Exchange Costs

Indirect costs due to bogie exchanges have already been accounted for e.g. in fuel and maintenance costs or through the use of utilisation coefficients in the case of delays. Direct costs arising from the physical exchange of bogies are introduced here. They include crew costs and operating and maintenance costs for the machinery.

Because of the conservation law for wagons, the number of wagons of type l undergoing bogie exchange at station i IBE is

$$\left|\sum_{k}\sum_{(j*,i)}\sum_{S*} FW^{(l,k)}_{(j*,i,s*)} - \sum_{k}\sum_{(i,j*)}\sum_{p*} FW^{(l,k)}_{(i,j*,p*)} + EW^{(l)}_{(j*,i)} - EW^{(l)}_{(i,j*)}\right|$$

$$+ \sum_{k}\sum_{(j,h)} \left(\sum_{s*} FW^{(l,k)}_{(j,h,s*)} + \sum_{p*} FW^{(l,k)}_{(j,h,p*)}\right) = \left| P^{(l)}_{(i)} \right| + R^{(l)}_{(i)}$$

where s* or (j*,i) denotes a b-type gauge path going through or ending at i and p* or (i,j*) denotes a b-type gauge path continuing after or initiating from i.

s*,(j*,i), p*, (i,j*) are defined for b= 1 or 2 but not both.

Using the above expression as a definition of $P_{(i)}^{(l)}$ and $R_{(i)}^{(l)}$ and using a dummy variable $X_{(i)}^{(l)}$, the bogie exchange costs (BOGEXCO[ST])
are given by

$$BOGEXCOST = CEB \sum_{i \varepsilon IBE} \sum_{l=1}^{L} NB(l) \; (X_{(i)}^{(l)} + R_{(i)}^{(l)})$$

where the $X_{(i)}^{(l)}$ are restricted by

$$P_{(i)}^{(l)} \leqslant X_{(i)}^{(l)}$$

$$-P_{(i)}^{(l)} \leqslant X_{(i)}^{(l)}$$

for every l and every i εIBE

Since the costs have to be minimised, $X_{(i)}^{(l)}$ will become $\left| P_{(i)}^{(l)} \right|$

(f) Now, the objective function, TOTALCOST, can be written down

TOTALCOST = CAPCOST + CREWCOST + FMCOST + TMCOST + BOGEXCOST

B.3 CONSTRAINTS

(a) All goods have to be delivered, possibly through different routes.

For every (i,j) εIMS X IMS, and for each class of goods k,

$$\sum_{l=1}^{L} NT(l,k) \; \left(\sum_{s \varepsilon S(i,j)} FW_{(i,j,s)}^{(l,k)} \right) = GOOD_{(i,j)}^{(k)}$$

(b) Availability and transhipment of empties.

Empty wagons of a given type needed at any main station can be sent from any other station with a surplus, moreover they can be transhipped via any other main stations. This constraint amounts to a conservation law for wagons.

For every wagon type l and for every main station i IMS

$$\sum_{(j,i)\varepsilon IML} EW^{(l)}_{(j,i)} - \sum_{\substack{(i,j)\\ \varepsilon IML}} EW^{(l)}_{(i,j)} = \sum_{k=1}^{K} \sum_{\substack{j\varepsilon IMS\\ j\neq i}} \left[\sum_{s\varepsilon IS(i,j)} FW^{(l,k)}_{(i,j,s)} - \sum_{s\varepsilon IS(j,i)} FW^{(l,k)}_{(j,i,s)} \right]$$

(c) Train Load(without locos)

Enough trains should run on any main link so that the nominal average train load is not exceeded.

For every $(i,j)\varepsilon IML$

$$\sum_{l=1}^{L} (EW^{(l)}_{(i,j)}\, WE(l) + \sum_{k=1}^{K} \Big(\sum_{\substack{(\bar{i},\bar{j})\\ i\neq j}} \sum_{s*} FW^{(l,k)}_{(\bar{i},\bar{j},s*)}\Big)(WE(l)+NT(l,k))) + Q(i,j)$$

$$\leqslant \; TRLOAD(i,j)NTR(i,j)$$

where Q(i,j) is defined below.

(d) Train Length

On any main link (i,j), enough trains should be run so that their nominal average length, expressed in number of standard wagons, is not exceeded. The formulation of this constraint is similar to that of (c) above.

(e) Line Capacity

On any line (i,j), the number of trains should not exceed the line's daily capacity.

For every $(i,j) \; \varepsilon IML$

$$NTR(i,j) \leqslant MAXTR(i,j)$$

(f) Locomotive requirements

The number of locomotives of a given type travelling daily on a given sublink of the network should at least be equal to the daily number of trains, times their requirements in this type of locomotive.

(g) Locomotive conservation law

All locomotives arriving at a station must leave it.

(h) Bogie exchange

Wagon bogies of a given type needed at any bogie exchange station can be sent on empty wagons from any other station with a surplus; moreover they can be transshipped via any other main stations.

For each type b of bogies, we have;

(i) At each bogie exchange station $i \in IBE$

$$\sum_{\substack{(i,j)\\ \in IML}} BOG^{(b)}_{(i,j)} - \sum_{\substack{(j,i)\\ \in IML}} BOG^{(b)}_{(j,i)} = \sum_{l} NB(l) \left(\sum_{k} \sum_{\substack{(j,h)\\ \in IML}} \sum_{s^*} FW^{(l,k)}_{(j,h,s^*)} - \sum_{k} \sum_{\substack{(h,j)\\ \in IML}} \sum_{p^*} FW^{(l,k)}_{(h,j,p^*)} + EW^{(l)}_{(j^*,i)} - EW^{(l)}_{(i,j^*)} \right)$$

where s^*, (j^*,i), p^*, (i,j^*) are defined above.

(ii) At any station $i \notin IBE$

$$\sum_{\substack{(i,j)\\ \in IML}} BOG^{(b)}_{(i,j)} - \sum_{\substack{(j,i)\\ \in IML}} BOG^{(b)}_{(j,i)} = 0$$

(iii) For each link (i,j)

$$\sum_{b} BOG^{(b)}_{(i,j)} \leq \sum_{l} NBEW(l) EW^{(l)}_{(i,j)}$$

(iv) The load $Q(i,j)$, included in (e) above is given by

$$Q(i,j) = \sum_{b} WB(b)\ BOG^{(b)}_{(i,j)}$$

B.4 THE LINEAR PROGRAMMING PROBLEM

The optimal use of the system resources, given certain utilisation levels of the motive power and rolling stock, is obtained by minimising the objective function subject to the constraints above. The decision variables are:

$FW^{(l,k)}_{(i,j,s)}$, $EW^{(l)}_{(i,j)}$, $NTR(i,j)$, $loc^{(m)}_{(i,j)}$, $BOG^{(b)}_{(i,j)}$.

All of these variables are non-negative.

ANNEX C

RAIL FREIGHT PROJECTIONS 1975-76/1994-95

At the time of commencement of the study, the most recently available rail freight tonnages covered the year 1974-75.(1) For the purposes of this analysis, those tonnage figures were broken down into 5 commodity classes; foodstuffs, general freight, containers, cars and iron and steel.(2) Because cost data were available for 1975-76, this year was selected as the base year for the study.

In the light of the available evidence,(3) the growth rate in all classes of freight traffic was assumed to be 4% per annum for the whole of the 20 year study period.

The tonnage figures for 1974-75 were increased by 4% to obtain base year tonnages (75-76). Table C.I shows the annual freight tonnages for the study's base year, 1975-76.

TABLE C.I

ANNUAL FREIGHT FLOWS FOR THE BASE YEAR 1975-76
('000 tonnes)

Class of Freight	Origin and Destination					
	Sydney Melbourne	Melbourne Sydney	Sydney Adelaide	Adelaide Sydney	Melbourne Adelaide	Adelaide Melbourne
Foodstuff	56	4	-	8	16	6
Iron and Steel	532	8	78	1	85	-
Cars	5	67	3	18	13	14
General Freight	157	253	58	140	220	280
Containers	369	388	-	-	173	196
TOTAL	1119	720	139	167	507	496

(1) This information was obtained from the Public Transport Commission of N.S.W. and the South Australian State Transport Authority, Rail Division.

(2) These classes represent an amalgamated version of BTE's internal classification of rail freight.

(3) BUREAU OF TRANSPORT ECONOMICS. Study on the East-West Rail Link, (to be published.)