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NAME
SPEHRITT
MEYER

ADDRESS
29 Dale Rd, Ashbury, S.A.
24-5-1975, 30 Ashbury, Rd

SIGNATURE
P. SCHRITT

DATE
31/7/72

THIS THESIS MUST NOT BE REMOVED FROM THE LIBRARY
City & Suburban Electric Railway and the Sydney Harbour Bridge
Bradfield
The Science of Engineering is many phased, all the arts and sciences come within its purview. It records and analyses every advance in Science, researches to thoroughly understand these advances, and by its natural magic - the art of applying the manifold seen and unseen phenomena in nature for the use and service of mankind - the science of engineering exercises the greatest of all influences on the material well being of any nation, recording, energising, creating, indeed making national existence possible. The highest plane of Engineering Science can only be attained by the perfect blending of the utility of material things with the beauty of spiritual things, and esteemed will be the work of the Engineer whose life is happily so influenced; its characteristics will be simplicity, harmony, breadth, its keynote, majesty, beauty.

In attempting to solve the traffic problems of this growing city, the arts and sciences, pure and applied must be availed of to their fullest extent. Mathematics, Chemistry, Physics, Geology, Mechanics, Architecture, Metallurgy, Electricity, Geodesy, Economics, the Production and Properties of Materials, the temperament, characteristics and habits of the people, the political needs of the day, indeed nature in
all her manifold aspects must be studied. The past history of the city must be known, present day conditions understood and the future visualised with imagination, origination, and a sound practical judgment.

Many proposals extending back as far as the year 1857 have been made for the extension of the railways into the City whilst the proposal for a bridge across the Harbour dates back to the year 1815. These proposals were at first dealt with as separate matters, but it became manifest that the trans-harbour connection must form an integral portion of the series of electric railways necessary to develop the metropolitan area, and link up with the existing suburban railway & tramway services.

There have been many proposals for bridges, tunnels & subways across the harbour and many and diverse locations for the electric railways more particularly for the City Railway. A brief description of the various proposals for the trans-harbour connection is given in Public Works Committee Inquiry on the Sydney Harbour Bridge presented to Parliament in 1913, and the various proposals for the City Railway in my report on the "Proposed Electric Railways for the City of Sydney" presented to Parliament and printed on August 26th, 1915.

Beyond this brief reference, the past history of these projects will not be further touched upon. Suffice it to say that on June 25th, 1912 the Hon. Arthur Griffith, the then Minister for Works issued the following instruction:

"With reference to the Sydney Harbour Bridge, the City Traffic, and the work covered by Mr. Hay's report, once Parliament has given the necessary authority for the carrying out of any of these works, the public would never tolerate delay, and I must ask, therefore, that steps be at once taken to push the work forward as far as possible in every detail, in order that a minimum of time only will be required subsequently to give effect to the Government's desires, whatever they may be. For this purpose the services of Mr. Bradfield should be set exclusively apart for these works and he be given authority to prepare all the preliminary work he can."

These instructions covered the Sydney Harbour Bridge, the City Railway, the Eastern Suburbs Railway and the Western Suburbs Railway.
Following these instructions the Sydney Harbour Bridge & City Transit Branch was inaugurated on 1st July 1912 and the Author appointed Chief Engineer. Subsequently the name of the Branch was changed to the Metropolitan Railway Construction Branch. On the transfer of the work of railway construction to the Railway Department on 1st January 1917 the Author has carried out all work in connection with Metropolitan Railway Construction under the Railway Department and for the Sydney Harbour Bridge under the Public Works Department.

The first officer appointed to the Branch was Miss K. M. Butler now my Confidential Secretary; she has at all times carried out her duties with foresight, tact and marked ability. In preparing the Specification for the Sydney Harbour Bridge she was my only assistant; the technique of the Specification is hers, and it would I think be impossible to find a better arranged or better printed specification. During my absence abroad in 1922 she carried out all correspondence with tenderers throughout the world, herself; she is present at all interviews with tenderers in Sydney, and myself excepted she alone knows of the many issues involved in tendering for the Bridge. Her conscientious and efficient help has materially lightened the responsibility which the design and construction of these two great engineering works have entailed, and in this Thesis I wish to place on record my sincere thanks to the lady for her invaluable assistance.

The Scheme of City and Suburban Electric Railways as outlined herein and the Sydney Harbour Bridge were originated by me. The construction of the City Railway and the Sydney Harbour Bridge has been commenced and for which I am directly responsible; the completed cost of these two works will approximate £12,000,000 sterling. The whole scheme including the Electrification of the Suburban Railways will total
£40,000,000 sterling.

In concluding this introduction may I add that anything I have or may accomplish was made possible in my student days by the work and influence of Professor Warren. He then taught me the sound principles of Engineering practice and in my life's work I have had the opportunity and sometimes I made the opportunity to apply them.
In Sydney, as in many other cities which were well established when the great railway construction boom of "the fifties" took place, the railway station was arranged as a terminal on the edge of the business section of the city, partly on account of lack of vision as to the future importance of the City, but chiefly on account of the cost of establishing the main station where land values were high. Then, as now, money was the controlling factor, and it was easier and cheaper to establish the terminal in the Cleveland Paddocks, just outside the City, rather than in the City itself.

Since that time, both the population and the land values of Sydney have increased enormously, and Central Station, constructed in 1906, is now as inadequate for traffic demands as the old station became.

A brief review of the growth of Sydney's population and improved capital values during the twenty years from 1901 to 1921, and the increase in traffic during the same period will indicate the nature of the traffic problem to-day.

Population and Unimproved Capital Values.

Greater Sydney in the census year of 1921 embraced an area of 368,057 acres, having a population of 1,030,800, and an unimproved capital value of £98,052,478. Since 1901 the population has increased at the rate of 3.6 per cent per annum and has more than doubled itself, having numbered 505,670 at that date. The rate of increase has been variable but steadily increasing, the rate over the 10 years period 1901-1911 being 3.4% per annum and the rate from 1911 to 1921 being 3.9% per annum. The increase has been confined largely to the more outlying suburbs, the greatest rate being in the Illawarra district suburbs where it was 8.4% per annum over the 10 years 1911-1921;
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<td>Dundas</td>
<td>80,342</td>
<td>3.2</td>
<td>110,382</td>
<td>10.4</td>
<td>296,452</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1,543,788</td>
<td>-</td>
<td>1,390,886</td>
<td>10.3</td>
<td>3,701,665</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>City of Sydney.</strong></td>
<td>20,432,004</td>
<td>1.6</td>
<td>23,940,030</td>
<td>4.1</td>
<td>35,887,376</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total Greater Sydney Area.</strong></td>
<td>41,355,193</td>
<td>2.0</td>
<td>53,718,613</td>
<td>6.2</td>
<td>98,053,473</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Districts outside Greater Sydney Area.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bankstown</td>
<td>-</td>
<td>-</td>
<td>291,049</td>
<td>5.4</td>
<td>491,233</td>
<td>-</td>
</tr>
<tr>
<td>Canley Vale</td>
<td>-</td>
<td>-</td>
<td>328,433</td>
<td>8.0</td>
<td>707,220</td>
<td>-</td>
</tr>
<tr>
<td>Cabramatta</td>
<td>-</td>
<td>-</td>
<td>63,702</td>
<td>10.5</td>
<td>171,942</td>
<td>3.2</td>
</tr>
<tr>
<td>Liverpool</td>
<td>-</td>
<td>-</td>
<td>197,884</td>
<td>2.6</td>
<td>254,482</td>
<td>1.2</td>
</tr>
<tr>
<td>Prospect</td>
<td>-</td>
<td>-</td>
<td>160,081</td>
<td>13.6</td>
<td>572,222</td>
<td>5.4</td>
</tr>
<tr>
<td>Sherwood</td>
<td>-</td>
<td>-</td>
<td>83,936</td>
<td>3.8</td>
<td>338,241</td>
<td>7.3</td>
</tr>
<tr>
<td>Fairfield</td>
<td>-</td>
<td>-</td>
<td>59,076</td>
<td>8.6</td>
<td>136,016</td>
<td>6.0</td>
</tr>
<tr>
<td>St. Mary's</td>
<td>-</td>
<td>-</td>
<td>139,258</td>
<td>3.3</td>
<td>189,184</td>
<td>6.0</td>
</tr>
<tr>
<td>Richmond</td>
<td>-</td>
<td>-</td>
<td>149,837</td>
<td>5.6</td>
<td>154,489</td>
<td>5.5</td>
</tr>
<tr>
<td>Campbelltown</td>
<td>-</td>
<td>-</td>
<td>41,279</td>
<td>13.2</td>
<td>142,176</td>
<td>2.0</td>
</tr>
<tr>
<td>Ingleburn</td>
<td>-</td>
<td>-</td>
<td>82,317</td>
<td>6.6</td>
<td>183,484</td>
<td>5.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,024,922</td>
<td>-</td>
<td>1,963,481</td>
<td>6.4</td>
<td>3,593,173</td>
<td>4.3</td>
</tr>
<tr>
<td>Total-Inner &amp; Outer Zone</td>
<td>42,360,160</td>
<td>-</td>
<td>55,652,094</td>
<td>6.2</td>
<td>101,551,651</td>
<td>4.0</td>
</tr>
</tbody>
</table>

*Non-incorporated areas not included in increase for district.
suburbs from Auburn to Parramatta having the next highest increase, viz. 6.7% per annum, the Northern Suburbs 6% per annum, and Ashfield to Homebush district, 4.7% per annum. Other portions of the Greater Sydney Area show little or no increase.

The variation in unimproved capital values has, to some extent, followed the increase in population, the Illawarra Suburbs showing 12.3% per annum increase, Auburn to Parramatta showing 10.3% per annum increase, the Northern Suburbs 8.75% increase and Ashfield to Homebush 6.5% increase. The Eastern and East Central Suburbs, however, though showing a population increase of under 1% per annum, showed an increase in unimproved capital value of 6 to 7% per annum, residential areas becoming business areas.

Tables I and II show in detail the variation in both population and unimproved capital values over these periods, while the plans in figures 1 and 2 indicate in different colours the total increase over 10 years from 1911 to 1921 for the various Municipalities. These show very clearly the extent to which the more distant lying suburbs have contributed to the total increase both in population and land values.
Traffic.

The traffic, both railway and tramway, has increased at even a greater rate than the population during these twenty years, 1901-1921.

In 1901 the total suburban railway traffic amounted to 23,421,136 passenger journeys per annum, whereas in 1921 it had become 104,307,959 passenger journeys per annum as shown in Figure 3, a total increase of 345%, or an average increase of 7.95% per annum.

Over the same period the tramway traffic had grown from 81,086,164 passenger journeys in 1901 to 308,737,663 passenger journeys in 1921, a total increase of 280% or an average increase of 6.9% per annum.

In the year ended June 30, 1923, the total railway suburban traffic had increased to 107,313,211 passenger journeys, while the tramway traffic for the year ended June 30, 1923 was 305,261,517 passenger journeys, a slight decrease since the year 1921. The increase in railway traffic for the different portions of the suburban railway is shown by accompanying diagram.

These figures are significant when considered in conjunction with the figures for population, indicating as they do that the combined train and tram journeys per head of population increased during that period from 205 to 427 per annum. Figures that are available for the passenger journeys per head of population in other large cities up to 1915 give 333 for New York and 240 for London, and include the surface, underground and overhead services. In that year the journeys per head in Sydney amounted to 390, or more than any other city in the world.

The present railway traffic of 107,313,211 passenger journeys per annum, analysed on a basis of 339 full days in the year, represents a daily traffic of 316,000 persons or 158,000 passengers in each direction. Of these passengers nearly seven-eighths pass through Central Station.

A traffic count was carried out at Central Station on May 6, 1920, and every person or
vehicle entering or leaving the station between 4 p.m. and 6.30 p.m. was counted by observers stationed at the various entrances to the station—two observers being stationed at each entrance. In these two hours and a half, 58,122 people entered Central Station and 10,972 people left the station. The maximum hour occurred between 5.10 p.m. and 6.10 pm, and during this time 37,200 people entered and 5,780 people left the station.

The maximum traffic rate occurred at 5.40 p.m. when passengers were entering the station at the rate of eight hundred per minute, and the rate for the whole hour did not fall far short of this. Figure 4 shows the loading of the different station entrances during this period.

Assuming that the maximum hour traffic represents about 15% of the total daily traffic in both directions, a figure that has been found to represent conditions in Sydney and New York, the daily traffic at Central Station at the time of the count in 1920 would be about 248,000 passengers, or 124,000 in each direction.

A comparison of this figure with figures quoted for other great Railway Stations of the world, viz., Liverpool Street Station, London, 200,000 per day; Gare St.Lazare, Paris, 250,000 per day (record), South Station Boston, 210,000 per day, shows that the normal daily traffic of Central Station, Sydney, is equal to, if not greater than, that of any other station in the world. Central Station, further, is a tram terminus as well as a train terminus and constitutes rather a transfer point than a terminal station.

Trams run past three sides of the station and into the station building and traverse the four principal streets running North and South—Elisabeth, Castlereagh, Pitt and George Streets. The tramway traffic has reached a point of such density that the city system is unable to cope with more traffic and increased tramway accommodation on the streets is just about impossible.
Two Minutes Peak 5:40 to 5:42 $1586 = 46950$ per hour
Fifteen " 5:33 to 5:48 $10384 = 43936"$
Thirty " 5:16 to 5:46 $20377 = 40754"$
Sixty " 5:10 to 6:10 $57195"$
Total " 4:00 to 6:30 $58122"$

Arrivals Grand Total
" by Tram from Hay Street
" Western Side
" Eastern Side
Vehicular Traffic.

The density of tramway traffic, particularly during the morning and evening rush when the headway on George, Pitt and Elizabeth Streets is 17 seconds per tram in one direction, and the headway on one track in each street at the intersection of King and George Streets is six seconds, greatly increases the difficulty of satisfactorily handling the vehicular traffic of the City. This traffic is now assuming very serious proportions, as the following table will show. At the intersection of Eddy Avenue and Elizabeth Streets a count on July 4, 1923 showed that nearly 24,000 vehicles passed between 7 a.m. and 6 p.m., or nearly 2,200 vehicles per hour. Other points in the City showed a smaller number of vehicles than this but at many of the points the traffic was, nevertheless, very heavy, the total number of vehicles entering and leaving the business portion of the City during the day being about 40,467 in each direction. The above figures are for vehicular traffic only and do not include trams. Detail figures are given in Table III.

On the northern side of the Harbour, similar conditions obtain: the terminal station is at Milson's Point. Tram and train disembark their teeming thousands at "The Point", who continue their journey across the water on commodious ferry steamers, plying at six minute intervals during the busy hours of the day. Counts of the Milson's Point Railway traffic were made in July 1919, and showed that, at that time, 12,000 passengers were carried on week days in each direction, the traffic over the maximum hour representing slightly over 15% of the day's traffic in each direction. These passengers, on landing at the Quay, either walk or take trams to their destination. Similarly from the hinterland of Manly, from Athol, Mosman, Cremorne, Neutral Bay, McMahon's Point, Balmain and Waker's Bay, trams carry many thousands of passengers to the water's edge to be conveyed to and from their daily avocations or pleasures, by privately owned ferry steamers. These ferries ply, of course, to many wharves along the harbour foreshores not served by tram or train.

The land area of Greater Sydney within a two-mile radius of Central Station is 7,040 acres,
### Table 3.

**Count of Vehicular Traffic, Both Passenger and Goods, at the Following Crossings, Intersections and Punts within the City's Precincts, Between the Hours of 7 a.m. and 6 p.m. on July 2nd, 1923**

<table>
<thead>
<tr>
<th>Crossing, punt or Intersection</th>
<th>Vehicles</th>
<th></th>
<th>Vehicles</th>
<th></th>
<th>Total No. Vehicles, Both Ways</th>
<th>Passenger Vehicles as percentage of Total Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passengers</td>
<td></td>
<td>Goods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>One Way</td>
<td>Both Ways</td>
<td>One Way</td>
<td>Both Ways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt. Macquarie</td>
<td>458</td>
<td>916</td>
<td>431</td>
<td>862</td>
<td>1,778</td>
<td>52%</td>
</tr>
<tr>
<td>Dawes' Point</td>
<td>36</td>
<td>72</td>
<td>200</td>
<td>400</td>
<td>472</td>
<td>15%</td>
</tr>
<tr>
<td>Boomerang and College Sts.</td>
<td>1,542</td>
<td>3,084</td>
<td>283</td>
<td>566</td>
<td>3,650</td>
<td>85%</td>
</tr>
<tr>
<td>William and College Sts.</td>
<td>347</td>
<td>694</td>
<td>695</td>
<td>1,790</td>
<td>2,484</td>
<td>28%</td>
</tr>
<tr>
<td>Oxford and College Sts.</td>
<td>5,026</td>
<td>10,052</td>
<td>3,264</td>
<td>6,528</td>
<td>16,580</td>
<td>60%</td>
</tr>
<tr>
<td>Elizabeth Street &amp; Eddy Ave.</td>
<td>4,917</td>
<td>9,834</td>
<td>6,959</td>
<td>13,918</td>
<td>23,752</td>
<td>41%</td>
</tr>
<tr>
<td>Central Railway Square</td>
<td>3,401</td>
<td>6,802</td>
<td>5,155</td>
<td>10,310</td>
<td>17,112</td>
<td>40%</td>
</tr>
<tr>
<td>Pyrmont Bridge</td>
<td>2,405</td>
<td>4,810</td>
<td>5,168</td>
<td>10,296</td>
<td>15,106</td>
<td>32%</td>
</tr>
</tbody>
</table>

**TOTALS:** 18,132 36,264 22,335 44,670 80,934

Gross total of all classes of vehicles: 40,467 one way.

The above figures may be taken as an average over the course of one week or six working days. Traffic was counted on 'Goods and Passenger' one way only, it being considered a satisfactory assumption that the figures for combined inward and outward traffic are double the figures for one way traffic.
and that enclosed between circles of two and four miles radius is 19,294 acres, as shown on plan in Figure 5, approximately 35 per cent of the population reside within the two mile radius, 26 per cent between the two and four mile radius, whilst 39 per cent occupy the remaining metropolitan area.

A city increasing in population is a prosperous City, and given facilities to travel, the number of journeys per head of population increases much more rapidly than the increase in population, and it becomes more and more difficult to make the channels of passenger transport equal to the ever growing demands. The traffic conditions necessitate provision being made to bring the people to the business area by a traffic system of greater capacity and speed than the existing tramway system, although this is not excelled in any part of the world. In other countries where similar conditions have arisen, the solution, in recent years, has always been by means of rapid transit electric railways.

As the railways and tramways are all owned by the State, it has been found possible to devise a scheme which will enable trains to be run between the suburbs and outlying districts, and the business area of the City, without compelling passengers to change from one Railway system to another as is usually necessary in large cities where the transit systems are controlled by separate authorities; or of changing from train or ferry to the tramway system as is at present necessary in Sydney.

In considering the problems involved in planning a rapid transit system, various questions of fundamental importance arise. Before describing the scheme as designed, these will be discussed.
FUNDAMENTALS TO BE CONSIDERED IN DETERMINING ROUTE, CAPACITY, ETC.

Many factors govern the selection of the most suitable route. Certain districts have to be served and some situations are far more desirable for station location than others. In an endeavour to confine the cost of resumptions to a reasonable figure, it is advisable to follow street lines wherever possible, while the cost of permanent underpinning makes it advisable to avoid heavy buildings where this can be done.

Two methods of construction, which may be designated as high level and low level, present themselves. In the high level scheme, advantage is taken of the natural contours of the city by locating the line partly underground and partly on viaduct, while in the low level location, the tracks would be located at such a depth that the surface contours had no influence on the location. This latter type of location is exemplified by the Central London Underground, which is located from 60 to nearly 200 feet below the surface.

For Sydney, at least, the advantages are wholly on the side of the high level proposal. While with this location the interference with property above ground is greater, a great deal of permanent underpinning can be avoided, and when property has to be resumed, some of the land can be re-sold at a profit. Generally speaking, these considerations will balance the increased cost of resumptions.

Grades, at least in the case of Sydney, are worse for a low level scheme than for a high level scheme - the ruling grade is the same, but long runs on maximum grade are necessitated. Long down grades, with consequent increase in the braking distance of trains necessitate longer block sections, and thus, by increasing the headway permissible between trains, reduce the capacity of the system.
Generally speaking, the high level scheme presents a simpler problem from the construction point of view, particularly in respect to constructing an underground station in such a location as Central Station or Circular Quay. In both cases the underground station entails more serious traffic disturbance during construction, while in localities such as Circular Quay, the nature of the ground and the proximity of tidal influence are serious considerations.

From the point of view of ventilation a low level scheme in a climate as warm as that of Sydney, would, with even elaborate ventilating equipment, cause a considerable amount of discomfort to passengers. In a high level scheme, however, with tunnel openings at Circular Quay and Goulburn Street, with comparatively short communication with the outside air at all stations no discomfort should be felt, even in the absence of any forced ventilation.

Grades and Curves are, of course, determining features in the layout of a rapid transit system, affecting as they do the speed attainable or permissible, and the load that can be handled. Modern equipment on multiple unit trains can usually give an acceleration on level tangent of 1 to 1\frac{1}{2} miles per hour per second, and with such equipment, a grade of 1 in 40 can be negotiated without seriously affecting the schedule speed. This grade may be considered the maximum for rapid transit conditions, though a grade of as much as 1 in 30 is permissible where the direction of the traffic is with the grade. At the same time, heavy down grades, particularly if of considerable length, so greatly increase the braking distance as to seriously affect the train capacity of the line and necessitate additional signalling equipment to ensure safe working under all conditions.

Curves having a radius greater than 500 feet are with modern electric stock quite satisfactory; in fact, curves of 330 feet radius at Grand Central Terminal, New York, and 230 feet radius at Charing Cross loop have been installed for station working.

In order to accommodate cars such as are used in steam working, curves of sharper radius
than 500 feet are not advisable and introduce difficulties in providing against superelevation and throwout.

**Flyovers.** Maximum capacity on rapid transit tracks cannot be obtained with the existence of grade crossings on any part of the line, and in underground railways it is usually possible to avoid them by constructing flyover junctions by suitable grading of the tracks at little extra cost. Where, however, the tracks are about the same level and are grouped together in a restricted width the construction of flyovers becomes more complicated and expensive though still necessary. Such a condition exists in the station yard south of Central Station where the construction of flyovers will entail considerable expense but are demanded by the necessity for ease in traffic working and considerations of safety. At other points on the City Railway, flyover junctions are obtained without serious difficulty.

**Train Capacity.** The headway, or interval between successive trains is determined largely by the braking distance required and the length of stop in a station. As before stated, the braking distance is a function of the speed of the train, the grading of the line having a considerable influence.

The station stop has a most important influence on the train capacity as the distance between the tail of a train stopped in a station and the head of the following train is usually the controlling factor.

It is most important, therefore, that every endeavour should be made to reduce the station stop to a minimum. Many considerations enter into the question of a station stop among which may be cited:

(a) the orderliness of routing of passengers;
(b) the design of car;
(c) Car and station lighting;
(d) arrangements and lighting of platform edge.
Of these, perhaps the most important is the routing and education of the travelling public. It is essential that passengers moving in opposite directions should be kept separate, and that entrances should be so arranged with regard to ticket offices and station conveniences as to avoid any intermingling of passengers. Waiting areas on the station should, if possible, be so arranged that waiting passengers do not prevent free movement of alighting passengers. The provision of indicators and signs giving passengers correct information regarding trains and ample directions as to location of entrances, exit, conveniences, etc., should be carefully developed.

The design of car to give a maximum of capacity with a maximum of convenience, with doors so arranged to ensure rapid ingress and egress, has a considerable influence on the length of station stop. The aim in designing such a car is to encourage alighting passengers to gather about a door before the train comes to a stop and to do this they must have ample passage ways of minimum length. This requires that the doors of the carriage be some distance removed from the ends of the carriage. These doors, to be effective, must be of ample width without any dividing post or framing and should be such that three persons can leave the car abreast.

Plan 6 shows how this has been obtained on the car designed for the City Railway. This car will be of steel construction throughout, and will seat 79 passengers and has a maximum capacity of 120. The two doors are each 5 feet 10 inches wide located at about the quarter points of the car.

Uniformity in the lighting of the car, such as can be obtained by a system of indirect lighting, overcomes the natural tendency for passengers to congregate in the best lighted area and prevents seated passengers being inconvenienced by shadows cast by standing passengers. An intensity of 3 foot candles measured at 3 feet above the floor of the carriage is aimed at in modern car lighting.

Platform lighting should be such that the platform edge is well defined. The platform edge should be flush with the car floor or preferably be so arranged that the step overlaps the plat
N. S. W. G. R.
61'-6" Side Loading Suburban Car.

Seating Capacity 79 Passengers
Maxim. 100
Weight empty - Motor 105,000 lb.
- Trailer 83,000 lb.

PLATE №6
form edge by a few inches with a small drop to the platform as in London. This obviates any hesitation caused by the gap between platform and step, particularly on curves.

On a system in which all factors such as the above have been given due regard, there is no difficulty in securing a station stop of 20 seconds even under conditions of heavy traffic.

In times of normal traffic, a station stop of 10 to 15 seconds is about the range on London Tubes, being somewhat higher during the evening rush, the maximum noted being 35 seconds, and the average of twenty-five consecutive trains during the busy period being 22 seconds.

Signalling. The train capacity of the line under the continuous overlap system of signalling is limited by the fact that the minimum distance between trains must equal the safe braking distance of a train at the maximum speed. This minimum space interval must be maintained even if the speed of the train is far below its maximum speed.

Ideal signalling would be obtained by automatically ensuring that at any speed the distance between any two trains was only one safe braking distance at that speed. In such a system, the movements of the train in advance would automatically check the speed of the train in its rear when the distance between the two threatened to become less than the safe braking distance for the speed at which the rear train was running. Such a scheme is the goal at which many signal engineers are aiming and progress has been made towards its attainment.

A system of speed control which was an advance towards the ideal was successfully installed in the New York Subways, in 1917. In this system the track was divided into sections in the same manner as for automatic signalling with train stops. In addition to enforcing obedience to caution and stop signals, the system permitted predetermined maximum running speeds with corresponding block lengths based on the brake equipment and the grade on which the train was running.

Driven by an axle of each car was a centrifugal speed measuring device, which, though a cam effected the vertical movement of a sleeve in a straight line relationship with the speed of the train.
Contact ramps arranged at intervals alongside the running rails were energised with high voltage, medium voltage, or were in a de-energised condition.

In the de-energised condition they put into operation the speed control device on the car; medium voltage was used to cut out the speed control element of the car in cases where the control element had been in operation in the previous block.

Provided the driver kept the speed below that allowable by the speed control element the control was entirely in his hands. If, however, the speed of the car exceeded the allowable speed an automatic brake application resulted, preventing the train reaching the end of the block. A whistle was arranged to warn the driver whenever the speed of the train approached the maximum allowed.

More recent developments in regard to speed control have resulted in an equipment which is independent of track circuits other than those required for the ordinary automatic signals and in which track ramps are replaced by an indicator consisting of a shallow U shaped structure of laminated iron having enlarged pole pieces and surrounded by a choke coil the circuit of which may be opened or closed as the signal indicates clear or caution.

Located on the car in such a manner as to pass over this indicator with a clearance of a few inches as shown on Figure 7 is a receiver consisting of a laminated iron yoke carrying enlarged pole pieces similar to those of the indicator and having a primary coil energised by a storage battery and a secondary coil having in its circuit a storage battery and relay.

When the circuit of the choke coil on the track indicator is open and a car passes over it, a sudden change of magnetic flux is induced in the receiver and produces a variation in the current passing through the relay which causes it to open. Under such conditions the relay, through suitable translating equipment causes an automatic application of the brake.

If, however, the circuit of the choke coil on the track indicator remains closed, this coil will then act as a choke to prevent any variation in the magnetic flux of the receiver with the
Automatic Train Control. Inductor and Receiver.
result that the relay controlling the brake equipment does not operate.

When full automatic speed control is in operation, or if a fixed hazard such as curves or bridges demands a limited maximum speed, a time element relay forms part of the car equipment and track indicators are located in pairs at such a distance apart as to suit the predetermined speed and the time of operation of the relay. The time element is caused to function as the first indicator is passed but an application of the brakes does not result unless the train takes more than the predetermined time before passing the second indicator, that is, unless the speed restriction is not observed. If, however, the train passes the second indicator before the predetermined time has elapsed, a service application of the brakes results and the train is brought to a stop.

This equipment is so designed that non-compliance with the fixed speed restrictions or signal indicators always results in a stop, it being necessary for the driver to descend from the train in order to operate the reset-key from the ground.

While complete automatic speed control will undoubtedly form an essential feature of rapid transit systems in the future, it has hardly yet passed from the experimental stage and modern traffic conditions can be well met by automatic signalling with continuous overlaps and train stops, with any special conditions for rapid station working or safety against some special hazard provided against by a modified form of speed control.

Automatic signals with train stops are now in use on practically all rapid transit systems. Figure 8 shows a typical train stop arrangement—while the installation of a speed control system near and in stations is now the custom on the express tracks of the Interboro Rapid Transit Co., New York.

Stations. The arrangement of stations has a pronounced influence on the lengths of station stop and hence on the capacity of the system. Imperfect track arrangements, especially at terminal stations, will also seriously decrease the train capacity and for this reason the loop type of ter-
VIEW OF THE AIR-BRAKE VALVE UPON THE TRUCK BENEATH THE CAB WHICH IS OPENED IF TRAIN ATTEMPTS TO RUN PAST TRAIN STOP
minal station, having the same train capacity as the railway, presents obvious advantages where its construction is possible.

In the handling of large numbers of passengers entering and leaving the station it is necessary to avoid interference between passengers moving in opposite directions and to this end separate entrances and exits are desirable, with passages so arranged that no conflicting passenger movement occurs between the station entrance and the train.

In moving passengers through a greater height than can comfortably be negotiated on stairs, escalators, generally of four feet width, have completely superseded any other form of elevator; such a four foot escalator can handle 10,800 persons per hour on lifts up to 60 feet in one run at a speed of 90 feet per minute.

Analyses of traffic movements in passage ways both in New York and Sydney indicate that a maximum capacity of 35 passengers per foot width per minute can be realised; while on stairs, 18 passengers down or 20 passengers up per foot width per minute represents the maximum capacity.

In the design of ramps, a grade of 1 in 9 is the steepest that can be permitted with safety and comfort to passengers, while a minimum grade of 1 in 12 is advisable.

THE CITY RAILWAY SCHEME AS DESIGNED.

The Metropolitan System:

The complete transit scheme for the City of Sydney comprises four interconnected loops, viz. the City loop and the Suburban loops to serve the Eastern, Western and Northern Suburbs, with spur lines therefrom to the outlying suburbs, and is shown by Plan 9.

Consider the part that the City Railway, the Sydney Harbour Bridge and the electrification of the Suburban Railways must play in the development in Sydney. The lines in black show the existing steam railways - those within the suburban area, i.e., between the Hawkesbury and Nepean Rivers and the Coast will be electrified. The first to be electrified will be the Railway - Sydney to Waterfall.
with the spur line, Loftus to National Park; whilst the Sutherland to Cronulla tramway will, at no distant date, be remodelled into an electric railway. A passenger at North Sydney could then take a train at Walker Street and reach Cronulla without changing trains. The second railway to be electrified will be the Bankstown Railway, whilst the Railways - Sydney to Parramatta, Sydney to Hornsby, via Strathfield, and Hornsby via the Bridge to the City, will follow, and afterwards the Railways in the whole of the suburban area, to Campbelltown, Penrith, Windsor and the Hawkesbury River will be worked electrically.

The white lines show the proposed electric railways which have already been approved by Parliament, viz., the City Railway, the Eastern Suburbs Railway, the Western Suburbs Railway and the Sydney Harbour Bridge, with its connecting railways from Wynyard Square to Bay Road Station. A railway will extend from Athol through Manly, via the Bridge to the City, whilst Manly, Narrabeen and Pittwater will also be connected to the City via the Bridge, and it will be seen at a glance how the Bridge and these Railways will open up the Northern Suburbs and give them direct Railway communication with the City and Southern Suburbs.

To-day it takes 84 minutes to reach the G.P.O. from Narrabeen by tram, boat and the George Street tram; but via Northbridge and the Bridge by electric train, it would take only half an hour. Manly to-day is about 40 minutes distant from the G.P.O. by boat and the George Street tram; via the Bridge with a non-stop train it would take 18 minutes, unless, as happens on the Illawarra Railway, the slow trains stop at the stations, but the through trains very often stop between the stations. From Spit Junction by tram, Manly Ferry and the George Street tram, the time occupied in travelling to the G.P.O. is 38 minutes; by tram, Cremorne Ferry and tram, the time is 33 minutes; and by tram, Milson's Point Ferry and George Street tram, the time is 40 minutes to the G.P.O., whilst via the Bridge the time from the Spit Junction to the G.P.O. should not exceed 16 minutes, with an electric
railway service stopping at the intermediate stations also. From Walker Street, North Sydney, by tram, Milson's Point Ferry and George Street tram to the G.P.O. to-day takes 20 minutes, whilst via the Bridge by train, the time would be 7 minutes, which includes the time necessary for the passengers to walk from Wynyard Square Station to the Post Office.

Eastwood and the Stations beyond, via the proposed Eastwood-St.Leonards Railway, will be two miles nearer the General Post Office via the Bridge than via the Central Station, whilst Hornsby and all stations beyond will be 7½ miles nearer the G.P.O. via the Bridge than via Central Station.

As the Railways are constructed to Cremorne, Mosman, Athol, Manly, Narrabeen, Pittwater, etc., the stations will provide for goods traffic as well as for passengers, and the distribution of coal, wood, meat, agricultural products, fruits, etc., will be expedited and considerably cheapened, whilst the City Merchant will be able to forward the daily purchases by rail to suitable centres and distribute them from these centres to the purchaser, saving not only time but money to both purchaser and merchant.

When the break of gauge question is settled, the Transcontinental Express will start at say Rockhampton on its run of 3,880 miles to Fremantle, and will pass through Sydney, via the Sydney Harbour Bridge, thus shortening the distance several miles. The same carriages will run right through, steam and electric locomotives only being changed at various pre-arranged stopping places, Sydney becoming, as it were, a wayside station. The Bridge is designed to carry this traffic.

Plan No. 10 is a Bird's-eye view of Sydney as it will be, showing the route of the City Railway, the bridge across the Harbour to Milson's Point, the bridge from Miller's Point to Peacock's Point, Balmain, and the arrangement of the wharves along the Harbour foreshores and twenty-three acres of Darling Harbour reclaimed and added to the Railway Goods Yard.

The City Loop:

The City Railway (Plan 11) junctions with the main line at Wells Street, Redfern, where eight
tracks will continue citywards as the City Railway while four tracks on the western side will lead to the existing Central Station to handle long distance traffic.

Between Walls Street and the new Central Station located to the east of the existing one and having its rail level 71.00 or 4 feet higher than at present, trains will be routed; the four up and four down tracks laid alternately will, by means of flyovers, be grouped into four pairs of up and down tracks laid alternately in pairs, cross connection between any two tracks being obtained without the necessity of using level crossings. For these tracks, the Cleveland Street Overbridge will be widened by two double track spans. In the flyover construction, the raised tracks will be carried on steel floor construction embedded in concrete and carried on brick piers save for short sections of viaduct between brick retaining walls. The total amount of depression of the lower tracks will be 9 feet, while the upper tracks will have a maximum elevation of 11 feet.

The new Central Station (Plan 12) - Rail level 71.00 - located to the East of Platform 15 of the present station will consist of four island platforms, served by steps from a subway at the north end and by a connection at the southern end with Devonshire Street subway. The subway at the North end will contain booking offices and all station conveniences and will be constructed throughout out of re-inforced concrete. Passenger and baggage facilities for this station will have direct connection with the present central station in which the steam long-distance traffic will terminate.

From Central Station, six tracks continue into the City, crossing Eddy Avenue, Hay Street and Campbell Street on arches of reinforced concrete construction, the intervening portions being carried on solid fill between masonry faced retaining walls of concrete. On this portion of the railway, the six tracks are arranged in the order two up, two down, one up, one down, from west to east, until Goulburn Street is reached. Here the tracks diverge, the two up and two down tracks to the west being taken around the western side of the City, the inner pair of these forming the North
Shore direct communication.

Between Campbell and Goulburn Streets, the natural contours permit of the change from viaduct to tunnel with a grade of 1 in 78, and at the southern building line of Goulburn Street all tracks are below surface level.

Plan No. 13 shows the construction of the Railway along Belmore Park, the bridges across Hay Street and Campbell Street; here the six tracks enter the Commissioners Offices and run underground before they reach Goulburn Street.

On the block bounded by Campbell, Goulburn, Elizabeth and Castlereagh Streets, will be erected an Office building 400 feet long by an average width of 126 feet and the maximum height allowed, viz., 150 feet. It will be a steel framed structure with concrete floors; the exterior walls will be faced with brick and sandstone. The main entrance front to Goulburn Street will be set back 40 feet from the Building line to leave room for a grass plot.

The four tracks turning west from Goulburn Street pass in 4-track flat top construction of steel beams and columns to Town Hall Station situated under George Street in front of the Town Hall.

Rail level at this station is 42.00, averaging 34 feet below the surface and the station is on a 20-chain curve. It is constructed with steel beams and girders throughout, floors and roof being of reinforced concrete and side walls of concrete fill between steel columns.

Access to the station is obtained from four sets of entrances and exits arranged on both sides of George Street, at Bathurst Street, Park Street and Druitt Street, and booking hall and station conveniences are located on an assembly floor located above the platforms and below the street. Track arrangements are such that one island platform is served by both up tracks, the other by both down tracks, thus facilitating the exchange of passengers between the City and North Shore connection.

Plan No. 14 shows the location of the Town Hall Station under George Street and the entrances
Hay & Campbell St  Bridges & proposed Commissioners Offices
VIEW SHOWING ENTRANCES TO THE TOWN HALL STATION SYDNEY
thereto. These will be placed on the footpath on the Eastern side of George Street which will be widened about 9 feet to allow of this; there are entrances in Druitt Street and in Bathurst Street near St. Andrew's Cathedral.

Beyond the Town Hall Station one up and one down track will rise, whilst the other two tracks fall, the four tracks continuing at two levels beneath York Street until Wynyard Square Station is reached.

The upper tracks, which form the North Sydney connection, are immediately beneath the surface under the centre of the street in double track flat top steel construction; whilst the two lower or City tracks are in single track tunnels located below and to each side of the higher construction.

Wynyard Square Station, being the junction for North Sydney traffic will be a two level station with rail levels R.L. 17.00 and R.L. 49.5, having a concourse floor between the two levels. This station is located below York Street and Wynyard Park and will be almost entirely of steel column and girder construction with reinforced concrete panels for floors and roof. Provision is made for terminating a certain proportion of both City and North Sydney trains and in order to facilitate the handling of the large traffic that is anticipated at this point, separate arrival and departure platforms are provided, there being five platforms in all.

Access to the station will be by three subways; a main entrance 50 feet wide through from George Street, an entrance from the corner of Barrack and Carrington Streets and an entrance from Margaret Street. The arrangement of passage-ways and stairs is such that traffic moving in opposite directions is kept distinct from street to platform.

From Wynyard Square Station the lower level tracks continue north and turn to the east in single track tunnel emerging from the surface at Harrington Street where a thirty foot cliff makes the transition from tunnel to viaduct possible. From this point the tracks are carried by viaduct across Harrington Lane, George Street and Circular Quay through a combined railway and ferry station which will occupy the sites of the Parramatta, Lavender Bay, North Sydney, Mosman and Manly Ferry
wharves. Rail level in the station will be R.L. 33.00 and platforms will be 27 feet above surface level. This building will house the four main ferries and their offices and will give improved facilities for handling their traffic. In addition, shops, parcels offices, conveniences and a large restaurant will be provided.

The building will be of steel frame construction, the railway supports being isolated from the rest of the building, and will be founded on iron and concrete caissons sunk to rock, the depth of which varies from 20 to 55 feet below the surface.

Plan No. 15 shows the railway as it will appear above ground from Harrington Street and Macquarie Street, also the station at Circular Quay with the Sydney Harbour Bridge in the background.

After crossing the Quay on viaduct, advantage is again taken of the surface contours to change over to tunnel construction under Macquarie Street, and the lines continue from here in single and double track tunnel in a wide sweep under the Botanical Gardens and Macquarie Street to St. James Station.

This station is situated under the northern end of Hyde Park and is designed to serve terminating as well as through traffic, being the junction for the Eastern Suburbs connection.

Rail level will be R.L. 56.00, about 45 feet below the surface and the usual station offices and conveniences will be located in a concourse 110 feet square located above the tracks at the centre of the station. The type of construction used for the concourse will be steel columns and girders with reinforced concrete floor and roof panels, but the remainder of the station for a length of about 200 feet to the north and south of the concourse platforms will be spanned by four symmetrical reinforced concrete arches of 24' span and 6 feet 6 inches rise carried on centre and side walls of concrete.

Access to the concourse is by easily graded subways from Queen's Square and Market Street, incoming and outgoing passengers being separately routed from street to platform.

Two island platforms will accommodate City Railway and Eastern Suburbs traffic, the city
traffic being handled on the two outer tracks and the Eastern Suburbs on the two inner.

Plan 16 shows a view of St. James' Station when completed. As will be seen, there are four tracks serving two island platforms. The construction will be of re-inforced concrete throughout; the station roof consisting of four reinforced concrete arches as shown; there will be the side walls, a supporting wall along the centre of each of the platforms and the centre wall between the centre tracks. Access to and from the platforms will be by means of stairways; the incoming and outgoing traffic is kept separate as can be seen from the plan.

South of St. James' Station the outer or city tracks continue in single track tunnel construction at low level to Liverpool Street Station, the inner tracks being carried in twin tunnel and construction just below the surface being so graded that south of Park Street they cross the down city tracks by flyover and continue towards Oxford Street to form the Eastern Suburbs connection.

Liverpool Street Station, at the southern end of Hyde Park is served by two tracks at R.L. 50.00, forty five feet below the surface, and has two side platforms, the whole being spanned by a reinforced concrete arch of 48 feet span, 520 feet long. Entrances and exits are provided at both ends of the station, to Liverpool Street and Bathurst Street, and subways convey passengers to the platforms at six points.

Plan 17 shows Liverpool Street Station when complete. As will be seen, the roof consists of a single reinforced concrete arch span; there are two side platforms with a double line of railway between. The incoming passengers enter at either end of each platform, whilst the outgoing passengers have four openings for egress.

From Liverpool Street the tracks proceed south in twin tunnel construction under Liverpool and Elizabeth Streets and emerging at Goulburn Street from the two eastern tracks on the 6 track viaduct leading to Central Station.

The route mileage of the City loop from Walls Street, Redfern and back to the same point is
St. James Station
Liverpool St Station
5 miles 7\(\frac{1}{2}\) chains of which 2 miles 47 chains is below ground, 34\(\frac{1}{2}\) chains on viaduct, and 2 miles 6 chains on the natural surface. The total track mileage of this section of the work is 15 miles 69 chains. The six stations on the city loop are approximately 50 chains apart and are all provided with platforms 520 feet long.

**North Sydney Connection:**

The North Sydney connection (Plan 18) via the Sydney Harbour Bridge is made from the upper level of Wynyard Square Station. From here, four tracks continue underground to immediately north of Grosvenor Street where they emerge. The two up tracks paralleling the main bridge approach via Princes Street on a 1 in 25 grade, the two down tracks sweeping outward towards Kent Street on embankment and viaduct on a grade of 1 in 39 to meet the main bridge approach south of George Street North. After traversing the Bridge the tracks curve to the north west on viaduct to Kirribilli Station located in front of the Town Hall, North Sydney, having access from Burton Street.

Continuing still on viaduct to the North West, North Sydney Station is reached. This station is situated between Miller and Walker Streets and will be an important station for both passenger and goods traffic. The line from this point continues west, passing in tunnel under the Church of England Grammar School and links up with the Milson's Point line at Bay Road Station.

The North Sydney passenger station (Plan 19) will extend from Walker Street to Blue's Point Road parallel to Blue Street. There will be two island platforms, each 520 feet, and a goods siding 11 chains long, between Walker Street and Alfred Street. All rail-borne produce will be delivered here in the centre of North Sydney, 150 feet above the present terminus.

Shops will be provided under the goods siding, which will be on viaduct, and it will be possible to unload direct from the trucks to the shops below. From Walker Street to the Bridge, the railway will be on viaduct and under the viaduct will be shops. There will be an arch bridge across
Alfred Street and one higher up across Arthur Street.

In the view showing North Sydney Railway Station and surroundings, the Railway Station proper is surmounted by a three storey building with a central portion carried two storeys high and finished with a dome. These buildings over the station will be used for residential business purposes, there being no noise, smoke or vibration owing to the electrical working of the Railway.

The outlook from these buildings would be unsurpassed and being at the Station, would provide the maximum of convenience.

The entrances to the buildings would be in Blue Street and Miller Street and the main entrance to the Station in Blue Street.

The upper portion of the central part of building under the dome, some 80 feet square, would make an excellent ballroom with side balconies all around and arced walls with domed ceiling under the outside dome.

Large open spaces are provided giving light and air to the residential and business portion and to the platforms below which would have glazed roofs.

The route mileage of this connection from Wynyard Square Station to Bay Road Station is 2 miles 50 chains, the track mileage being 10 miles 50 chains.

Eastern Suburbs Connection:

As before stated, the Eastern Suburbs Railways, consisting of one up and one down track, junctions with the City Railway at St. James' Station, crossing by flyover the down city track just south of Park Street.

At the Oxford Street corner of Hyde Park is situated Oxford Street Station at a minimum depth below the surface to permit of constructing a concourse floor above the platforms. This station, as well as others on this line, is arranged with one island platform serving both tracks.

From Oxford Street Station the line follows Oxford Street at a minimum depth below the surface, rising on a 1 in 40 grade to Victoria Barracks, Darlinghurst station being located under
Taylor Square, rail level at this point being 35 feet below the surface.

From Victoria Barracks, the tracks are in tunnel under private property to Glenmore Station which is an open-air station at the top of Realey Street, midway between the Oxford Street and Bellevue Hill tramways. The line from Glenmore Station to Paddington Station runs parallel to Caledonia Lane in shallow open-cut, this being also an open station and located at Jersey Road.

From here on, through Edgecliffe Station which is situated at Wallis Street near Edgecliffe Road, to Grosvenor Street, the line is chiefly in open-cut and on high embankment, Bondi Junction Station being in open-cut with rail level about 25 feet below the surface.

From Bondi Junction Station the tracks are generally in open-cut about 20 feet deep through Little Coogee Station at Frenchman's Road, Coogee Station at Avoca Street and Belmore Road, and Faccyville Station at Bunnerong Road.

From Anzac Parade the tracks proceed generally on embankment in a westerly and N.Westerly direction to join the existing Railway by flyover connection north of Redfern Station. Stations on this loop will be provided near Roseberry Racecourse, at Botany Road, Waterloo and at Henderson Road, Alexandria.

Western Suburbs Connection:

The Western Suburbs Connection joins the City Loop by flyover junction north of Wynyard Square Station and continues in two single track tunnels on a grade of 1 in 40, passing under Darling Harbour with 45 feet clearance between the tunnel roof and mean high water level, through two open-air stations in the eastern part of Balmain to a deep level station at Darling Street near the Balmain Town Hall. Turning to the south after leaving Balmain station, the line continues in open-cut to Weston Road, stations being provided at Beattie Street and Weston Road and provision being made for a flyover connection to Drummoyne.

Continuing to the south on embankment through stations at Carrington Street, Rozelle, and
Belmain Road, Leichhardt, and in open-cut and tunnel through a station at Parramatta Road and Norton Street, Annandale, junction is effected with the main suburban line by flyover connection between Petersham and Stanmore.

**Train Capacity of Scheme:**

Based on a 20-second station stop, an acceleration of 1½ miles per hour per second and a deceleration of 1½ miles per hour per second, and a maximum speed of 35 miles per hour the capacity of a single line of railway with automatic signals and train stops works out at 36 trains per hour. By installing a scheme of signalling involving speed control in a modified form such that obedience to caution signals is enforced as well as obedience to stop signals, the train capacity of a single line is increased to 42 trains per hour.

For the immediate equipment of the City Railway the installation of speed control is not contemplated so that the train capacity of a single track may be considered as 36 trains per hour. The conditions obtaining with this headway are shown on Plans 20, 21, 22, and 23, in which time-distance, speed-distance curves are shown for the city loop and the North Shore connection. It will be seen that near Wynyard Square Station and between Liverpool Street and St. James' Stations, the distance between the head of one train and the tail of the preceding train is about 1,700 feet. This distance is less than that required for free running conditions under a continuous overlap system with a maximum speed of 35 m.p.h. At any speed 4½ times the safe braking distance at that speed is required between trains for free running, or 2,000 feet for 35 m.p.h., so that at these two points some modified form of automatic speed control would be required to enable these stations to work to capacity.

With the continuous overlap system of signalling, including automatic train stops, the capacity of Central Station on the suburban side will amount to 216 through trains per hour.

The capacity of the tracks traversing the western side of the City and feeding the North
Shore Bridge will equal 144 trains per hour, while the capacity of the tracks traversing the eastern side of the City will equal 72 trains per hour. Liverpool Street Station will have this capacity while at St. James' Station, the capacity when acting as a terminal station for Eastern Suburbs traffic will be 132 trains per hour.

Wynyard Square Station, however, being the junction for the North Sydney connection, will have a capacity of 216 trains per hour.

With a two-track connection to Eastern Suburbs and a similar connection to Western Suburbs, the capacity of the city railway will be 324 trains per hour, made up as follows:

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**Time of Journey:**

It will be seen from the time-distance curves for the city loop that the time of journey from Central Station around the loop and back to Central Station, assuming 20-second station stops at stations other than Wynyard Square and 30 seconds at Wynyard Square is 11 minutes 38 seconds, the distance being 3 miles 63 chains. The average running time between stations is 1 minute 35 seconds and the average running speed 23 m.p.h. The longest time between stations is 2 minutes 10 seconds between St. James' and Circular Quay and the shortest run is 1 minute 5 seconds between St. James' and Liverpool Street.

On the North Sydney connection the time of journey between Bay Road and Wynyard Square Station - assuming a 20-second station stop at North Sydney and Kirribilli - averages 7 minutes 21 seconds, the total distance being approximately 2 miles 50 chains. The distance from Wynyard Square Station across the Sydney Harbour Bridge to Kirribilli Station is just over 1½ miles, the time taken between the two being 4 minutes 13 seconds on the up journey and 3 minutes 32 seconds on the down
journey. The running speed over the connection to Bay Road will average 23.4 miles per hour.

**CITY AND SUBURBAN ELECTRIFICATION:**

The extent of the Railway Electrification proposed in the Greater Sydney Area (Plan No. 24) Sydney to Waterfall, National Park, Bankstown, Penrith and Campbelltown, Richmond and to the Hawkesbury River, is shown in blue; the Railways approved for immediate construction - the City Railway, the Eastern and Western Suburbs Railways, and the Sydney Harbour Bridge, are shown in red; whilst the Railways outlined for future construction — North Sydney to Mosman and Athol, North Sydney to Manly via Northbridge and thence to Narrabeen and Barrenjoey, Gordon to Narrabeen, St. Leonards to Eastwood, Bondi Junction to Watson's Bay, Randwick to La Perouse, Sutherland to Cronulla, Bankstown to East Hills and Tempe to Salt Pan Creek, are shown in yellow.

The Harbour, which dominates the layout of the Railways, extends inland about 12 miles, with a foreshore line of 188 miles, and does not average a mile in width throughout its length. The complete transit scheme which necessitates a Bridge across the Harbour from Dawes' Point to Milson's Point, a bridge to Peacock Point, Balmain, will form four inter-connection loops, viz., the City loop and three suburban loops to serve the Eastern, Western and Northern Suburbs, with spur lines connected thereto to the outlying suburbs.

Passengers from all tramway suburbs will have their time of journey shortened by more than half, and will travel cheaper and with more comfort by electric railway than by tram.

**Traffic and Power Requirements:**

The electrification of the inner zone suburban railways will eventually embrace, besides the City Railway, the Main Suburban line to Parramatta, the Illawarra Line to Waterfall, the Bankstown Line, the Strathfield—Hornsby Line to Hornsby, and the Milson's Point line to Hornsby, a total, including sidings, crossings, &c. of about 200 track miles.

Excluding the Milson's Point Line, it is anticipated that 144 trains, carrying 100,000
passengers will eventually have to be handled during the maximum hour and, assuming a power requirement of 600 k.w. per train, will require a power supply of over 36,000 k.w.

That portion of the City and Suburban Railway Electrification to be immediately completed and open for operation in 1925, extends from St. James' Station on the City Railway to Waterfall on the Illawarra Line, overhead structures being provided and sub-station capacity being made sufficient to provide for the electrification of the Bankstown line.

The traffic to be handled over this portion of the system will, during the maximum hour, total 35 trains between St. James' Station and Erskineville, 25 of which will go beyond Erskineville 15 to Bankstown, 10 to Hurstville and 4 beyond Hurstville, and the passengers carried into the city during the maximum hour will approximate 25,000.

The total power requirements for this section will be about 20,000 k.w. during the maximum hour, the load factor being of the order of .4.

System:

The system to be adopted is direct current 1,500 volts, supplied to the trains by overhead contact wire and collected by pantograph.

Power will be generated at the White Bay and Ultimo Power Houses, portion being at 6,600 volts 25 cycles and portion at 11,000 volts 50 cycles and will be transmitted to substations situated at Prince Alfred Park and Meek's Road, Marrickville, by lead covered, jute served cable, laid in bitumen in troughing. From Meek's Road, transmission will be by overhead 33,000 volts line to outlying substations. At substations the power will be converted to 1,500 volts D.C. for feeding to overhead contact wire.

Power House and Sub-Stations:

As stated above, the power required in 1925 is about 20,000 k.w., while for the complete electrification of the inner suburban zone it amounts to about 36,000 k.w. Turbo-Generator units
of size suitable for the development of the whole of the power required for the inner zone are being installed at White Bay Power House.

The initial plant comprises two turbo-alternator units of 29,000 k.v.a. each (about 22,500 k.w.), 50 cycles 11,000 volts, and two turbo-alternator units of 18,750 k.w. each, 25 cycles 6,600 volts. One of these latter is now being built in Sydney, the other being on order. The 25 cycle units will be also used for tramway supplies.

The necessary switch and control gear for these units is, of course, included, while 8 new boilers with an evaporation of 60,000 lb. per hour at 215 lb. sq. in. and 200° F. superheat, and 6 with a normal evaporation of 80,000 lb. per hour and a max. evaporation of 100,000 lb. per hour at 275 lb. sq. in. and 225° F. superheat, are to be installed.

Power generated at 25 cycles 6,600 volts will be transmitted from Ultimo to the Prince Alfred Park Sub-station; 8 feeders of .2 sq. inches cross section, lead covered, jute served, laid in trenching and surrounded by bitumen, being used. It will here be converted and supplied to the Sydney section of the City Railway at 1,500 volts D.C.

Power generated at 50 cycles 11,000 volts will be transmitted to Hock's Road Sub-station, Harrickville, by six underground feeders of .2 square inches, cross section. At this sub-station portion of the power will be converted to 1,500 volts D.C., while the remainder will be stepped up to 33,000 volts A.C. and transmitted to Hurstville, Sutherland and Waterfall Sub-stations by overhead transmission line.

Sub-station capacities and equipment are as follows:

At Prince Alfred Park Sub-station, the immediate load anticipated is 7,000 k.w.; this will be supplied by 2 convertor units of 4,500 k.w. output each, converting from 6,600 volts 25 cycles to 1,500 volts D.C., with a third unit as spare. Provision is made for the addition of another unit of the same size later.
Meek's Road Sub-station, Marrickville, is supplied directly from White Bay Power House at 11,000 volts 50 cycles, conversion to 1,500 D.C. being effected by 3 converter units of 3,000 k.w. output each, the anticipated load on the sub-station in 1925 being 7,000, increasing to an ultimate load of 12,000 k.w. At this sub-station, step-up transformers will be used to raise the voltage to 33,000 volts for transmission to sub-stations beyond, the power to be transmitted being up to 10,000 k.w. Ultimately a fourth converter unit of 3,000 k.w. output will be installed.

Hurstville sub-station will receive power at 33,000 volts 50 cycles from Meek's Road. One converter unit of 2,000 k.w. output and two of 1,500 k.w. output will comprise the immediate installation, the 1,500 k.w. machines being ultimately replaceable by machines of 3,000 k.w. output. This sub-station will be loaded to the extent of 4,000 k.w. in 1925, the ultimate load on it being 5,000 k.w. At this, and further sub-stations, transformers will be installed to cut down the voltage from 33,000 volts, for supply to the motor converters.

At Sutherland Sub-station, with a normal load of 1,000 k.w., provision will have to be made for a very heavy holiday traffic, which will increase the loading to somewhere near 4,000 k.w. It is proposed to install two 1,500 k.w. motor converters here, power being received as at Hurstville at 33,000 volts 50 cycles.

Waterfall Sub-station completes the present programme, one 1,600 k.w. converter being required. The immediate load on this sub-station will be in the region of 600 k.w.

Secondary Distribution:

For the City Railway the main centre of distribution is the Prince Alfred Park Sub-station, the electrified portions of the suburban lines being supplied from sub-stations as already detailed.

Traction current at 1,500 volts D.C. is transmitted to the overhead catenary system which is continuous and anchored in sections of half a mile.

For the underground portion of the City Railway a catenary of stranded copper of .25 sq. inch.
section supports a copper contact wire of similar section, the whole acting as a feeder system. On this portion of the work the catenary is supported at 30 feet interval on double insulators and the copper contact wire is attached by means of flexible hangers.

For the open air section, extending south from Campbell Street and out to the suburban areas, a steel catenary consisting of 7 strands of No. 8 double Galvanised wire (Copper Equivalent .01 sq. inches.) supports a contact wire of "Phono-Electric" alloy having a sectional area of .209 square inches (Copper Equivalent .1 square inches.) the whole being paralleled by a copper feeder of .39 sq inches, section tapped into the contact wire at every quarter mile. This section of the catenary system is carried on structures of half a mile. Between Central Station and Campbell Street, however, structures will be designed to act as signal bridges as well as supports for the catenary system.

At anchor structures, both catenary and contact wires will be anchored, the catenary with an initial tension of 2,000 lb. and the contact wire with a minimum tension of 1,000 lbs.

To provide for traffic movements under special conditions, particularly of an emergency nature, the line will be sectionalised and sectioning switches installed at convenient points.

**Lighting:**

Lighting for the City Railway is provided by duplicate ring main systems at 2,200 volts 50 cycles, one main for Down and one for Up tracks. These cables (.06 sq. in concentric) are taken underground at Prince Alfred Park Sub-station and pass into a duct system, consisting of 3" pipes set in concrete along the 6 track portion of the City Railway as far as Campbell Street, and an open concrete rack along the side wall of the tunnels.

At the various stations the lighting mains are looped out to transformers which reduce the voltage to 240 volts, whence it is reticulated for lighting purposes at 120 volts A.C.

At Central Station these transformers are of 100 k.w. capacity each, while at St. James' and Liverpool Street they are of 50 k.w. capacity each. At the latter two stations provision is made
for automatic emergency lighting by a 5 k.w. installation of storage batteries, together with mercury vapour rectifiers.

Tunnel lighting will be purely for emergency purposes, lights being spaced about 20 feet apart and switches so arranged that lights can be switched on at one end of a section and switched off at the other end.

**Power for Signalling:**

Power for signalling is provided by a high tension signal main (2,200 volts 50 cycles) of .04 square inch concentric cable for each track, carried in concrete racks against the tunnel wall and looped out at each signal location to suitable oil switches and transformers of 1 to 2 K.V.A. capacity, supplying current at 120 volts or less for the low tension signalling equipment. This together with a stand by transformer is contained in a special refuge near each signal location.

The ring main system ensures a supply from either end in the event of one location being out of service. For other electric services, such as lifts, escalators, fans, etc., current will be supplied from 600 volt D.C. services which are available in the city area.

**Rolling Stock:**

To handle traffic on that portion of the lines to be electrified immediately, 262 cars will be required, half of these being motor cars and half trailers. It is proposed to couple 70 to 80% of these permanently in 8 car units, the remainder being coupled in 4 car units and perhaps also units of 2 and 6 cars. The weights of motor cars and trailers, unloaded, are respectively 105,000 lb. and 72,000 lb. and their seating capacity 79 for the motor car and 83 for the trailer if driver's compartment is omitted. If a driver's compartment is included in the trailer, the seating capacity is reduced to that of the motor car. Total capacity of these cars, including standing passengers will be 120.

Motor cars will be equipped with four motors wound for 750 volts each or two motors wound
for 1,500 volts, and giving, on level tangent, an acceleration of 1.5 m.p.h. per second.

Collection will be from overhead contact wire by pantograph located at the opposite end of the car to the driver's compartment, the hornless type of pantograph being under consideration. Control equipment will probably be electro-pneumatic.

**DETAILS OF DESIGN.**

**Track Layout:**

In laying out tracks for the city railway a minimum radius of 500 feet was adhered to, and all curves under 20 chains radius were transitioned with a curve of the form of a cubic parabola having a length of equal to \( \frac{85000 \times \theta}{C} \), where \( \theta \) equals the difference in curvature, i.e., the difference between the reciprocals of the radii where the difference of curvature did not exceed .00076 curves were directly compounded.

Ruling grades were limited to 1 in 30 with the traffic and 1 in 40 against it and in all cases compensation has been allowed for curves on grades, a curve being considered equivalent to a grade of 1 in 0.5 \( R \), where \( R \) is the radius in feet. Gradients are connected by vertical easement curves of parabolic form of such length that the rate of change of grade is not greater than 1 per cent per chain for convex cases.

Multiple tracks are spaced a minimum distance of 12 feet between centres, which distance is increased by twice the throwout due to curvature, plus one sixth the difference between the super-elevation on the two tracks, or

\[
D = 12.0 + \frac{660 + \theta}{R / 6}
\]

Rails and fastenings are Australian Standard 100 lb. rail, and check rails are to be fitted to the inner rails of all curves 14 chains or less radius.

Switch rails are to be 20 feet long with the outer rail of turnout curve tangential to the switch rail.
Station details:

The layout of stations in so far as the arrangement of tracks and platforms is concerned has been described earlier. In the design of these stations provision has been made for the maximum traffic that is likely ever to be realised. Passage-ways, stairs, barriers and conveniences have to this end been made ample for dealing with the following maximum hourly traffic in either direction:

<table>
<thead>
<tr>
<th>Station</th>
<th>Traffic (per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wynyard Square</td>
<td>48,000</td>
</tr>
<tr>
<td>Town Hall</td>
<td>21,000</td>
</tr>
<tr>
<td>Central</td>
<td>21,000</td>
</tr>
<tr>
<td>Liverpool Street</td>
<td>15,000</td>
</tr>
<tr>
<td>St. James'</td>
<td>9,000</td>
</tr>
<tr>
<td>Circular Quay</td>
<td>6,000</td>
</tr>
</tbody>
</table>

These figures are based on a total daily passenger traffic of 750,000 passengers exclusive of North Sydney, whose ultimate daily traffic is estimated at 300,000 passengers.

The ultimate maximum hour traffic on the City Railway in one direction is estimated at 120,000, made up of 40% Wynyard Square, 17.5% each at Central and Town Hall, 12.5% at Liverpool Street, 7.5% at St. James' and 5% at Circular Quay.

Platforms have been made with a clear length of 520 feet; and a width at the centre of at least 28 feet for island platforms and 12½ feet for side platforms. Passage-ways and stairs have been so arranged that incoming traffic is kept distinct from outgoing traffic, the same order of direction being maintained on all the stations. Ticket offices have sufficient window accommodation to accommodate maximum traffic and are so placed as to be passed by all incoming passengers. Lavatories and cloak rooms are so situated as to be convenient to both incoming and outgoing passengers while at the same time being well out of the way of all traffic movement.

Access to all stations will be by stairs and easily graded subways from the points of great convenience on the adjacent streets. Entrance stairs in parks and on footpaths are in all cases uncovered, the unsightliness of a surface structure weighing against the question of exposure to weather.
On platform walls, subway and concourse walls, a glazed tile surface for a height of 6 feet
6 inches ensures cleanliness, while at the same time permits of a decoration scheme in which each
station is given distinct color, the body work being of a light cream color throughout.

Station lighting is so arranged that a failure of three separate sources of supply is
necessary to effect a failure in the lighting; two of these sources are represented by two high
tension ring mains traversing the system and feeding the lighting reticulation through two independent
transformers; the third consists in a storage battery of sufficient capacity to give partial lighting
in case of failure of both ring mains or transformers.

Provision is made for hosing down all subways and platforms and drinking fountains are pro-
vided in suitable locations on the platforms. Telephone facilities are provided throughout for the
general public as well as the railway staff.

Cross Section of Tunnel:

In deciding on the section to be adopted for single track tunnel, the throwout and overhang
of the largest carriage in the Service had to be considered.

This car is 72 feet 8 inches long; the whole symmetrically pivoted on two points on the
track centre line 51 feet 4 inches apart.

The throwout with this car amounts to \( \frac{330}{R} \), where \( R \) is the radius in feet, and the overhang
equals approximately twice the superelevation.

The standard structure and load diagrams are shown in Plan 25 in which 6 feet 9 inches is
shown as the side clearance on tangent. On curves of minimum radius, this clearance is increased to
7'6" and as much of the City Railway is on sharp curves, construction was greatly simplified by ad-
opting a tunnel section 15 feet wide throughout.

Provision for overhead wiring necessitated a height above rail of 17 feet 3 inches and a
section having parallel sides 15 feet wide for 9 feet 9 inches above rail, and a semi-circular top of
7 feet 6 inches radius, was adopted.

By displacing the tunnel centre line towards the centre of curvature by an amount equal to four thirds of the superelevation, it is possible to use this tunnel section, without widening, on all portions of the track.

The road bed on the underground portion of the City Railway will be composed of concrete (as shown in figure 26), sleepers being embedded in it for one third of their length from each end, the concrete sloping towards a central track drain. Provision will be made at the sides of the road bed for carrying conduit or troughing for lighting and signalling services. The average depth of concrete over the road bed will be approximately 4 inches.

Viaduct Construction:

The viaduct construction from Central Station to Campbell Street consists of solid fill between gravity section retaining walls. These walls are designed to take the thrust from the backing plus a vertical surcharge of 5 feet, which is equivalent to train load. Along Elizabeth Street the wall is carried upon concrete foundations consisting of piers 7 feet square spaced 25 feet 3½ inches centre to centre and connected by concrete arches whose intrados is 4 feet 6 inches below surface level.

Bridges across Campbell Street and Hay Street are elliptical arches of reinforced concrete having spans of 50 feet and 81 feet 8 inches, and the crown thicknesses of 15 inches and 24 inches respectively. The ratio of rise to span is approximately 1 to 5. The bridge over Eddy Avenue, consisting of three roadway spans and two footpath spans, while shaped to conform to the elliptical arches at Hay and Campbell Streets, is designed as a series of reinforced concrete girder ribs carrying a reinforced concrete slab. The upper surface of concrete slabs and arches is waterproofed with three quarters of an inch of Trinidad Asphalt, protected with 3 inches of concrete. This will effectively prevent any seepage through the concrete, and the consequent inconvenience and disfigurement.
THE CITY RAILWAY
Concrete Road Bed on Rock
Formation in Tunnel
Scale 1" = 1 foot
C.1
The retaining walls throughout are faced with 3 inch rock-faced sandstone masonry bonded into the concrete, while the arches are faced with dressed sandstone, and carry an ornamental sandstone parapet.

Concrete:

As concrete will play a very large part in the construction of the City Railway both in the form of mass concrete and reinforced concrete, a series of tests were carried out prior to the commencement of concreting to verify results obtained in America with regard to water, rodding, etc., using local materials and carried out on a larger scale than possible in a laboratory. Blocks made from one bag batches of sandstone and bluemetal concrete in the proportions of 1:2:4½; 1:3:6; 1:4:8 were made in duplicate pairs, and for both wet and dry mixes, one block of each pair being tamped in the ordinary manner and the other rodded with a pointed rod of small diameter.

Eight-inch cubes were then cut out from the large blocks, four cubes from each block, and after dressing and facing were broken when four months old with the following results:

"With dry batches 'tamping' brought mortar to the surface and had a considerable compacting effect, while 'rodding' appeared useless owing to the concrete being too stiff to flow back into the hole made by the rod.

With wet batches 'tamping' was practically impossible and at most could only be done very lightly and with no compacting effect. 'Roddng', however, seemed to have a pronounced compacting effect and brought clear water and air bubbles to the surface. This was particularly noticeable in the case of poor concrete.

For Bluemetal Concrete made in the proportions 1:2:4½ with 1½" metal for the large aggregate the strength at 4 months obtained for a mix containing about 8 per cent of water and 'tamped' was 3,000 lb. per sq. inch, while the same mix 'rodded' gave 3,280 lbs. per sq. inch, an increase of about 10 per cent.
Mixed in the same proportions but using 10 per cent of water the strength when 'tamped' was only 2,140 lbs. per square inch, and when 'rodded' 2,350 lbs. per square inch, the specimens of 'rodded' concrete again showing an increase in strength of about 10 per cent; the specimens of wet concrete, however, showed only about two thirds of the strength attained in the dry concrete.

"The tests of 1:3:6 Bluestone concrete made with 24" metal, at the same age, 4 months, showed a compressive strength of 2,650 lbs. per sq. inch dry and 2,400 lb. sq. inch wet, and no improvement was apparent in the case of the 'rodded' concrete."

"In the case of 1:4:8 concrete the number of blocks tested was too few to establish any decided difference between specimens of 'rodded' and 'tamped' concrete, nor was the difference between the strength of dry and wet concrete very marked, a strength of about 2,100 lb. per sq. inch at 4 months for the dry and 1,950 for the wet being obtained.

Generally speaking, the effect of the 'rodding' was to increase the compressive strength of the concrete, the maximum increase obtained being nearly 20 per cent. 'Rodding' gave better comparative results with wet mixtures than with dry mixtures, but did not compensate for the detrimental effect due to excess water. In no case did the 'rodding' of wet concrete increase its strength sufficiently to make it as strong as the same concrete mixed with less water. 'Rodding' for a longer period than in the above mentioned tests would, no doubt, further increase the strength, but is hardly practicable on most work, and any reduction in the quantity of cement used, that had to be offset by a long period of 'rodding', would not prove economical. On very wet work, however, such as is sometimes necessary on reinforced work, 'rodding' should be carried out to the fullest extent possible in order to compensate for the decrease in strength due to excess water, and give a concrete of normal strength. A combination of 'rodding' and 'tamping' would likely prove most satisfactory."
Coke Concrete:

In view of the necessity for using concrete made with a coke aggregate in situations where weight was of importance as for the floor of the Sydney Harbour Bridge, tests were also carried out to establish the most satisfactory mixture from the point of view of strength as well as weight.

Hard burned smelting or metallurgical coke was used, the large aggregate being crushed to pass a 1½ inch ring, coke dust passing a ½ inch ring and Nepean sand being used in different tests as fine aggregate. A wide range of varying proportions were mixed both of coke aggregate entirely, and of coke and Nepean sand.

Of these a concrete of the proportion 1:2:4 using coke and Nepean sand gave the greatest strength, averaging 2,400 lb. per square inch at 3 months for a unit weight of 100 lb. per cubic foot.

Using all coke aggregate the weights were much lower, varying from 82 to 89 lbs. per cubic foot, with strengths at 3 months varying from 1,250 lb. per square inch to 2,200 lb. per square inch. Coke concrete of the proportions 1 cement, 3 coke dust, 4 large coke aggregate (1½") gave an average strength at 3 months of 2,000 lb. for a unit weight of 84 lb. per cubic foot.

All the mixes of coke with coke dust and no sand gave a concrete that was not very smooth working compared with that resulting from the use of Nepean sand as fine aggregate.

The Specification provides for the coke concrete as follows:

16 C.Ft. of Metallurgical Coke broken to pass through a ring 1½ inches diameter, but caught on a sieve of ½ inch mesh;

10 C.Ft. of coke grit, more or less, screened through a sieve of ½ inch mesh, but caught on a sieve of 900 meshes per square inch and not less than 375 (4 c.ft.) of cement. Weight 84 lbs. per cu. foot.

Construction Equipment:

The constructional work in general has been described in a previous chapter; the mechanical equipment at present installed is as follows:
Air Supply:

The supply of compressed air for excavating and other air tools throughout the Works is provided by Compressor plants at St. James', Liverpool Street, Goulburn Street and Ultimo. The compressor house at St. James' comprises three 14 x 12 "Ingersoll-Rand" Compressors, driven at 175 R.P.M. by 60 H.P. motors through "Lenix" drives. At this speed, each Compressor delivers 370 cu. ft. of free air per minute at a pressure varying from 90 to 100 lb. per square inch. Receivers 3 feet 6 inches diameter are provided for each Compressor, and cooling water is circulated to a cooling tower by a "Worthington Duplex" Pump.

At Liverpool Street, two 12 x 12 Compressors of similar pattern and one 14 x 12 "Sullivan" Compressor, driven by 60 H.P. motors through "Lenix" drives, are installed. These deliver 270 cu. ft. of free air per minute at 175 R.P.M. and 90 to 100 lb. pressure, the installation generally being similar to that at St. James'.

At Goulburn Street a 14 x 12 "Ingersoll-Rand" Compressor delivers 420 cu. ft. of free air per minute to the portion of the work south of Goulburn Street. This Compressor, which is run at a higher speed than those previously mentioned, is driven by an 80 H.P. motor.

At Ultimo, two 14 x 12 Compressors of the same make supply air for driving the tunnels for a new circulating water supply to Ultimo Power House, rendered necessary by the reclamation of a portion of Darling Harbour.

The "Lenix" Short Drives used with these Compressors give a considerably greater arc of contact between belt and pulleys than can be obtained with open drives, and consequently, give higher efficiency. The short pulley centres assure economy in housing space, and lighter and shorter belts can be used at an automatically maintained tension which practically eliminates slip. Plate-No. 27 illustrates the interior of the Liverpool St. Station Compressor House, equipped with three Compressors with short drives.
Compressor House - Liverpool Street
One portable Compressor, which before the installation of a compressor plant at Goulburn Street, supplied air for Sections 2 and 3, is now used wherever required at points remote from the permanent supply.

Through Sections 4, 5, and 6, air-mains 3 inch and 4 inch diameter, run from end to end of the job, and are connected throughout to ½ inch and 1 inch pipes which supply the various machines through flexible hosing.

Ventilation for the tunnels during construction is supplied at the North end of St. James' Station by a 12 inch "Rooth" Blower, motor driven, and a similar unit supplies air at Park Street to the tunnel on the Up City East track. A 9 inch "Buffalo" Fan, motor driven at 1,000 R.P.M., supplied air during construction to the Down City East Tunnel near Park Street, but has since been removed, and with an American Blower Co's Fan of similar size, is now supplying air to the headings in the twin-tunnel construction south of Liverpool Street Station. At each of the four shafts for the circulating water tunnels at Ultimo, 9 inch "Buffalo" Fans supply air to the working face.

Air Tools:

The air tools in use consist largely of "Ingersoll-Rand" water type jack-hammers, and include a type CC25 pavement breaker, which is used for heavy digging where blasting is not permitted. A lighter air pick, or scabbing tool, is also used on cleaning up work.

The air pressure to these tools varies from 90 lb. per square inch, the latter figure representing the lowest pressure at which these tools work satisfactorily. "Little David" air drills are used throughout the work for field drilling and a "Sullivan" Turbinair Hoist is used for hoisting skips from the headings in the twin tunnels south of Liverpool Street Station. This hoist, which is exceedingly compact, can hoist 2,000 lb. at 110 feet per minute, and develops about 6½ HP.

In addition to this equipment, the Smith's shop contains a 2 cwt. air driven "Pilkington" Hammer, and a "Leyner" air-driven drill-sharpening machine.
In the western heading on Section 3, compressed air is used to drive a steam winch which hoists the skips from the heading.

Excavating Equipment:

On the excavation of Liverpool Street Station a 1/4 yard "Ruston Proctor" Steam navvy, and a "Bucyrus" Navvy of similar size were used, while the excavation for St. James' Station and the portion of Section 5 north of Park Street were excavated by a Class 14 "Bucyrus" Drag-line Excavator, having a 1 1/2 yard bucket and a 70 foot boom. This excavator has shifted as much as 1,370 tons of material in one day and has averaged 1,260 tons per day for one month, digging on the average at a depth of 22 feet.

A "Ruston Hornsby" No. 6 Steam Shovel of 1/2 yard capacity, equipped with a slewing engine as well as raking and hauling engines, has recently been added to the excavating equipment. For handling material from shafts, kibbles of 25 cubic feet capacity, and spoil boxes of 2 cubic yards capacity, are largely used, while side and end tipping trucks of 1/4 yard and 1/2 yard capacity are used for handling spoil in the tunnels.

For drilling holes from the surface to the tunnel roof for pouring concrete, a "Southern Cross" well-boring plant is being used. This is a petrol driven unit and drills to 6 inches diameter. In softer material a tripod type hand operated drill is used for the same purpose.

Hoisting machinery:

For general lifting work throughout the job, four 5-ton, and nine 3-ton electric traveling cranes are giving good service, while in addition there is one 2-ton stiff leg electric crane, one 7-ton stiff leg steam crane, one 5-ton "Harmon" Steam crane, two 3-ton "Grafton" travelling steam cranes, and two stiff leg hand cranes of two ton and five ton capacity. The power shafts at Ultimo, on the circulating water tunnels, are equipped with poppet-heads and cages, operated by 30-cwt dog-clutch hoists operating at 150 feet per minute, and connected to converted tramway motors developing about 20 HP.
Concrete mixing to date has been performed by one 16 c.f.t. steam driven "Foote" mixer, and three 10 c.f.t. electrically driven "Armstrong-Holland" Mixers. Three 10 c.f.t. electrically driven "Foote" Mixers have been purchased and will shortly be added to this equipment.

Concrete is handled both in barrows and by chutes. Barrows are of the usual types and of 5 cubic feet capacity. Several types of chute have been employed, both locally made and imported, that giving the most satisfactory results being the imported "Insley" Chute. This chute is of deep parabolic section, about 12 inches wide, by 13 inches deep, and is obtained in lengths of 10, 20 and 30 feet, provided with suitable hoppers, swivel heads and plates.

Transport:

For handling spoil the following fleet of motor lorries is maintained:

| 12 4-ton "Thornycroft" Lorries  |
| 1 5-ton "Lorry  |
| 3 4-ton "Sentinel" Steam Lorries |
| 1 5-ton "A.E.C." Lorry. |

All these lorries are equipped with end-dumping steel bodies. In addition, a one-ton "Ford" truck is used for light run-about work. Plate 23 shows the Fleet of Lorries.

A Garage is well equipped with tools for light repair work, including a double emery wheel, and a sensitive drill, all motor driven through line shafting.

Workshops:

Workshops have been established in Hyde Park near Liverpool Street to handle general repair work, concrete form construction, and such mechanical work as is necessary on a work of this magnitude. These shops consist of a Wood-working Shop, Smith's Shop, Toolsmith's Shop and fitting-shop.

The wood-working shop is equipped with a 36 inch bandsaw, 24 inch and 42 inch circular saws 20 inch docking saw, 20 inch thicknessing machine, and 12 inch buzz-planer. In addition are a bandsaw sharpening machine and a bandsaw setting machine. All these machines are separately driven by
Fleet of Motor Lorries
electric motors off the 600 volt supply.

The fitting shop is equipped with a "Vanguard" lathe 10 inch centres and 10 foot bed; a 3 foot 6 inch radial drill; pipe screwing machine for screwing up to 4 inch pipe; a power hacksaw; power grindstone; double emery wheels and a circular saw-sharpening machine. All these machines are motor driven through line shafting.

In addition to the general fitting equipment are an oxy-acetylene welding and cutting plant complete with acetylene generator, and a plant for cleaning and repairing jack-hammer drills. Fitters' benches are provided, and a small hand-forgé and a 2-ton hand traveller complete the equipment of this shop.

A two cwt. "Pilkington" Hammer, air driven, has been provided in the Smiths' Shop for handling the heavier work, while a "Leyner" Drill sharpening machine has been installed in the Toolsmiths' Shop.

A small Plumbers' Shop handles all the pipe and plumbing work for the job.

**Lighting:**

The lighting of workshops, offices and tunnels is effected by motor generator sets rated at 6 k.w. installed in the compressor houses at St. James', Liverpool Street and Ultimo. These operate on 600 volts, D.C., and supply current for lighting at 120 volts. A larger set, 15 k.w. rating, is now being installed at Ultimo.
NORTON GRIFFITH CONTRACT.

By an agreement dated the 24th April, 1915, the Government entrusted the work of construction to the Firm of Messrs. Norton Griffith & Co., who were to receive 5% on the cost of construction, exclusive of the expenditure on land, plant, &c., the railway material to be supplied by the Department.

Although actual construction was not commenced during the year 1915, the plans necessary to enable Messrs. Norton Griffith & Co. to arrange for the installation of plant were supplied. Borings to test the nature of the foundations and general nature of the country to be passed through were carried out, and also the very important work of inspecting the buildings which will be affected by Subway Construction along the proposed lines. Numerous investigations connected with the land resumptions for the City Railway, Eastern Suburbs Railway, and the western Suburbs Railway, were also completed during the year 1915 to enable the Contractors to push forward with constructional operations in the New Year. A general and subway specification governing the construction of the City and Suburban Electric Railways was also completed.

The Macquarie Street site was handed over to Messrs. Norton Griffith & Co., on June 18th, 1916, together with working drawings to enable excavation to be commenced on Section 7.

Up to the end of December, 1916, very little progress was made by Messrs. Norton Griffith & Co. with the cut and cover excavation on Section 7 and the foundations for Macquarie Street Bridge, whilst on Section 3 the only work carried out was a small amount of excavation for the retaining wall along Eddy Avenue and Elizabeth Street, and alterations to the "Oddfellows" Hall.
Work in connection with the City Electric Railway was continued by Messrs. Norton Griffith & Co., up to May 12th, 1917, when, the Agreement having been terminated by the Government, all operations by the Company were stopped and the work measured up.

The work on the Western and Southern sides of the City was of a preliminary character only, consisting of temporary fencing and the erection of plant.

On Section No. 7 the cut and cover excavation had in places been carried down to formation level, the cuts on the inner and outer loop extending from Macquarie Street to a distance of 18 chains through the Botanical Gardens. The top headings for the two tunnels under the drive to Government House were driven for a distance of about 4 chains, and the brick piers for Macquarie Street Bridge commenced.

In a report by Mr. Davis, then Director General of Public Works, concerning the Norton Griffith contract, he stated, in respect to the City Railway, that "seeing the magnitude of the work and that it had only practically just commenced, it was a matter of speculation as to what would have been the result, as far as costs were concerned, had the Norton Griffith Contracts been continued. The result could not have been otherwise than to saddle the State with an expenditure much in excess of the estimate."

On the 16th May, 1917, work was resumed on the City Railway under the direction of the Railway Commissioners.

Work on the open cut and cover excavation, and the tunnel headings in the Botanical Gardens, was taken up at points where work was suspended by Messrs. Norton
Griffith & Co. and re-organised for the purpose of securing more efficient and economical methods of working, and in the disposal of the surplus spoil.

During the year ended 30/6/1917 bores along the route of the City Railway, the Eastern Suburbs and the Western Suburbs Railway were completed.

Stoppage owing to war conditions. Work in connection with the City Electric Railway was continued up to 7th July, 1917, when the cut and cover and tunnel excavations in the Botanical Gardens were suspended.

Brickwork in cut and cover construction was continued until 4/3/1917, a very satisfactory rate of progress was made – over 1,000 bricks per man per day being maintained.

All work in connection with the Macquarie Street Bridge was completed on the 11th March, 1918, and the road thrown open for traffic on the 12th March, 1918.

By direction of the Government all construction on the City Railway was stopped on 30th June, 1918.

Resumption of Construction after War Period.

After being closed down from July, 1917 - owing to war conditions - a period of 4½ years, construction work was resumed on the City Railway on Monday, 20th February, 1922, when the excavations for the Liverpool Street Station, and shaft sinking for the concrete foundations of the Retaining Wall in Elizabeth Street were commenced. Photo No. 29 illustrates the clearing of the site of Liverpool Street Station in Hyde Park.

Photo No. 30 shows clearing of Belmore Park for Retaining Wall facing Elizabeth Street. In drawing up the scheme of re-organisation for re-commencing constructional operations under the Railway Commissioners, it was decided to proceed with
Sections 2 to 7 for the purpose of bringing these tracks into the City, and for opening up the line as far as St. James' Station, Queen's Square, which it was proposed to use as a terminal station until the completion of the loop.

At the end of June, 1923, practically 16 months after the resumption of constructional operations in 1922, the work on the several sections extending from Central Station to Queen's Square showed good progress.

Photo No. 51 shows Northern Concourse and Retaining Walls in progress at Central Station. At the Central Station the open cut excavations for the north concourse, together with the approach ramps on the eastern and western sides, were practically completed, and the excavation for the footings of the reinforced concrete columns and walls of the North Concourse pushed well forward. This work was somewhat delayed owing to an elevated water-tank which obstructed the operations. A new site was selected for a water supply tank at the intersection of Chalmers Street and Devonshire Street Subway. A 15" pipe line was laid to connect the existing service with the new tank, on the completion of which the obstructing tank will be removed.

Good progress has been made with the various sewer connections and diversions necessitated by the construction of this new station.

The Eastern and Western Retaining Walls, extending from Central Station to Eddy Avenue, were pushed well forward, and the brick wall backed with concrete on the western side practically completed.

Overhead Bridge Construction. The progress in connection with the overhead bridge construction was somewhat delayed owing to the short supply of stone required for facing purposes - which is being obtained from the State Quarries at Maroubra. It was com-
sidered advisable not to erect any falsework in either Eddy Avenue, Hay Street or Campbell Street, until such time as sufficient facing stone has been delivered on the ground to enable the several arches to be turned rapidly and all obstruction to traffic removed as quickly as possible.

Pending the supply of facing arch stone the abutments of the several bridges were pushed forward. At the Eddy Avenue Bridge - work on which was commenced in May, 1922 - the south abutment, and the pier on the footpath alignment had been concreted to ground level. On the Northern side of the bridge the stone-faced abutment and the footpath pier had been completed up to the springing line of the arch. The facing stones for the arch of the northern footpath were being delivered and the preparatory work for the falsework required for the erection of the arch was also pushed forward. Photo No. 32 shows Northern Abutment and Footpath Pier of Eddy Avenue Bridge in progress.

Photo No. 33 shows masonry-faced Retaining Wall Eddy Avenue to Hay Street.

The masonry faced retaining wall extending from Eddy Avenue to Hay Street was, at the end of June, 1923, practically completed up to the moulded course to carry the parapet. The concrete backing of this wall was also completed.

Up to the end of this period 53,100 cubic feet of sandstone masonry had been set in this wall, and 9,500 cubic yards of concrete placed in the backing. The end of the year saw the South Abutment of the Hay Street Bridge practically completed and the North Abutment well advanced.

Extending from Hay to Campbell Street the foundations for the retaining walls supporting the overhead tracks were completed, and the stone faced wall facing Elizabeth Street was well advanced; a commencement had also been made with the masonry construction facing Elizabeth Street.
Photo No. 34 shows Retaining Walls and Street Bridges Eddy Avenue to Campbell Street. At the Campbell Street Bridge the South Abutment had been completed up to the springing level of the arch. Work on the Northern Abutment was delayed owing to the necessity for removing hotel premises on this site. Immediately these buildings were demolished work on the excavation for the North Abutment was commenced and the work is now being pushed forward.

Photo No. 35 shows excavation in progress in area between Campbell Street and Goulburn Street: S. T. Leigh's building and Oddfellow's Hall prior to demolition. From Campbell Street to Goulburn Street, facing Elizabeth Street, a line of buildings had to be demolished to make room for the Commissioners' Railway Offices to be erected on this block bounded by Campbell, Elizabeth, Goulburn and Castlereagh Streets. The buildings from Campbell Street north up to the Oddfellows' Hall having been cleared away, a commencement was made on the excavations and the preparatory foundation work for the erection of the steel columns to carry this building.

Cleveland Street Bridge. At this time the Metropolitan Board of Water Supply and Sewerage had practically completed the alterations to the water supply service necessitated by the proposed widening of the Cleveland Street Bridge. This work consisted of lowering 2 water pipes 36" and 42" diameter which form the main water supply for Sydney and the Eastern Suburbs. Immediately the water Supply Board completes this large diversion the construction of the three additional arches to carry the five new tracks on the eastern side of existing line will be proceeded with.

Construction between Goulburn Street and Liverpool Street Station. The construction necessary to carry the two tracks on the Eastern side of the City from Goulburn Street
Retaining Wall - Elizabeth Street & Eddy Avenue and Hay & Campbell St Bridges
Excavation between Campbell & Goulburn Streets
to Liverpool Street Station, will be partly flat-top steel and concrete construction, and partly by tunnel. The flat top construction will pass under buildings on the western side of Elizabeth Street.

Pending the demolition of the remaining buildings on the area between Campbell and Goulburn Streets no work was commenced on the flat top construction, which will involve a considerable amount of open cut work in Elizabeth Street. At the end of January, 1923, however, the twin tunnels to connect Liverpool Street Station with the flat top construction further south were commenced.

The method of constructing these twin tunnels to pass under and near to the walls of Mark Foy's Furniture Warehouse at the corner of Liverpool and Elizabeth Streets differed materially from the methods of tunnelling adopted on the other sections.

Three narrow headings were first driven to a point 20 ft. South of Mark Foy's building; these drives were made sufficiently wide only to enable the brick side walls of the tunnel arches to be constructed. On the completion of these three brick walls up to the springing line, top headings were driven in each of the tunnels. The floor of these drives, extending in each case to the full width of the arch, form convenient working areas for the construction of the tunnel arches, for which special steel centres have been designed. These centres consist of 80 lb. steel rails bent to curvature of the tunnel arch, connected together with necessary fishplates, bolts, and bearing plates on the three walls. "T" irons, bent to the same curvature as the rails, were suspended by bolts from the rails at a distance necessary for the concrete lining. Arrangements were made to follow up the miners driving the forward heading with the concrete gangs forming the roof of the tunnels. Photo 36 shows Twin Tunnel con-
Twin Tunnel Construction - South of Liverpool Street Station
struction from Liverpool Street toward Goulburn Street: method of constructing side walls and tunnel arch reinforced with steel rails.

The concrete for the arches is mixed in a concrete mixer placed on the upper ground level near the southern entrance to the Liverpool Street Station. The concrete is poured through chutes into receiving side-tipping trucks running on narrow gauge lines traversing the working areas previously referred to. The concrete is dumped from the trucks on to concrete boards in each tunnel and shovelled on to the lagging carried by the curved "T" iron. The lagging is bevelled on each side to make close joints to the specified curvature. The lagging is held firmly in position by wooden bulkheads and diaphragms, strutted on to the overhead rails.

Liverpool Street Station. The excavation for this station commenced in February 1922, was completed to its full depth at the end of June 1923, the quantity excavated being 93,500 cubic yards.

The "Sycerus" Dragline Excavator which proved very efficient and economical on other sections of the railway was not available for the excavation of this station which was carried out by navvies supplemented by two steam shovels for a portion of the period.

Photo No. 37 shows Liverpool Street Station at end of June 1923: placing concrete reinforcements for main arch. In addition to the excavation completed at the end of June 1923, a considerable amount of excavation for the arch skewbacks and subways had been carried out. The sidewalks and skewbacks for the central portion of the Station had also been completed and the false-work for supporting 120 feet of arch erected in place. Up to the end of the year three sections of the
Placing Concrete Reinforcements - Liverpool St. Station  June 1923
reinforced concrete arch, amounting to 85 lineal feet, were poured.

Liverpool Street to St. James’. Photo No. 38 shows open cut special construction
Liverpool Street Station towards St. James’. The tunnels through this area were
arranged in three sections viz:-- A double track tunnel carried from Liverpool
Street Station to meet the special construction excavated further North by open cut;
the Up and Down City East single tunnels driven north and south from shafts sunk to
formation level near Park Street. At the end of the year the double track tunnel
had been driven through to the open cut in Hyde Park, and the concrete lining
practically completed. From the Up City East tunnel 5,400 cubic yards had been
excavated and the concrete lining pushed forward simultaneously; 4/5ths of the ex-
cavated area being concreted.

From the Down City East tunnel 6,000 cubic yards of material have been
removed and about 1,220 yards of concrete lining placed in position. The con-
creting of these tunnels was carried out by a very efficient and economical method.
Six inch diameter holes were bored from the surface through to the crown of the
arch, the spacing of the holes being arranged to give one in a 17 foot length, which
is the amount of arch work placed at one pouring. The concrete was mixed by concrete-
mixers on the surface and discharged through these holes on to the false-work provided
in the tunnels for the side walls and arches. The concrete was carried out with no
interference whatsoever to the excavating work proceeding in the tunnels, both
operations being carried out simultaneously.

Photo No. 39 shows double track tunnel diverging into two single track
tunnels between Liverpool Street Station and Park Street. The excavation of the arch
Open Cut - Special Construction - North from Liverpool St Station
Double Track Tunnel diverging into two Single Track Tunnels - North from Liverpool St Station
between Liverpool Street Station and Park Street, where the two main tracks diverge from the double-line tunnel into two single track tunnels, was taken out by means of the "Bucyrus" Dragline Excavator, a total of 40,000 cubic yards being removed up to the end of the year, when the cut was within 10 feet of its required depth.

St. James' Station. Up to February 19th 1923, the "Bucyrus" Dragline Excavator had removed a total quantity of 103,000 cubic yards from this area when it finally cut out and was removed to another section. The remainder of the excavation, about 12,000 cubic yards, was removed by two steam navvies and a crane working in the bottom of the cutting. At the end of the year the forming of this cutting was practically completed and a commencement made with the concreting of the side walls of the station.

Photo 40 shows open cut excavation from St. James' Station down to formation level. A drive for sewer connections from the station, 320 feet long, had been completed and a connection made with the Main Bondi Sewer traversing Elizabeth Street.

From St. James' Station towards Macquarie Street. Photo 41 shows double and single track tunnels from St. James' Station towards Macquarie Street. At the beginning of April 1923, work was commenced on the three tunnels from the north end of St. James' Station towards Circular Quay. These tunnels consist of two single-track tunnels for the Up and Down City East routes, and a double-track tunnel for the Eastern Suburbs tracks.

Eastern Suburbs. Photo No. 42 shows excavation for Eastern Suburbs tracks between St. James' Station and Park Street: St. James' Station and tunnels towards Macquarie Street shown in background. The excavation for the Eastern Suburbs tracks between the Southern end of St. James' Station and Park Street had been pushed forward, and, at the end of the year carried down to formation level and made ready for concreting. The total quantity removed from this cutting was 55,000 cubic yards, a portion of which was done by the
Excavation - St James Station
Double & Single Track Tunnels - North from St James Station
Excavation for Eastern Suburbs Connection at St James Station
Dragline Excavator, and the remainder by steam navvies.

**Circulating Water Intake for Ultimo Power House.** At the end of the year two of the four proposed shafts for this tunnel had been sunk approximately 40 ft. to the invert level. A tunnel is being driven from each side of these shafts through hard sandstone. Air compressing plant had been installed and also electric light throughout. At each of the heads, arrangements are being completed for the installation of electric winches for handling the excavated material.

As the filling up of Darling Harbour with spoil proceeded, the restriction of the headwaters of Darling Harbour caused a certain amount of mixing of outlet water with the circulating water near the intake, with a resultant rise of temperature of the water at the intake. When about 5 acres had been reclaimed the temperature of circulating water on the intake side had risen some 20 degrees Fahrenheit and seriously affected the efficiency of the power house.

**Photo No. 45 shows Darling Harbour reclamation: erection of coffer-dam in connection with circulating water, Ultimo Power House.** A coffer-dam, consisting of timber piles & walings with 3 thicknesses of 12 inch x 3 inch sheeting, was therefore erected to act as a baffle and ensure the removal of the discharged circulating water from the vicinity of the intake.

This has proved quite successful, and save for the maintenance of a channel for discharged circulating water, filling in is proceeding without further inconvenience to the power house authorities.

**Principal items of construction carried out:**

From the re-opening of the City Railway Construction works on 20th February, 1922, up to the end of September, 1923 - a period of 19 months - the following principal items of construction were carried out:
## Excavations:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cu. yds.</th>
<th>Cu. yds.</th>
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<tbody>
<tr>
<td>General Earthworks in walls etc.</td>
<td>19,465</td>
<td></td>
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<tr>
<td>Bridge Abutments</td>
<td>12,909</td>
<td></td>
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<tr>
<td>Open cut - Station areas</td>
<td>220,764</td>
<td></td>
</tr>
<tr>
<td>Tunnels</td>
<td>29,173</td>
<td></td>
</tr>
<tr>
<td>Open cut sections between stations</td>
<td>106,142</td>
<td>398,453</td>
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</table>

## Concrete placed:

<table>
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<tr>
<th>Description</th>
<th>Cu. yds.</th>
<th>Cu. yds.</th>
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</thead>
<tbody>
<tr>
<td>Miscellaneous works</td>
<td>14,832</td>
<td></td>
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<tr>
<td>Bridges</td>
<td>13,497</td>
<td></td>
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<tr>
<td>Station walls etc.</td>
<td>2,582</td>
<td></td>
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<tr>
<td>Tunnels</td>
<td>5,773</td>
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<tr>
<td>Open Cut areas</td>
<td>1,566</td>
<td>38,250</td>
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## Brickwork:

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<tr>
<th>Description</th>
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<th>Cu. yds.</th>
</tr>
</thead>
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<tr>
<td>Retaining Walls</td>
<td>193</td>
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<tr>
<td>Tunnels</td>
<td>561</td>
<td>754</td>
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</table>

## Masonry:

<table>
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<tr>
<th>Description</th>
<th>Cu. yds.</th>
<th>Cu. yds.</th>
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</thead>
<tbody>
<tr>
<td>Retaining Walls</td>
<td>53,546</td>
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</tr>
<tr>
<td>Bridges</td>
<td>16,237</td>
<td>69,783</td>
</tr>
</tbody>
</table>

**Concrete Mixing and Placing.** Photo No. 44 shows "Foote" concrete mixer pouring concrete in Southern Abutment of Campbell Street Bridge. With the concrete plant, referred to under "construction equipment", the mixers were worked under heavy duty conditions, especially when pouring massed concrete behind the masonry-faced walls in Elizabeth Street and in the abutments of the bridges over Hay Street and Campbell Street.

In one abutment of the Hay Street Bridge, 2340 cubic yards of concrete were poured.
in 19 days with one concrete mixer, which gave an average pouring of 123 cubic yards of concrete per day.

One mixer of the "Armstrong-Holland" 10 ft. capacity type delivered up to 160 cubic yards of concrete in 8 hours, which is an exceptionally good record.
BOOKKEEPING AND COST-KEEPING SYSTEMS.

The City Railway was for constructional purposes divided into Sections numbered from 1 to 13, the even numbers representing the six stations on the City Railway loop, and the odd numbers, the construction between stations. This arrangement is found to be very convenient for costing purposes.

For each Section of line a general Estimate of Cost was prepared. The "General", or "Sectional Estimates", were then subdivided into Detailed Estimates, giving the exact plan quantities for each class of work to be carried out, together with the estimated cost of labour, material etc., making up the cost per unit.

In Railway Construction Works, and subway work such as now being carried out on the City Railway, the bulk of the expenditure will be for five works items as follows:

1. Earthworks, Open Cut,
2. Earthworks in Tunnels,
3. Concrete,
4. Brickwork,
5. Masonry.

On the City Railway the Earthworks consists principally of excavation in "Cut and Cover", and Excavation in Tunnels. The excavation for subway stations are carried out by mechanical excavators, and the methods vary but little from the methods adopted for taking out the "Cut and Cover" excavations between stations. The excavations for subway stations will, however, cost more per cubic yard owing to the quantity of rock-trimming etc. required in connection with subways, subway entrances, etc.
As a guide to the Field Engineers, and the Costing Clerks, the various works to be carried out in any Section were given "Works Charge Numbers" under which all costs for wages, material, stores and "overhead" are grouped for costing purposes.

These "Work Charge Numbers" were derived from a decimal subdivision of "Capital Headings" used in the compilation of the Capital Cost Statement which is presented to Parliament on the completion of the railway.

The main Capital Headings, or classification of railway/expenditure are as follows:

<table>
<thead>
<tr>
<th>1.00</th>
<th>Surveys,</th>
<th>9.00</th>
<th>Fencing and Gates,</th>
<th>17.00</th>
<th>Signal and Interlocking,</th>
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<tbody>
<tr>
<td>2.00</td>
<td>Engineering,</td>
<td>10.00</td>
<td>Ballasting,</td>
<td>18.00</td>
<td>Telegraph and Telephone Lines,</td>
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<tr>
<td>3.00</td>
<td>Land Resumptions,</td>
<td>11.00</td>
<td>Sleepers,</td>
<td>19.00</td>
<td>Jetties and Wharves,</td>
</tr>
<tr>
<td>4.00</td>
<td>Clearing,</td>
<td>12.00</td>
<td>Rails and Fastenings,</td>
<td>20.00</td>
<td>Workshops,</td>
</tr>
<tr>
<td>5.00</td>
<td>Earthworks,</td>
<td>13.00</td>
<td>Track laying,</td>
<td>21.00</td>
<td>Machinery,</td>
</tr>
<tr>
<td>6.00</td>
<td>Tunnels (including Cut and Cover),</td>
<td>14.00</td>
<td>Buildings,</td>
<td>22.00</td>
<td>Rolling Stock,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.00</td>
<td>Roads,</td>
<td>23.00</td>
<td>Miscellaneous,</td>
</tr>
<tr>
<td>7.00</td>
<td>Bridges,</td>
<td>16.00</td>
<td>Water Supply,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>Level Crossings,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The decimal notation enables a subdivision to be made of these capital headings from .01 to .99 to cover the various classes of work under the several headings for which detailed costs are required to be kept.

A prefix number is given to the Charge Numbers to indicate the Section
of railway where the work was carried out.

As an illustration of the system the sixth Capital Heading - Tunnels -
is subdivided thus:

6.30 "Tunnels" (Capital Heading).
6.01 Excavation in Tunnels (Works Charge Numbers).
6.02 Concrete in Tunnels (do. do. do.).
6.03 Brickwork in Tunnels (do. do. do.).

etc., etc.,

For convenience in cost-keeping the decimal points are omitted in practice, e.g., 5/601 would be the Charge Number for Excavation in Tunnels - Section 5; 5/602 - Concrete in Tunnels Section 5, etc.; further, 5/701 would be the Charge for Excavation in Bridges, Section 5; 5/702 - Concrete in Bridges, Section 5; 6/1402 Concrete in St. James' Station (Section 6 - Capital Heading 14, Buildings).

It will be understood that the various classes of concrete used in the various sections will be costed separately, and the details of such costs given on a Schedule attached to the Cost Statement.

Before entering upon a description of the costing methods adopted on the City Railway, brief reference will be made to the book-keeping system, into which the costing system must interlock for the purpose of securing the necessary audit check on the expenditure for Wages, Material, Stores, Plant and General Overhead Accounts.

In all large engineering works, as in all modern commercial undertakings, it is the general practice to keep accounts by the double-entry
method, as experience has shown that this is the only system whereby a reliable audit check can be obtained.

This method was adopted for use on the City Railway, and the General Ledger is balanced on abstracted postings at the end of each month.

Being a Government enterprise, all payments are made on the usual Government Voucher System. All vouchers for wages, material, and in fact, all expenditure, are certified by the Chief Engineer and forwarded to the Chief Accountant for payment.

An "Appropriation Account" is, therefore, kept in the General Ledger, which is in practice a simple credit account showing the drawings from the Chief Accountant's funds, as provided by Parliamentary vote. This "Appropriation Account" is checked and reconciled with the books of the Accounts Branch every month.

All vouchers certified by the Chief Engineer are numbered, and posted in a "Voucher Debit Book", which is practically a columnar journal, designed for the purpose of grouping the main items of expenditure and thereby reducing the labour of posting to the General Ledger. The debit columns are posted monthly in the General Ledger to the impersonal accounts, such as Wages, Stores, etc., provided for the purpose of giving the necessary dissection of expenditure.

It will be understood from this brief explanation that up to this point the General Ledger will show one Credit Account, representing the total expenditure on the line.

The other accounts in this ledger will be a number of debit accounts, the total of which must balance with the credit or appropriation account representing the total expenditure on the line.
At this stage, therefore, the costs of works actually carried out do not appear in the General Ledger.

To enable a "Capital Expenditure Statement" to be prepared at any time, accounts representing the Capital Headings previously listed were opened in the General Ledger, and it is these special accounts which provide the means for interlocking the Cost Accounts, as will now be explained.

**COST ACCOUNTING:** It will be understood from the foregoing that after posting the Voucher Debit Book to the General Ledger, the latter will contain a dissection of expenditure into Wages, Material, Stores, etc.

On each Section of line the usual timekeeping arrangements are made for recording the exact time worked by each employee. At the end of every two weeks the time books are made up and checked, and then "Wages Sheets" are prepared giving the names and occupations of all employees, together with the wages due for the period.

After being certified, the amount of this voucher will be entered into the Voucher Debit Book and then posted in the General Ledger to Wages Account, which will always show, on inspection, the total wages paid to the end of any given period.

In a similar manner, all vouchers for supplies of material and stores will appear to the debit of their respective accounts.

It will be obvious that what will eventually be required in the General Ledger will be the expenditure - not under wages, stores, etc. - but under the Capital Headings given in the foregoing.
To secure this, the Cost Clerks, aided by the Timekeepers and Storekeepers, are required to keep an exact appropriation of all wages paid and all material and stores issued, to the "Works Charge Numbers" as given in the detailed estimates. For example, on say Section 4, the Cost Clerk will, at the end of any period, be in possession of an appropriation sheet showing the exact wages expenditure on every item of work in progress during the period. He will also have "Material", and "Stores Dissection Sheets", showing the value of Material and Stores issued to the various Charge Numbers during the period. In a similar manner, wages, and store-dissection sheets will be available from the other Sections.

The totals of these wages appropriation sheets and the Material and Stores Dissection Sheets must balance with the total Wages Sheets and the total Material and Stores issues for the period covered.

The Cost Clerks will also at the end of a Pay Period receive from the Engineers in charge of Sections returns which are called "Engineer's Measurement Sheets". These Sheets give the actual measurements, expressed in cubic yards and cubic feet, of all work carried out during the period.

From these returns Monthly Cost Statements are prepared. To facilitate the work of ascertaining the unit cost of the several works items expressed in shillings, pence and decimals of pence per unit of measurement, Comptometers are used in the Field Office. These machines enable the work to be carried out promptly, and the actual costs accurately determined, whilst all the facts relating to the work are fresh in the minds of the engineers. On completion, and after examination by the Chief Engineer, the Monthly Cost Statements pass to
the Book-keeper at the Head Office.

Journal entries are then passed debiting the various Capital Expenditure Accounts in the General Ledger, and crediting such accounts as have been drawn upon during the period, viz., Wages, Material and Stores.

It will be understood that various "Material Accounts" are kept to cover the various classes of material used in construction.

After posting these journal entries, the General Ledger Balances when abstracted will show:

(a). The total Appropriation or Expenditure on the Railway, reconciled with the books of the Accounts Branch (Credit Account),

(b). The Total Capital Expenditure (Debits Accounts) under the required Capital Headings,

(c). Debit Balances of Material and other Accounts.

The totals of (b + c) should equal (a). As regards (c), the balance to debit of Stores Account, for instance, represents the value of General Stores held in the various stores controlled by the Storekeepers on the several sections of railway.

The Storekeeping methods will not be described here, but it may be said that all stores are issued on docket only. The Storekeepers are provided with alphabetically arranged Store Cards— one card for each line of Stores held. All receipts and issues are posted to the Cards, the aggregate totals of which should agree with the balance of the Store Account in the General Ledger. Periodical Audit Checks are made to determine this. This brief resume will indicate the principles adopted in keeping a close check on
the costing operations by means of the financial books, the General Ledger being in fact similar in purpose to the "Private Ledger" kept by Manufacturing and Commercial Houses.

**DETAILED COSTS:** As previously stated the bulk of railway construction expenditure will be for Earthworks, Concrete, Brickwork and Masonry.

In preparing the estimates for these great items of expenditure, the practice is to subdivide the costs into Wages, Material, etc. The working costs are kept strictly in accordance with the dissection laid down by the estimates, and it becomes possible to compare the working costs of one period with that of another, and also with the estimate, with a full knowledge of the cause of any disclosed rise or fall in the costs per unit.

Table IV illustrates a typical Cost Card which is used for recording the Working Costs of each Charge Item for the period, and also the average costs to date of last return.

This typical card covers the working costs of Excavation in the Tunnels passing through Section 5. Similar cards are used for each separate tunnel, the totals being grouped on the typical card illustrated, which is a summary card for all the tunnels in the Section.

It will be seen from this card that the estimated quantity of work to be carried out, and the estimated rates for wages, material and other Charges against the work are shown at the head of the respective columns in red figures.

Comparisons between the estimated quantities and rates, and the quantities and rates for the works carried out to the date given, are, therefore, instantly available by inspection of these cards.
### TABLE 17

<table>
<thead>
<tr>
<th>Date</th>
<th>Rate (Per Cent of $100)</th>
<th>No. of Labourers</th>
<th>Wages</th>
<th>Explosives</th>
<th>Sharpies</th>
<th>Total</th>
<th>Misc. Charges</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 1</td>
<td>65</td>
<td>217</td>
<td>6.07</td>
<td>2.98</td>
<td>10</td>
<td>5.8</td>
<td>3.59</td>
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<td>64</td>
<td>248</td>
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<td>3005</td>
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### SECTION B

**LOCATION BETWEEN LIVERPOOL STREET STATION AND ST. JAMES’**

<table>
<thead>
<tr>
<th>Wages</th>
<th>Explosives</th>
<th>Sharpies</th>
<th>Grand Total</th>
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<tbody>
<tr>
<td>8.97</td>
<td>3.82</td>
<td>12.79</td>
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<td>8.97</td>
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<tr>
<td>8.97</td>
<td>3.82</td>
<td>12.79</td>
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</table>

**Final Remarks**

- Overhead to be added Costs.

### Remarks

- No. of Days...
The "Wages" Costs shown on this card, represent the actual cost of the wages actually paid for work carried out, and does not include wages paid for holidays or on account of accidents, etc. It is a clear cut wages charge, and consequently is comparable pay by pay. When a rise in the wages cost is shown, there must be an "engineering reason" for the rise. Monthly Conferences presided over by the Chief Engineer are held when the costs given on these cards are reviewed item by item. A rise in wages cost cannot be explained as caused by wet weather or any other reason, as such charges are kept separate under the heading of "miscellaneous".

This system is very useful in keeping a close check on the costs of the works carried out by the several gangers in, say, a section of tunnel. Each ganger's work is measured up separately, and costed separately. If the cost per unit by one ganger exceeds that of another working in exactly similar country, there at once arises a matter for inquiry. This constant and vigilant check on the wages costs of the five great items of expenditure previously referred to as making up the bulk of the capital cost of a railway, is of the utmost value in securing the most economical methods of working. The dissectons of costs also furnishes valuable data for use in the Designing Branch for estimating future works of similar character.

"OVERHEAD" OR GENERAL EXPENSES: In addition to the direct charges against a Works Item for Wages, Materials, Stores and Miscellaneous Expenditure, there are numerous expenses incurred on a construction job, which cannot be allocated at once to the works in progress except by rule-of-thumb methods which only tend to confuse the actual working costs.

These "Overhead" expenses consist of unproductive labour costs - such as Watchmen, Caretakers, etc. - and the cost of erecting buildings, putting in water
and air services, together with minor charges largely foreign to actual constructional operations.

These "Overhead" expenses must be allocated to the various capital headings making up the Capital Expenditure Statement.

Much difference of opinion exists as to the best method of distributing these expenses, and many text books on Cost Accounting devote considerable space to the subject.

In the case of the City Railway the method adopted in dealing with the overhead expenses is simple, and has the merit of securing fairly accurate data as to the percentage which should be added to the primary estimates for the various Works Items to cover such charges.

The Overhead Charges are kept in special accounts in the General Ledger in the form of "Construction Suspense Accounts."

At regular intervals a statement is prepared showing the quantities of each class of work carried out. The rate for "overhead" as given in the original detail estimates is then written in against the various quantities and the amounts extended. The total of all the items is then compared with the total of the Construction Suspense Accounts taken from the General Ledger.

The object of this comparison is to determine early if the rates estimated for the total overhead expenses are sufficient to cover the actual costs as revealed by the General Ledger.

If the examination is considered satisfactory, the overhead to be added to the primary costs is shown on the cost cards in a column provided for the purpose.

The actual allocation of Overhead to the capital headings is not made until
the works items are completed, when it is possible to make the allocation with a true
knowledge of all the facts, and with all the Ledger Accounts fully posted, and the
actual figures available for allocation purposes.

This method in practice is found to be much clearer, and much more satis-
factory than the system of writing off a portion of the "overhead" monthly, with often
no proper regard for the equity of the allocation.

The "Trial Balance" taken out on the completion of a section of the line
shows (a) the actual working costs of all the items making up the Capital Headings;
and (b) the list and totals of all the Overhead or Suspense Accounts. From this
Trial Balance the Capital Expenditure Statement, giving the completed costs, is
prepared.

CONSTRUCTION GRAPHS: Plate 45 illustrates a typical "Construction Graph",
one of which is kept regularly plotted up for each of the great items of construction-
al expenditure previously referred to.

These graphs, compiled from the Cost Cards, are found extremely useful both
for Field and Head Office use. At the Monthly Conference on Construction Costs, at
which the Field Engineers attend, the graphs provide a ready means for ascertaining
at a glance the proportion of any work carried out to date, with the actual working
costs compared with the estimated quantities and rates.
SYDNEY HARBOUR BRIDGE.

Location.

Coming now to the Bridge, it will be interesting to note that the first suggestion for a bridge from Sydney to North Sydney was made by Francis H. Greenway, Government Architect, the site selected by him was from "Dawes' Battery to the North Shore", in 1815.

The earliest recorded drawing of a bridge (Plate No. 45) was made in 1857 by a Sydney Engineer, Mr. Peter Henderson, at the same site, which at this date is the best location.

Location: In attempting a solution for the complex traffic problems of Sydney the author gave careful attention to important local conditions connected with the construction of the Sydney Harbour Bridge, which should properly be considered an integral link in a broad scheme for modern rapid transit facilities necessary for the requirements of a great and expanding city, destined to be the most important seaport on the Pacific Coast. The first of these conditions to be considered is that of location. There are three possible locations as shown on Plate No. 47.

From Dawes' Point to McMahon's Point.
From Dawes' Point to Wilson's Point.
From Fort Macquarie to Kirribilli Point.

The location, Dawes' Point to McMahon's Point necessitated either a bridge with a clear span of 2,250 feet from shore to shore, or a bridge with two piers in the fairway, and these are inadmissible on account of navigation requirements. (Plate No. 43)

The location, Dawes' Point to Wilson's Point requires, to have the piers founded on either shore, a bridge of 1,600 feet clear span. This location is the central one; it follows the route of long established lines of tramway and vehicular traffic on the
Northern side of the harbour, and would provide for the present and for the expanding railway, tramway, and vehicular traffic much more efficiently than would either of the other two crossings.

The crossing from Fort Macquarie to Kirribilli Point would require a bridge of 1700 feet clear span to keep the piers on either shore, and the location would not serve the railway, and tramway as well as the crossing from Dawes' Point to Milson's Point would, but when the second bridge across the Harbour is built it will probably be located here and will probably be an eyebar cable suspension bridge as the traffic to be catered for will be mostly vehicular and pedestrian traffic. Motor transport will have increased so enormously as to demand an almost exclusive vehicular traffic bridge.

Taking all factors into consideration - viz preliminary surveys, estimates of cost, and the present and future traffic requirements - the choice of location should undoubtedly be first given to the Dawes' Point-Milson's Point Crossing as most suitable for a bridge to meet most efficiently and economically the railway and vehicular requirements of this great city.

**Foundations.** One of the most important considerations in connection with the design is the foundations of the main piers, and again exhaustive tests have determined that the choice of the Dawes' Point-Milson's Point is the best and most economical.

The crossing from Dawes' Point to McMahon's Point for any financially practicable bridge would require two piers in the fairway, one of which would have to be founded about 120 feet and the other about 172 feet below High Water Mark on rock (Plate No. 49). This depth is beyond that to which caissons can be sunk under air pressure.

Bores put down to test the nature of the formation at the sites of these two
SYDNEY HARBOUR BRIDGE
DAWES POINT TO McMAHON'S POINT
DESIGN RECOMMENDED BY ADVISORY BOARD
1903

CROSS SECTION
WITH RAILWAY
AS APPROVED BY ADVISORY BOARD

CROSS SECTION
WITHOUT RAILWAY
AS SUBMITTED TO PARLIAMENT
piers, indicated that the material overlying the rock was not sufficiently stable to withstand the calculated pressure, as it consisted of layers of silt, sand, shells, and clay.

To test the supporting power of this material overlying the rock, a cast iron cylinder, 6 ft. diameter was sunk by the pneumatic process to a depth of 90 ft. below High Water Mark, and samples of the strata passed through were retained for examination. This cylinder, at the depth of 90 ft. was loaded with a test load equivalent to a pressure of 7 tons per square foot of area, but it consistently sank under the loading. In 16 days the total settlement was found to be 44 inches, and the skin friction .23 tons per square foot. From this experiment it was evident that a safe foundation for the bridge could only be obtained by carrying the piers down to rock.

Bores were put down along the lines of crossing between Fort Macquarie and Kirribilli Point, also from Dawes' Point to Wilson's Point. The material overlying the rock being similar to that on the line of crossing to McMahon's Point. In putting down bores in the fairway it was found that when rock was reached fresh water invariably arose in the bore casing.

At some remote epoch a faulting of the earth's crust took place, and the country between the Blue Mountains and the South Pacific Ocean, subsided. Rocky cliffs once above ground became submerged by the waters of Sydney Harbour. The sandstone cliffs to be observed in and around Sydney are frequently found to be undercut by the process of air-weathering, the result being overhanging ledges of rock jutting out beyond the solid face of the rock. There was a possibility that the rocky foreshores of the harbour might have been undercut by this process of weathering prior to submerging, or subsequently, by erosion due to tides and currents, and to test the solidity of the rock on the foreshores
diamond drill bores were put down - three on the southern, and two on the northern side of the Harbour. The diamond drill bores were sunk to depths ranging from 52 feet to 77 feet below mean sea level, and there was no indication of air weathering prior to subsidence, or of water erosion subsequently.

Samples of the material passed through were retained, and the rock was proved to be good hard sandstone. As mentioned previously, the bores indicated that excellent foundations for the bridge piers would be obtained on either shore about 20 feet below mean sea level.

As a precaution against possible danger from subsidence during coal mining operations in the future, an area of 10 acres at the site of each of the main piers has been reserved against mining. There will be ample room, however, between the areas so reserved to permit of mining operations being carried on under the waters of the Harbour.

The location finally decided upon by the author between Dawes' Point and Wilson's Point, was most satisfactory as regards the foundations for the main piers of the bridge located on either shore. These piers will be founded on solid rock situated about 20 feet below mean sea level, and the great cost of founding piers in the fairway, even if allowed by the Harbour Trust, at the great depth of 172 feet below H. W. M. has been avoided.

HEADWAY FOR SHIPPING:

A most important aspect affecting the business efficiency of a great seaport, is that of the headway available for shipping under bridges erected, or to be erected over the fairway. The Parramatta River Bridge, for example, is undoubtedly blocking the development of Sydney above that bridge, and the bridge must be remodelled to suit present and future requirements, the sooner the better.
The character of the world's shipping has radically changed during the last quarter of a century.

In 1900 there were 22,369,353 tons of merchant shipping afloat propelled by steam, and 6,386,000 tons under sail, a total of 28,757,358 tons distributed over 27,640 vessels.

In 1923 there are 62,335,373 tons steam, and 2,850,865 tons under sail, or a total of 65,186,238 tons distributed over 33,507 vessels.

Sailing tonnage now forms a very small and practically negligible portion of the world's merchant shipping.

The interest of present day shippers centres in steamers and motor vessels, particularly in those built of steel and iron. The real test of the strength of the various merchant fleets of the world is to be found in the statistics of sea-going steel and iron vessels.

From the figures quoted it will be seen that from the beginning of the present century the shipping tonnage of the world has more than doubled.

The number of merchant ships had not greatly increased during this period, but the average size is far larger.

During the last ten years there had been a large increase in the use of oil instead of coal, in the sea-carrying trade of the world, apart from the progress which the movement has already made in the great war fleets - the British Navy now depending almost exclusively on liquid fuel.

The rate at which the sailing ship is disappearing from the seas and the oil-burning vessel is replacing the coal-burning vessel is revealed in the following table:--
<table>
<thead>
<tr>
<th></th>
<th>1914</th>
<th>1923</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>per cent of total</strong></td>
<td>1914</td>
<td>1923</td>
</tr>
<tr>
<td>Gross tonnage.</td>
<td>8.05</td>
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<tr>
<td>Sail Power only</td>
<td></td>
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<tr>
<td>Oil etc., in Internal Combustion Engines</td>
<td>0.45</td>
<td>2.56</td>
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<tr>
<td>Oil fuel for Boilers</td>
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<td>24.23</td>
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<tr>
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<td>68.87</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td>100.00</td>
<td>100.00</td>
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</table>

Less than 60% of the tonnage of the merchant marine now depends entirely upon coal, while in 1914 the percentage was nearly 80.

In commenting upon the fact that the future lies with the oil-burning ship, which enjoys many economic and other advantages, including cleanliness, the latest edition of Lloyd's Register states that it is disturbing to learn that of the 3049 steamers fitted for burning oil fuel only 601 representing 3,792,676 tons are registered in Great Britain and Ireland, and that 1,769 steamers of 8,709,776 tons are registered in the United States of America.

The following table gives the tonnage and leading dimensions of some of the great vessels built for the trans-Atlantic, and for the Australian trade.
<table>
<thead>
<tr>
<th>Owner</th>
<th>American Shipping Board</th>
<th>&quot;Leviathan&quot; (Vaterland)</th>
<th>&quot;Olympic&quot;</th>
<th>&quot;Majestic&quot;</th>
<th>&quot;Ceramic&quot;</th>
<th>&quot;Mooltan&quot; &quot;Maloja&quot;</th>
<th>&quot;Nestor&quot; &quot;Ulysses&quot;</th>
<th>&quot;Orama&quot; &quot;Gronsay&quot;</th>
<th>&quot;Aorangi&quot; (Motor Ship)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of Completion</td>
<td></td>
<td>1914</td>
<td>1911</td>
<td>1922</td>
<td>1913</td>
<td>Sept. 1923</td>
<td>Oct. 1923</td>
<td>1913</td>
<td>May 1924</td>
</tr>
<tr>
<td>Gross Tonnage</td>
<td></td>
<td>59,956</td>
<td>46,439</td>
<td>56,451</td>
<td>18,495</td>
<td>20,700</td>
<td>14,600</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Length Overall</td>
<td></td>
<td>950' 7&quot;</td>
<td>962' 9&quot;</td>
<td>964' 6&quot;</td>
<td>674' 9&quot;</td>
<td>623' 6&quot;</td>
<td>580' 9&quot;</td>
<td>668'</td>
<td>660'</td>
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<td>Breadth Extreme</td>
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<td>100' 0&quot;</td>
<td>92' 6&quot;</td>
<td>100' 6&quot;</td>
<td>69' 6&quot;</td>
<td>73' 4&quot;</td>
<td>68' 4&quot;</td>
<td>75'</td>
<td>72'</td>
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<tr>
<td>Loaded</td>
<td></td>
<td>39' 6&quot;</td>
<td>34' 7&quot;</td>
<td>38' 10&quot;</td>
<td>34' 8&quot;</td>
<td>31' 6&quot;</td>
<td>32' 10&quot;</td>
<td>29'</td>
<td>27' 6&quot;</td>
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<td>Masts above water</td>
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<td>Height of wireless</td>
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Similar liners to those now engaged on the trans-Atlantic trade will at no very distant date be seen in Sydney Harbour, and it is the height required for the funnels, and the wireless aerials of such vessels, which determines the headway to be provided under a bridge across Sydney Harbour.

From the Table it will be seen that the "Olympic" has funnels 137 ft. and the "Majestic" 156 feet above light load water line. The wireless aerials are much higher than this, those on the "Olympic" are carried 195 ft. above the light load water line, and on the "Majestic" 216 feet.

There is a limit, however, to the height to which the deck/bridge can be carried above High Water level, and the most that can be done is to provide the maximum headway permissible under the governing factors of engineering and financial requirements.

Within certain limits masts can be made telescopic, and in the headway under the Sydney Harbour Bridge it was not considered necessary to provide full clearance for the aerials of such liners as the "Olympic" or the "Majestic".

The bridges erected across the East River, New York, U. S. A., all have a clear headway of 135 feet above High Water Mark, and the same height has been provided for the Philadelphia - Camden Bridge now in course of erection across the Delaware River.

The Forth Bridge over the Firth of Forth, Scotland, and also the Quebec Bridge over the St. Lawrence River, have headways of 150 feet at High Water Mark. The range of tide at Quebec, however, is 20 feet, whilst in Sydney Harbour, Mean High Water is only 5.04 feet above Mean Low Water.

The shipping traffic under any of the bridges mentioned will not develop to the extent, nor be as important as that which will be passed under the Sydney Harbour Bridge in
future years.

It may be here interesting to note that the headway under a bridge proposed across the English Channel is 180 feet. The headway available under the Tower Bridge, London is 145 feet; on the Baltic Canal, 137 feet; and on the Manchester Ship-Canal, 75 feet, but comparatively small overseas vessels not only have telescope masts but require to have the tops of their funnels removed before they can pass up the canal to Manchester.

To make a reasonable provision for these future developments in the shipping business of Australia's greatest seaport, a headway of 170 feet at High Water was decided upon. This height will allow mail steamers up to 20,000 gross tonnage to pass under the Bridge without the necessity for telescopic masts, and will also permit the funnels of the largest vessels afloat today to pass under the bridge deck, and allow a reasonable margin for future development. In the future, larger vessels than the present leviathans will assuredly be constructed, and though the internal combustion engine vessel may replace coal and oil burning steamers - thus rendering a less height of funnel necessary - consideration of the larger sized vessels of the future demand that the headway shall be kept as great as is reasonably practicable. Today Sydney's shipping is exceeded by only four Ports in the United Kingdom, London, Liverpool, the Tyne and Cardiff; within 50 years Sydney will probably be the Premier Port of the Empire, and it is essential that the greatest headway practicable must be provided and even with a clear headway of 170 feet at High Water, the largest Mail and Passenger Steamers which will ultimately enter Sydney Harbour will require to be provided with telescopic masts.

In fixing this height, which is 20 feet higher than that of any similar bridge - although the Quebec Bridge affords 170 feet at Low Water owing to the great range of the tide - the cost of electric current consumption for a frequent service of electric trains across
The bridge will be about £10,000 per annum more than it would be with a bridge of 150 feet headway.

As the bridge will return a handsome profit from railway passenger traffic at the outset, this added cost for the 20 feet additional headway is not excessive when it is considered that this increased height will provide uninterrupted headway for probably 98 per cent of the steamers trading to Sydney in the future.

The Traffic Requirements:

Before determining upon the type of Bridge and the length of span, the prospective traffic requirements must be studied so that the design of the deck members and main girders may, as far as can reasonably be foreseen, adequately provide for future requirements. Plate No. 50 shows the cross section of the bridge which provides for four lines of railway traffic, six lines of vehicular traffic and two footways each 10 feet wide.

Dealing first with the railway loading, two classes of railway loading will cross the bridge, viz., long distance passenger and goods trains hauled by electric locomotives, and multiple unit suburban stock.

The present limit of passenger train weight in New South Wales is 320 tons determined by the existing draw gear and headstocks, whilst for goods traffic the maximum weight of train is 900 tons. The electric locomotive requirements decided upon are that the locomotive must be capable of hauling a 500 ton passenger train or 1000 ton freight train around curves of 3 chains radius and on an up grade of 1 in 39 at a speed of 20 miles per hour. The mathematics of this determination are ordinary railway problems and have not been included in this thesis.

The electric locomotive decided upon weighs 160 tons, having 4 driving wheels each with an axle load of 56000 lb. The horse power of the locomotive is 2400 for one hour's
CANTILEVER BRIDGE SUSPENDED SPAN
rating. The weight on the driving axles necessary to give the tractive effort required is 100 tons, and in determining on the locomotive this weight has been taken as 60% of the total weight of locomotive. In the latest practice 80%, and in some instances, all, of the weight comes on the driving wheels, and there is no reason, except possibly for the heaviest types, why the total weight should not come on the driving wheels.

With electric locomotives so designed, the maximum axle load would be less than assumed, as the total load would be spread over a greater number of driving wheels, and the axle loads would be less and would produce smaller stresses.

The conventional locomotive loading adopted will meet all present and future requirements as far as can be foreseen, the loading will give considerable latitude in the design of the locomotive, as it would allow other types of equal power and hauling capacity to pass over the bridge without causing an increased stress on any part of the deck of the bridge.

The all steel motor car decided upon for the suburban railways when electrified, and illustrated previously, weighs 105,000 lb. and with passengers 117,000 lb., an average weight of 1,900 lb. per foot of car.

The tare per foot of American all steel long distance rolling stock averages 1760 lb. per foot; New South Wales rolling stock 1140 lb. per foot, and is to be widened to 10' 6" which will increase the tare by 10 per cent or an average tare of 1254 lb. per foot.

Loaded American Stock averages 2200 lb. per foot whilst New South Wales stock, when widened, will average about 1325 lb. per foot. For climatic reasons the New South Wales rolling stock is not required to carry heavy fittings such as steam heating apparatus, double windows, etc., and in fixing upon a weight per foot of 2200 lb. a wide margin has been allowed for the improvement of cars and fittings whether suburban electric or long distance cars.
The roadway is 57 feet wide and provides adequate width for 6 lines of vehicular traffic, the heavy slow, the medium average speed and the light fast traffic, will be regulated in three lines in either direction. In considering what the loading may be, some of the heaviest steam wagons carry twice the load on the back axle as on the front axle, but the tendency is to more nearly equalize the loading on the front and back axles.

The Department of Bridges, New York, have increased their conventional loading to four wheel loads of 18,000 lb. each, wheel base 12' x 5', space occupied 30' x 12', total load 60,000 lb. equivalent to 167 lb. per sq. ft.

To provide against the maximum effect of vehicular traffic, on the floor plates stringers and other subsidiary members, which may traverse the roadway, a conventional motor lorry, total weight 64,000 lb., wheel base 12' x 6', overall length 24', width 12', space occupied 30' x 12', front axle load 18,000 lb. and back axle load 36,000 lb. was adopted, average load over space occupied 150 lb. per sq. ft. The average load providing as it does for all classes of vehicle will be very much less than 150 lb. per sq. ft. Horse drawn vehicles will gradually disappear.

To arrive at an average load per ft. of roadway, two lines of 10 heavy lorries, each weighing 12 tons, length 22', half a lorry length between each lorry in the line, or a line length of 330 feet; two lines of 14 lorries, 5 tons each, and two lines of 14 lorries each weighing 4 tons, each of the four lines a length of 330 feet, have been taken. This is much heavier and much denser traffic than exists anywhere on the streets of Sydney today. Under these conditions the average weight is 58 lb. per sq. ft. For the main trusses the average weight per sq. ft. has been taken at 60 lb., whilst for the deck system 100 lb. per sq. ft. has been taken, outside the area occupied by the conventional motor lorry.

When some event of outstanding interest takes place on the harbour, it is probable
that portions of the footway will be densely packed and all flooring plates, stringers and cross girders have to withstand a live load of 100 lb. per sq. ft. of footway, but for free movement over the bridge each pedestrian would require 5 sq. ft. of floor space and, assuming the average person as weighing 160 lbs, this would be equivalent to a live load per sq. ft. of 30 lb. or 300 lb. per each footway which is 10 feet wide.

**SUMMARY:** It is highly improbable that all four trains will be in the exact positions necessary to produce the maximum stress, and that the length of these four trains will each be 1,100 ft., including the two locomotives. The railway loads, therefore, have been considered as producing 75% of the stresses produced by two coupled conventional electric locomotives followed by a train of 1,000 feet long weighing 3,080 lbs. per lineal ft. on two of the tracks, the remaining two tracks each carrying a train consisting of multiple unit stock weighing 2,200 lbs. per lineal foot and 1,100 ft. long.

From an extensive series of calculations the effect on the stresses due to the long distance loading averages 40% in excess of that of the multiple unit stock loading, and thus the railway loading has been taken as 75% of the total stresses produced by two trains at 2200 lbs. per ft. run and two goods trains at 3080 lbs. per ft. run.

The total loading on main trusses per foot run is as under, the maximum loaded length to be 1100 ft. and 300 ft. minimum.

<table>
<thead>
<tr>
<th></th>
<th>Footway</th>
<th>Roadway</th>
<th>Railway</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 ft. @ 30 lbs. per sq. ft.</td>
<td>57 ft. @ 60 lbs. per sq. ft.</td>
<td>75% (2 @ 2200 + 2 @ 3080)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600 lbs. per ft. run.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3420 lbs. per ft. run.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7920 lbs. per ft. run.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11,940 lbs. per ft. run.</td>
</tr>
</tbody>
</table>

The live loading for the main trusses has therefore been determined upon as 12,000 lbs. per ft. of bridge, that is 6,000 lbs. per lineal foot of each main girder.
GOODS TRAFFIC:

When Mosman and Manly are connected to the City and the Manly railway is extended through Narrabeen to Pittwater, an appreciable goods traffic will develop. The loading adopted is such as would enable goods traffic weighing 3000 lbs. per lineal foot hauled by one or two 160 ton electric locomotives as may be necessary according to the total weight of the train, to be taken across the Bridge, at any time providing the adjacent track is carrying only multiple unit stock.

All portions of the deck of the Bridge will be capable of withstanding the stress due to two 160 ton electric locomotives coupled.

Should it be necessary for heavy goods traffic to traverse the Bridge, a train weighing 6,000 lbs. per lineal ft. hauled by two 160 ton electric locomotives could be taken across on either of the two inner tracks when the adjacent track is unloaded, or a train weighing 5,000 lbs. per lineal ft. hauled by two similar locomotives could be taken across on any track, the adjacent track being unloaded when the roadway traffic is at its minimum, say between midnight and 5 a.m. Such trains would not cause greater stresses in the main girders than those for which they are designed.

These loadings are all fully set out in the Specification on which tenders are called.
MATERIAL AVAILABLE.

Steel manufactured in Australia:

Steel Works have been established at Lithgow and Newcastle and the policy of the State and Federal Governments is that as much of the material as can be manufactured in Australia should be so manufactured; consequently consideration had to be given to the possibility of manufacturing the steel in Australia.

Medium carbon steel and mild steel for rivets are being manufactured, the former rolled as flats up to 18 inches wide and angles, tees, rolled joists, channels and other shapes of various sizes. The Broken Hill Proprietary Company Limited have intimated that they do not intend to manufacture alloy steels or roll plates but that they will roll flats up to 30 inches wide if they receive orders for such steel for the construction of the Sydney Harbour Bridge. They have manufactured small ingots of silicon steel from which specimens have been cut and tested.

The Broken Hill Proprietary Company have a testing laboratory in which physical and chemical tests are made, but to have an independent investigation, the author arranged that a research into the physical and chemical properties should be undertaken at the Peter Nicol Russell School of Engineering of the Sydney University. This School has the best-equipped testing laboratory in Australia. The physical tests have the personal attention of Professor Warren, while the chemical analyses have been carried out by Assistant Professor Eastaugh.

The results of these tests indicated that steels made by the Broken Hill Proprietary Company at Newcastle (in July 1923) had the following physical and chemical properties:
### SUMMARY OF RESULTS OF TESTS MADE AT SYDNEY UNIVERSITY ON STEELS MANUFACTURED BY THE BROKEN HILL PROPRIETARY COMPANY LIMITED AT NEWCASTLE:

Physical Tests, each figure is the mean of Two Tests, except the Impact Test (mean of three), and the Modulus of Elasticity (one result).

<table>
<thead>
<tr>
<th>Description</th>
<th>Ultimate Stress</th>
<th>Apparent limit of elasticity</th>
<th>Contraction from auto. graphic diagrams</th>
<th>Total elongation on 8&quot;</th>
<th>Modulus of Elasticity lb. per sq. in. cent.</th>
<th>Impact test in lb.</th>
<th>Machine energy in ft.</th>
<th>C.</th>
<th>P.</th>
<th>Mn.</th>
<th>Si.</th>
<th>S.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Carbon Structural Steel.</strong></td>
<td>61,900</td>
<td>27.6</td>
<td>18.4</td>
<td>56.1</td>
<td>31.2</td>
<td>29,430,000</td>
<td>35.7</td>
<td>0.30</td>
<td>0.017</td>
<td>0.53</td>
<td>0.048</td>
<td>0.030</td>
</tr>
<tr>
<td><strong>High Carbon Structural Steel.</strong></td>
<td>93,300</td>
<td>41.6</td>
<td>22.8</td>
<td>40.6</td>
<td>20.2</td>
<td>29,430,000</td>
<td>8.0</td>
<td>0.43</td>
<td>0.016</td>
<td>0.54</td>
<td>0.15</td>
<td>0.026</td>
</tr>
<tr>
<td><strong>High Silicon Structural Steel.</strong></td>
<td>79,000</td>
<td>35.2</td>
<td>21.5</td>
<td>50.0</td>
<td>25.6</td>
<td>29,870,000</td>
<td>35.1</td>
<td>0.36</td>
<td>0.018</td>
<td>0.51</td>
<td>0.36</td>
<td>0.017</td>
</tr>
<tr>
<td><strong>Rivet Steel.</strong></td>
<td>49,300</td>
<td>22.0</td>
<td>14.4</td>
<td>64.4</td>
<td>35.1</td>
<td>29,880,000</td>
<td>57.3</td>
<td>0.18</td>
<td>0.012</td>
<td>0.41</td>
<td>0.042</td>
<td>0.024</td>
</tr>
</tbody>
</table>

The results of these tests show that the steel is very low in its Sulphur and Phosphorus contents, and that the physical test required can be attained.
Carbon Steel:

Ordinary rolled steel for bridge work is divided into three classes: soft, medium, and high carbon steel: but the exact limits are not accurately defined. Generally soft steel has an ultimate tensile strength of from 50,000 to 60,000 lbs. per sq. in., medium carbon steel from 60,000 to 70,000 lbs. per sq. in., and high carbon steel of 70,000 to 80,000 lbs. per sq. in. Soft steel is used for making rivets, and medium carbon steel for other bridge members. High carbon steel is used in eyebars, but for eyebars it has been largely replaced by alloy steel. High carbon steel is unsuitable for bridge members, as it is too brittle to withstand the various manipulations of fabrication. For bridge work carbon steel should not contain more than the following proportions of the elements named:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Rivet Steel Per Cent</th>
<th>All Other Steel Acid per cent</th>
<th>Basic per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.045</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.60</td>
<td>0.70</td>
<td>0.70</td>
</tr>
</tbody>
</table>

To meet the following specification as to the tensile properties the carbon contents shall be as small as possible in order that the material shall be as ductile as possible. Specimens cut from the finished material should conform to the following requirements.
<table>
<thead>
<tr>
<th>Material.</th>
<th>Ultimate tensile strength lbs. per sq. in.</th>
<th>Minimum yield point lbs. per sq. in.</th>
<th>Minimum elongation per cent in 8 in.</th>
<th>Minimum reduction of area per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates &amp; Shapes up to and including 1&quot; thick.</td>
<td>62,000 to 72,000</td>
<td>35,000</td>
<td>1,500,000 ultimate</td>
<td>40</td>
</tr>
<tr>
<td>Plates &amp; Shapes over 1&quot; thick.</td>
<td>62,000 to 72,000</td>
<td>33,000</td>
<td>22 per cent. 20 &quot; for sheared plates.</td>
<td>38</td>
</tr>
<tr>
<td>Eyestar Flats (unannealed).</td>
<td>66,000 to 76,000</td>
<td>35,000</td>
<td>22 per cent.</td>
<td>35</td>
</tr>
<tr>
<td>Rivets.</td>
<td>48,000 to 58,000</td>
<td>28,000</td>
<td>1,500,000 ultimate.</td>
<td>50</td>
</tr>
<tr>
<td>Pins &amp; Rollers (annealed).</td>
<td>65,000 to 75,000</td>
<td>35,000</td>
<td>22 per cent in 2 inches.</td>
<td>35</td>
</tr>
</tbody>
</table>

**Heat treated steel eyesteps.**

Recent research has shown that the metals are not the exceedingly stable products they are commonly thought to be and that physical treatment affects the properties of steel in a manner which could hardly be anticipated. The effect of heat treatment upon the tensile strength, yield point, elongation and ductility of steel is very marked, and curves showing ultimate strength and ductility over a large range of temperature reveal the existence of critical points; the material may be very ductile at a certain temperature, but if the temperature is raised some 70 degrees the material becomes brittle, if the temperature is still further raised it may again become ductile and again brittle. The effect of heat treatment appears to be that the particles in steel can be reduced in size and a finer grained and stronger material obtained.
In 1914 the American Bridge Company undertook a series of experiments to ascertain if it was possible to produce carbon steel eyebars with similar qualities to nickel steel eyebars but at a less cost. After considerable experimenting, eyebars with a minimum ultimate strength of 80,000 lbs. per sq. in., a minimum elastic limit of 50,000 lbs. per sq. in., and a minimum elongation of 8 per cent in 18 feet were produced. Eyebars to this specification were supplied for a number of important bridges. From the experience gained in manufacturing these heat treated eyebars it was decided to carry out another series of tests on full sized eyebars. The following table shows the result of testing eight eyebars each 12" x 2", the first four being 15' 1" centre to centre of pins, and the last four 33' 8" centre to centre.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Tensile Strength lb. per sq. in.</th>
<th>Elastic Limit lb. per sq. in.</th>
<th>Elongation per cent in 5 ft.</th>
<th>10 ft.</th>
<th>18 ft.</th>
<th>Reduction in area.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 5</td>
<td>113,900</td>
<td>76500</td>
<td>9.9</td>
<td>7.1</td>
<td>-</td>
<td>23.7</td>
</tr>
<tr>
<td>M 6</td>
<td>113,100</td>
<td>78000</td>
<td>11.9</td>
<td>9.2</td>
<td>-</td>
<td>29.3</td>
</tr>
<tr>
<td>M 7</td>
<td>125,100</td>
<td>84000</td>
<td>7.5</td>
<td>7.2</td>
<td>-</td>
<td>25.4</td>
</tr>
<tr>
<td>M 8</td>
<td>108,200</td>
<td>73700</td>
<td>5.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M 13</td>
<td>113,800</td>
<td>81100</td>
<td>9.2</td>
<td>-</td>
<td>6.9</td>
<td>15.5</td>
</tr>
<tr>
<td>M 14</td>
<td>126,800</td>
<td>86300</td>
<td>9.6</td>
<td>-</td>
<td>6.1</td>
<td>21.7</td>
</tr>
<tr>
<td>M 15</td>
<td>120,000</td>
<td>83500</td>
<td>8.9</td>
<td>-</td>
<td>6.3</td>
<td>16.5</td>
</tr>
<tr>
<td>M 16</td>
<td>132,600</td>
<td>89800</td>
<td>8.5</td>
<td>-</td>
<td>6.3</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Photographs of these eyebars (Plans Nos. 51-57 inclusive) showing the structure and character of the fracture, its position in the body of the bar, and in some instances, the angle of bend where fracture took place, were.

As a result of these experiments, the American Bridge Company have placed on the market carbon steel heat treated eyebars with a minimum ultimate strength of 105,000 lbs. per sq. in., a minimum elastic limit of 75,000 lbs. per sq. inch, and a minimum elongation in 18 ft.
of 5 per cent. These eyebars have a greater tensile strength than nickel steel eyebars, and at considerably less cost.

**Silicon Steel:**

Of recent years silicon steel has been used in several important bridges in America. It is made in a similar manner to carbon steel.

Silicon steel for bridge work shall not contain more than following proportions of the elements named:

<table>
<thead>
<tr>
<th>Element</th>
<th>Acid Per Cent</th>
<th>Basic Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus (maximum)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Silicon (minimum)</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Specimens cut from the finished product and tested in tension should show the following physical properties:

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Strength lbs. per sq. in.</th>
<th>Minimum yield point lb. per sq. in.</th>
<th>Minimum elongation per cent. in 2 in.</th>
<th>Minimum reduction of area per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates and Shapes</td>
<td>80,000 to 95,000.</td>
<td>45,000</td>
<td>1,600,000</td>
<td>35 Ultimate</td>
</tr>
</tbody>
</table>

**Alloy Steels:**

Research has also shown that small quantities of other metals added to steels
greatly increases their strength and durability. Sulphur and phosphorous detrimentally affect the properties of steel; nickel greatly increases its tensile strength; chromium increases its hardness and tends to render it non-corrosive; molybdenum and cobalt, carbon and silicon, add to its strength and hardness, and small quantities of these metals have a great effect on the properties of steel. The effect of the use of these alloy steels in long span bridge construction is apparent.

In the Specification besides carbon, silicon and heat treated carbon steels, nickel steel, chrome nickel steel, chrome nickel molybdenum steel, and cobalt nickel chrome steel can be made use of, provided these alloy steels have the physical and chemical properties outlined hereafter.

Nickel Steel.

The first use of nickel steel in a bridge of importance was the Blackwell's Island Bridge completed in 1909.

For Bridge Work Nickel Steel should have the following chemical composition.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Rivet Steel.</th>
<th>All Other Steel.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acid Per Cent.</td>
<td>Basic Per Cent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel (minimum).</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Phosphorous (maximum).</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.045</td>
<td>0.045</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Specimens cut from the finished material shall conform to the following physical requirements:
<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Strength</th>
<th>Minimum yield point</th>
<th>Minimum elongation per cent in 8 in.</th>
<th>Minimum reduction of area per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates and Shapes</td>
<td>55,000 to 100,000</td>
<td>50,000</td>
<td>1,600,000</td>
<td>40</td>
</tr>
<tr>
<td>Eyebar Flats (unannealed)</td>
<td>95,000 to 110,000</td>
<td>55,000</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Pins (annealed)</td>
<td>90,000 to 105,000</td>
<td>55,000</td>
<td>1,800,000</td>
<td>35</td>
</tr>
<tr>
<td>Rivet Steel</td>
<td>70,000 to 80,000</td>
<td>45,000</td>
<td>in 2 inches</td>
<td>40</td>
</tr>
</tbody>
</table>

Chrome Nickel Steel.

Chrome Nickel Steel can be made synthetically, but as a commercial product it is generally made from the naturally occurring Mayari ore which is mined in Cuba. By a slight modification of the open hearth process Mayari steel is manufactured without the necessity of adding alloying elements in the furnace or ladle.

It is necessary to test Mayari steel more thoroughly than a synthetic steel.

Chrome nickel steel is made with the following chemical composition:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Acid Per Cent.</th>
<th>Basic per cent.</th>
<th>Acid Per Cent.</th>
<th>Basic Per Cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese (maximum)</td>
<td>0.60</td>
<td>0.60</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.04</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.045</td>
<td>0.045</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.30</td>
<td>0.30</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Nickel (minimum)</td>
<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
</tr>
</tbody>
</table>
In addition to the above, chrome nickel steel may contain such percentages of chromium, vanadium, or other metals as may be necessary to meet the physical requirements set out in the next table. Steel containing not more than 3 per cent of nickel may contain up to 0.45 per cent carbon.

Specimens cut from the finished products should conform to the following physical requirements:

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Strength lbs. per sq. in.</th>
<th>Minimum yield point lbs. per sq. in.</th>
<th>Minimum elongation per cent in 8 in.</th>
<th>Minimum reduction of area per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates and Shapes up to</td>
<td>85,000 to 100,000</td>
<td>50,000</td>
<td>1,600,000</td>
<td>30</td>
</tr>
<tr>
<td>and including 1&quot; thick.</td>
<td></td>
<td></td>
<td>ultimate</td>
<td></td>
</tr>
<tr>
<td>Plates and Shapes over 1&quot; thick.</td>
<td>85,000 to 100,000</td>
<td>50,000</td>
<td>A</td>
<td>8</td>
</tr>
<tr>
<td>Eyebar Steel (annealed).</td>
<td>95,000 to 110,000</td>
<td>55,000</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Rivet Steel.</td>
<td>70,000 to 80,000</td>
<td>45,000</td>
<td>1,600,000</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ultimate</td>
<td></td>
</tr>
</tbody>
</table>

(A). Elongation per cent, ultimate less 1 per cent for each 1/16" or fraction above one inch, minimum 14 per cent.

(B). Percentage reduction, 30 less 2 for each 1/16" or fraction above one inch, minimum 24 per cent.

Cobalt Nickel Chrome Steel.

In Europe cobalt nickel chrome steel has been produced from a naturally occurring ore, but owing to the unrest in Europe this steel is not likely to be manufactured.
The ore is difficult to smelt and requires a special type of open hearth furnace. The following table shows the chemical analyses of the ore and steel produced. The chemical analysis of the steel is the mean of four different casts.

<table>
<thead>
<tr>
<th>IRON ORE</th>
<th>CHEMICAL ANALYSES</th>
<th>STEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore as received</td>
<td>Per Cent.</td>
<td>Carbon</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.23</td>
<td>Manganese</td>
</tr>
<tr>
<td>Chromium</td>
<td>2.35</td>
<td>Silicon</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.90</td>
<td>Sulphur</td>
</tr>
<tr>
<td>Cobalt</td>
<td>12.32</td>
<td>Phosphorous</td>
</tr>
<tr>
<td>Silica</td>
<td>9.25</td>
<td>Nickel</td>
</tr>
<tr>
<td>Alumina</td>
<td>6.65</td>
<td>Chromium</td>
</tr>
<tr>
<td>Lime</td>
<td>2.14</td>
<td>Cobalt</td>
</tr>
<tr>
<td>Magnesia</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Phosphorous</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TENSILE TESTS.**

Mean of specimens taken from four different casts:

- Ultimate Strength, Lbs. per sq. in. 127,500
- Yield Point, Lbs. per sq. in. 72,150
- Elongation in two inches per cent. 12.6
- Contraction of area, per cent. 22.6

**Chrome Nickel Molybdenum Steel.**

Since the termination of the war a chrome nickel molybdenum steel has been placed on the market by Sir William Armstrong Whitworth & Company, who call it Vibrac Steel. It is claimed that this steel is very ductile having a much higher impact value than nickel or chrome nickel steels; also very high ultimate strength and elastic limit.

To investigate its chemical composition and physical properties, samples were submitted and tested at Sydney University. The results of these tests given in the following table show that the properties of Vibrac Steel were as stated, and if the price is not too
high will be a valuable addition to the alloy steel used for long span bridge construction.

RESULTS OF TESTS MADE ON VIBRAC STEEL AT SYDNEY UNIVERSITY.

<table>
<thead>
<tr>
<th>Description</th>
<th>Physical Properties</th>
<th>Chemical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Stress</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lbs. per Tons per sq. in.</td>
<td>Impact Test in Izod ft-lb. lbers.</td>
</tr>
<tr>
<td></td>
<td>Apparent limit of elasticity from autographic diagrams. Tons per sq. in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction of area. Per Cent.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total elongation per cent on 8 inches.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modulus of elasticity. lbs. per sq. in.</td>
<td></td>
</tr>
<tr>
<td>Plate 1 Across Grain</td>
<td>133,500 59.6 51.2 34 12 28,900,000 0.34 0.10 0.25 0.16 0.54 0.51 2.49 0.59</td>
<td></td>
</tr>
<tr>
<td>Plate 2 With the Grain</td>
<td>126,600 56.5 49.3 50 13 28,900,000 0.33 0.12 0.25 0.14 0.54 0.52 2.43 0.57</td>
<td></td>
</tr>
<tr>
<td>Plate 2 Across Grain</td>
<td>126,000 56.2 49.3 43 8 0.33 0.12 0.25 0.14 0.54 0.52 2.43 0.57</td>
<td></td>
</tr>
<tr>
<td>Plate 1 With the Grain</td>
<td>123,900 55.3 48.6 54 12 0.34 0.10 0.25 0.16 0.54 0.51 2.49 0.59</td>
<td></td>
</tr>
</tbody>
</table>

The selection of materials for a structure of this magnitude is a very important part of the design and the highest quality of material obtainable - consistent with cost - should be used.

The steel must have a high elastic limit, a high ultimate strength, be ductile as indicated by the elongation and by the reduction in area of the specimens tested. Ductili-
ty is necessary in order that the steel may withstand the various manipulations without injury during fabrication.

In Sydney an intense cold is not experienced, therefore high carbon steel and heat treated steels can be used without the fear that their brittleness would be increased during an extremely cold winter.

With the steel now available reliance can be placed on the quality of the material being uniform and therefore working stresses can be used with confidence proportionately higher than would be permissible with ordinary commercial steels.

Ordinary carbon steel eyebars can be made with a guaranteed minimum elastic limit of 30,000 lbs. per sq. in., heat treated carbon steel eyebars 75,000 lbs. per sq. in., and nickel and chrome nickel steel eyebars with a minimum elastic limit of 47,000 lbs. per sq. in; the working stresses in these eyebars are 20,000, 45,000 and 29,000 lbs. per sq. in. respectively whereas the working stress in riveted tension members of carbon steel is 18,000 lbs. per sq. in. The working stress for riveted tension members of silicon steel is 23,500 lbs. per sq. in., of nickel or chrome nickel steel 26,100 lbs. per sq. in. and of chrome nickel molybdenum steel 31,500 lbs. per sq. in.

These working stresses allow an ample margin of safety under the worst possible combination of loading.

After the failure of the Phoenix Quebec Bridge, the Board of Engineers carried out a number of tests to determine the ultimate strength of models of some of the typical nickel steel compression members and still more recently, the Bureau of Standards of the United States of America in collaboration with the American Bridge Company and the Pennsylvania Steel Company have made a complete investigation of a number of nickel, chrome nickel, silicon, chrome and high carbon steel columns.
In these tests the behaviour under loads and the distribution of stress throughout the member, and the details were analysed, the specimens representing typical compression members for three bridges of long span recently erected in America.

From the results of these tests the following unit stresses over the gross section for compression members of the Sydney Harbour Bridge were determined:

<table>
<thead>
<tr>
<th>Material</th>
<th>Allowable Stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel</td>
<td></td>
</tr>
<tr>
<td>less than 50</td>
<td>14,000 lbs. per sq in.</td>
</tr>
<tr>
<td>over 50 and less</td>
<td></td>
</tr>
<tr>
<td>than 100</td>
<td>18,000 lbs. per sq in.</td>
</tr>
<tr>
<td>Silicon Steel</td>
<td></td>
</tr>
<tr>
<td>less than 50</td>
<td>17,500 lbs. per sq in.</td>
</tr>
<tr>
<td>over 50 and less</td>
<td></td>
</tr>
<tr>
<td>than 100</td>
<td>22,500 lbs. per sq in.</td>
</tr>
<tr>
<td>Nickel or Chrome</td>
<td></td>
</tr>
<tr>
<td>Nickel Steel</td>
<td></td>
</tr>
<tr>
<td>less than 50</td>
<td>19,600 lbs. per sq in.</td>
</tr>
<tr>
<td>over 50 and less</td>
<td></td>
</tr>
<tr>
<td>than 100</td>
<td>25,200 lbs. per sq in.</td>
</tr>
<tr>
<td>Chrome Molybdenum Steel</td>
<td></td>
</tr>
<tr>
<td>less than 50</td>
<td>22,400 lbs. per sq in.</td>
</tr>
<tr>
<td>over 50 and less</td>
<td></td>
</tr>
<tr>
<td>than 100</td>
<td>28,000 lbs. per sq in.</td>
</tr>
</tbody>
</table>

While the design is being worked out in detail model tests of typical compression members will be made and it is expected that when corrected for slenderness ratio and bending stress due to weight of the member, the following minimum requirements will be attained:

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel</td>
<td>25,000 lbs. per sq in.</td>
</tr>
<tr>
<td>Elastic limit</td>
<td></td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>35,000 lbs. per sq in.</td>
</tr>
<tr>
<td>Nickel or Chrome Nickel Steel</td>
<td>41,000 lbs. per sq in.</td>
</tr>
<tr>
<td>Elastic limit</td>
<td></td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>52,000 lbs. per sq in.</td>
</tr>
</tbody>
</table>
Should the tests not reach these minimum requirements the design of the member itself would be modified or lower unit stresses would be required.

However, from the tests above referred to, it is not anticipated that difficulty will be experienced in conforming with the above unit stresses, which would allow ample factor of safety on the elastic limit of the column as a whole.

The choice of the steel to be used in the various members of the Sydney Harbour Bridge needs a careful study of the economics of the structure.

This choice is governed by:

1. The unit prices of the various classes of steel.
2. The effect of individual members on the dead load stresses throughout the structure.
3. The size of sections in the make up of individual members considered from the viewpoint of sizes obtainable and the type of cross section of member which can be designed with these sections.
4. The weight of individual members as affecting fabrication and erection of these members.

Speaking generally, nickel steel has been adopted throughout the cantilever arms and suspended span, while carbon steel has been chosen for the anchor arm, except some of the top chord eyebars near the main post. Here the large stresses would have required an unduly large number of carbon steel eyebars, thus complicating connections or necessitating three rows of eyebars which was regarded as inadvisable.

The use of nickel steel in the channel span kept down the dead load stresses, and enables an economic scheme of erection to be designed.

Carbon steel in the anchor arms reduced the cost, as owing to the configuration of the approaches, it is most likely that the anchor arms will be erected on falsework and the large bottom chord sections can be erected with comparative ease.
Carbon steel in the anchor arm is of advantage in that the increased weight of the anchor arm reduces the uplift on the anchor pier and consequently saves masonry. Also the dead load stresses in the top and bottom chords of the anchor arms are reduced, but the dead load shears carried by the web members and the reaction on the main pier are increased.

With regard to the anchor arms the total increase in weight of the web members is probably as great as the total reduction of weight of the chords due to the use of carbon steel.

From a critical review of the design of the Sydney Harbour Bridge it is concluded that the types of steel used for the respective members gives the most economic result from the point of view of total cost and ease of erection.
SYDNEY HARBOUR BRIDGE.

Types of Superstructure.

In the design of a long span bridge for a great metropolis, the premier considerations are utility of purpose, and convenience for traffic of all kinds, both over the bridge and under it, combined with economical investigation of first cost, maintenance and revenue. Having investigated the location, foundations, headway, and the loading which the Bridge will eventually have to carry, and knowing the various steels available for construction, the next determination is the type of superstructure. In this connection there are not only the purely technical considerations of cost and maintenance as regards the type of bridge, but also aesthetic considerations on account of the proximity of the structure with the city as a whole, and with the surrounding landscape.

The chief desiderata for a long span bridge are:

- The bridge shall have the maximum amount of rigidity vertically under the rolling load, and laterally under wind pressure, so that by its freedom from vibration - either when carrying its congested daily traffic or when resisting the force of a raging gale - it may gain the confidence of the public and enjoy the reputation of being the most rigid and strongest bridge in the world.

- The bridge shall be simple to erect and safe during all stages of erection, so that at any time the incomplete structure will be as secure against a hurricane as the completed bridge.

- No untried material shall be used in its construction.

- The maximum economy must be obtained consistent with the ultimate usefulness of the Bridge and with the preceding conditions, utility of purpose to be leavened but not dominated
by aesthetic considerations.

Long Span Bridges may be classified as under:

**Simple Spans:**

Forty years ago, the Simple Span Truss generally in vogue in America was a double intersection Pratt Truss with parallel chords; twenty years later, and up to the present, the type most used is a single intersection Pratt Truss with subdivided panels and a curved top chord, this latter making for economy, whilst the stresses are more definite.

A Simple Truss Bridge is a more rigid bridge than either a Suspension Bridge or a Cantilever Bridge, for when the span is loaded it exerts no upward force on adjacent spans as occurs in a Cantilever system, or on other portions of the same span as in a Suspension Bridge. The Simple Span, however, must be either erected in position or on falsework which, across Sydney Harbour, would be extremely costly on account of foundations, and quite inadmissible on account of navigation, or the bridge would have to be floated into position and placed on its bearings as the tide fell, but because of the headway required, 170 feet, this would be impracticable on account of the risk and cost.

With each advance in the production of higher grade steels and in shop and field methods the length of Simple Spans has grown year by year. In 1889, the Hawkesbury River Bridge was completed with a simple span of 412 feet. In 1891, the Cairo single track railway Bridge had a simple span of 518 feet; the Municipal Bridge in St. Louis, U.S.A., has three simple spans of 666 feet, carrying a double track railway and roadways. The Metropolis Bridge over the Ohio River, U.S.A., was designed for a double track Simple Span of 720 feet. No absolute ruling can be given as to the length at which the Simple Span becomes economical compared with the Cantilever Span.

With the higher grades of steel now available - heat-treated carbon and alloy steels -
about 800 feet may be taken as the absolute limit beyond which it would not be ad-
visable to go without thoroughly investigating the relative merits of a Simple Truss Span
and a Cantilever Bridge, and there are very few, if any, locations in which a simple span
of this magnitude could be erected, as the location and method required for erection would
probably necessitate a shorter span or a cantilever bridge. If a Simple Span is erected on
the cantilever principle, generally a considerable amount of metal, both in the span to be
erected and in adjacent spans used in its erection, has to be employed for erection purposes
alone. This metal is useless after erection is complete, and generally would make the cost
of a Simple Span greater than a Cantilever Bridge.

The practical limit of a Simple Span may, therefore, be taken as about 700 feet; al-
though when, as in the suspended span of a Cantilever Bridge, the central span could be lift-
ed into place, a longer span up to 800 feet could be employed.

The bending moment in a beam is a function of the square of its length, and on this
account there is often a mistaken conception that the weight of steel in a span is also in
proportion to the square of its length. It is in a measure true for spans up to 250 or 300
feet, but the ratio of increase increases with the span. Between 300 and 1,100 feet the in-
crease in weight is constantly increasing, until at about 1,200 feet a span increases in
weight approximately as the cube of the length. Above 1200 feet this exponent increases
much more rapidly until, at from 1800 to 2000 feet, the weight of carbon steel required for
the dead load and a moderate live load becomes infinite. Simple Span Bridges constructed
of nickel steel and chrome nickel steels would require an infinite weight of steel for spans
of approximately 2,500 to 2,700 feet; whilst with the most recent heat-treated alloy steels
with a span of 3,000 feet or thereabouts the weight of steel required would be infinite.
Simple Spans above 800 feet would be uneconomical and impracticable of erection.
A bridge across the Harbour from Dawes' Point to Milson's Point could be constructed in two spans of 800 feet each, with a pier in the fairway. A centre pier is not admissible on account of the requirements of navigation, and the staging required to erect a Simple Span would not only be costly, but almost impracticable, on account of the foundations and interference of navigation, therefore, a bridge of two such Simple Spans would not be adopted.

**Suspension Bridges:**

The statical action of the Suspension Bridge is as follows:

The loads applied to the floor are transmitted through hangers to long continuous cables passing over main towers at the ends of the channel span, and thence to massive anchorages, whose mass resists the tension of the cable. As the cable passes over the main towers a vertical load is applied at each tower cap, and transmitted thence through the towers to the foundations of the main piers as a vertical pressure.

As a moving load comes on the span, it produces a downward deflection of the cable in the immediate neighbourhood of the load and tends to produce an upward deflection of the more remote parts of the cable. This tendency of the cable to distort from its position of dead load equilibrium has nothing to resist it in the simplest type but the very light mass of the cable and floor, hence a continuous wave motion of large proportions is produced in the cable and floor as the load advances. To overcome this lack of rigidity the system is stiffened, either by the introduction of a horizontal stiffening truss along the floor line, or by bracing the cable itself by means of a truss. There is no known method of bracing a wire cable satisfactorily, but if, as has been proposed in modern designs for very large spans of over 3,000 feet, the cable is composed of a chain of eyebars, such a bracing system is possible. Stiffened eyebar cable Suspension Bridges then develop into nothing more or
less than inverted braced. Arches having, however, far less rigidity than the arch proper, and a less satisfactory appearance.

The usual practice, then, with a cable Suspension Bridge, is to use the stiffening truss along the line of the floor. This truss distributes any load applied in the floor to a longer length of cable, the length of the portion depending on the rigidity of the truss, and by this means the rigidity of the whole structure is increased sufficiently to enable its adoption as a highway or railway bridge carrying heavy traffic. A number of very long spans have been bridged on this method, the most notable being three over the East River, New York, viz:—

Brooklyn Bridge - Span 1695' 6" - Open to Traffic 1883. Plate No. 58.
Present Traffic 2 tracks light electric railway, 2 tracks trolley cars, 2 roadways 16'9" wide, 1 footway 15 ft. wide, Total load 2380 lbs/ft.

Williamsburg Bridge - Span 1600' - Open to Traffic 1903. Plate No. 59.
Present Traffic 2 tracks light electric railway, 4 tracks trolley cars, 2 roadways 20' wide, 2 footways 17'8" wide, Total, 5,700 lbs/ft.

Manhattan Bridge - Span 1470' - Open to Traffic 1909. Plate No. 60.
Present Traffic 2 tracks light electric railway, 2 tracks trolley cars, 1 roadway 35' wide, 1 roadway 23' wide, 2 footways 13'7" wide, Total, 5320 lbs/ft.

Another large Suspension Bridge is now under erection over the Delaware River, U.S.A., between Philadelphia, Pa., and Camden, N.J., span 1750 ft., to carry 6000 lbs. per lin. ft. of bridge, including ultimately, two electric railway tracks. The proposed Detroit-River Bridge is to be a Suspension Bridge of 1805 feet span carrying highway traffic only.
It is important to note that in each of the above cases the load approximates to a uniform load spread over the whole length of the structure, a condition for which Suspension Bridges are more suitable.

In the Quebec Bridge of 1800 ft. span the economic limit of cantilever construction has been very nearly reached, though with the steels now at the disposal of the Engineer, spans up to 2000 ft. or slightly over are quite practicable.

If economy alone had been considered a Cable Suspension Bridge at Quebec would have been somewhat cheaper than the Cantilever Bridge of 1800 ft. span, but the Cantilever Bridge of 1800 ft. span, but the Cantilever type has a much greater rigidity under moving load and temperature. Comparisons were made for the Quebec Bridge, and the estimated deflections were as under:

<table>
<thead>
<tr>
<th>Design</th>
<th>Cantilever Design</th>
<th>Suspension Design live load only</th>
<th>Suspension Design live load and temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection</td>
<td>11(\frac{3}{4}) inches.</td>
<td>2 feet.</td>
<td>7 feet.</td>
</tr>
</tbody>
</table>

There are two reasons for the greater deflections of Suspension Bridges:

(a). The up and down movement due to temperature in the cables of a suspension span, which in a cantilever bridge is horizontal.

(b). The fact that higher unit stresses are allowed in the wires of the cable than in the members of the cantilever. The unit working stresses in the steel wires of the cables may be 60,000 lbs. per sq. inch, but in the members of the cantilever bridge from 12,000 to 20,000 lbs. per sq. inch if the material is ordinary carbon steel. One of the fundamental laws of the mechanics of materials is the proportionality of stress and strain and with three times the working stress, the extension in the cables must be approximately three times as great, in obedience
to Hooke's Law, "Ut tensio sic vis."

When a moving load travels over a Suspension Bridge it subjects it to partial deflections which may be compared to a wave motion. This motion is obviated by the use of stiffening trusses, and the deeper the truss the smaller the deflection. It is advantageous to make these stiffening trusses as deep as practical considerations will permit, but the deeper the truss the more equalizing it will perform and, therefore, the heavier it will have to be.

A Suspension Bridge generally consists of a main span and two side spans; there are two types of side spans, one when the side spans are hung from the cables as in the Manhattan Bridge and one when they are supported independently of the cables, as in the Williamsburg Bridge. There are also two types of stiffening trusses for the main span, a continuous truss as in the Manhattan Bridge and the bridge now being erected across the Delaware River, Philadelphia, and a truss hinged at one or more points, as in the Brooklyn Bridge.

For a bridge to carry highway, tramway, and light electric railway traffic, the most suitable type of Suspension Bridge would have comparatively shallow stiffening girders, continuous over the main span, with side spans suspended from the cables, because there would, with this class of traffic, be no moving loads heavy enough to cause appreciable local deflection.

If the Suspension Bridge is to carry heavy railway traffic it should have deep stiffening trusses over the centre span, the depth of truss would be about 1/40th of the length of the centre span, whilst the side spans should be supported independently of the cables. For long span bridges over 2200 feet for heavy railway traffic, the Suspension type only is practicable, and, provided the stiffening trusses over the centre span are deep enough, and the side spans are not suspended from the cables, it is perfectly practicable to build a suitable Suspension Bridge for heavy railway traffic of such dimensions.
Suspension bridges of very long spans are practicable, where Cantilever spans are not practicable, because of the greater ultimate strength of wire cables, compared with fabricated steel plates and shapes forming the members of the Cantilever design.

The maximum limiting span for a wire cable Suspension Bridge has been calculated to be 4,335 feet, with an ultimate strength of steel wire at 180,000 lbs. per sq. inch, and a working stress of 60,000 lbs. per sq. inch.

With later alloy steels Suspension spans up to 5,000 ft. are feasible. With steel wire cables of the above strength, with a versed sine of 1/6th the span - which is the most suitable sag for the cable - the limiting length of a cable is 15,160 ft., i.e., the theoretical span at which a wire cable of the above material would break under its own weight.

An eyebar chain of alloy steel with a working stress of 30,000 lb. per sq. inch and a versine of 1/6th of span would have a limiting span of 7,010 feet, i.e., under these conditions would break under its own weight. Hence the limit of span length for an eyebar chain suspension bridge to carry live loads is considerably below that of a cable suspension bridge.

With heat-treated carbon steel eyebars as recently manufactured, with an elastic limit of 75,000 lb. where a working stress of 45,000 lb. may be allowed, the limiting span would be about 10,000 feet.

The Manhattan Bridge of 1,470 ft. span under the maximum loading of 16,000 lb. per ft., for which it was designed, would have a centre deflection due to live load and temperature of 11.66 ft., whilst under the loading of 12,000 lb. per foot the deflection would be 9.02 feet.

A straight wire suspension bridge of 1,600 feet span designed for a load of 12,000 lb. per ft., the maximum loaded length 1,100 ft., 66% of which consists of main line heavy electric railway loading with heavy concentrated loads due to locomotives, would have a centre deflection of 12.72 ft. due to live load and temperature, assuming the sag of the cable to be 1/6th of the
span, a unit stress of 60,000 lb. per sq. in. in the cables, and a range of temperature of 120 degrees.

The detailed calculations are as follows:

**Span:** 1,600 ft. centres of towers.

**Sag of Cable:** 200 ft.

**Depth of Stiffening Truss:** 40 ft.

**Range of Temperature:** 120 deg. F.

**Permissible Cable Stress:** 60,000 lugs. sq. in.

**Other Permissible Stresses and Loading:** As in Sydney Harbour Bridge Specifications.

Assume stiffening truss horizontal, hinged at towers; side spans 700 ft., suspended; sag of side span cable = 50 ft. Two stiffening trusses only.

**Length of Cable:**

**Main Span BE:**

Origin at A,

Equation is \[ y = \frac{4f}{l^2} (l - x) \]

When \[ x = 12 \], \[ y = 5.955 \]

Then \[ f = 194.045 \].

Length \[ s = l \left( 1 + \frac{8}{3} n^2 - \frac{8}{5} n \right) \] where \[ n = \frac{f}{l} = 123125 \].

\[ s = 1576 \times 1.03896 = 1637.4 \text{ ft.} \]
SIDE SPANS CD.

Origin at A, Equation is \[ y = \frac{4f'}{l} x (1-x) \]

Length \[ S' = \frac{1}{L} \left\{ 1 + \frac{3}{8} n_1^2 - \frac{32}{8} n_1^4 + \frac{1}{2} (1 - 8 n_1^2) \tan \alpha - \frac{1}{8} \tan^4 \alpha \right\} \]

where \( n_1' = \frac{f'}{L} = 0.0727, \tan \alpha = 0.3402 \)

Then \[ = \frac{688 \times 1.0575}{2} = 734.5 \text{ ft.} \]

Saddle at Tower BC. 40.0
Saddle at Anchor EF. 40.0
End of Truss to Saddle DE. 20.0
Saddle to Anchorage FG. 60.0

\[ 894.5 \times 2 = 1789.0 \text{ ft.} \]

\[ 3426.4 \text{ ft.} \]

LENGTH \( S \) say 3400 feet.

DEAD LOAD ASSUMPTIONS:

Wts. per ft. per truss. lbs.
Truss 3,290
Wind Trusses 570
Floor 7,700
Cables 2,050
Hangers 240

13,850 lbs/ft. per truss.
Average Area of chord of stiffening truss = 214 + 46 = 260 sq. in. Nickel Steel (say).

Area of Cable = 580 sq. ins. (say).

Then we have for \( H \), the horizontal component of cable stress towers:

**Dead Load.**

\[
H = \frac{13,850 \times 1576 \times 1576}{8 \times 194.045} = 22,150,000 \text{ lbs.}
\]

**Live Load.**

The influence line for \( H \) may be assumed to be a parabola as shown, and the stiffening truss to be very stiff, so that deformations of the truss do not affect the general form of the structure.

Here \( z = \frac{3L^3}{16h^2} \), where \( \nu = \frac{1}{1 + \frac{15h^2}{16F_k} \frac{F_c}{F_k}} \)

where \( h \) = depth of truss

\( F_c \) = Chord Area

\( F_k \) = Cable Area.

Here \( \frac{F_c}{F_k} = \frac{260}{580} = .488 \)

\[
\nu' = \frac{1}{1 + \frac{16 \times 40 \times 40 \times 3400 \times .4490}{16 \times 194.045 \times 194.045 \times 1576}} = .964
\]

\[
z = \frac{3 \times 1576 \times .964}{16 \times 194.045} = 1.470
\]

Equation of \( H \) is \( H = \frac{3x(1576 - x)}{4 \times 194.045 \times 1576} \cdot .966 \)

or \( H = .003736x - .00000237x^2 \).
Then for load of 6,600 lbs/ft (Live Load and Impact), between 238 and 1338 ft.

\[
\text{Area} = \int_{238}^{1338} \left(0.003756x - 0.00000237x^3\right) dx
= \left(0.001968x^2 - 0.00000079x^3\right)_{238}^{1338}
= 1450 - 95 = 1355
\]

\[
H = 1355 \times 6600 = 8,940,000 \text{ lbs.}
\]

\[\text{Temperature:}\]

\[
H = -\varepsilon Ec_k(1 - \nu)
\]

\[
H = -0.0000061 \times 29,000,000 \times 60 \times 580 \times 0.0345
= -212,000 \text{ lbs.}
\]

\[
\text{Total } H
\]

\[
H = 22,150,000
\]

\[
8,940,000
\]

\[
212,000
\]

\[
31,302,000 \text{ lbs.}
\]

\[\text{TOTAL TENSION IN CABLES:}\]

\[
T_c = \frac{w'l^2}{8T} \sqrt{1 + \frac{16t^2}{l^2}}
\]

\[
= \frac{13,850 \times 1600 \times 1600}{8 \times 200} \sqrt{1 + \frac{16 \times 200 \times 200}{1600 \times 1600}}
= 24,800,000 \text{ lbs/}
\]

\[
T = \frac{24,800,000}{22,150,000} = 1.118.
\]

\[
\text{Total } T
\]

\[
1.118 \times 31,302,000 = 35,000,000 \text{ lbs.}
\]

\[
\text{Area of cable} = \frac{35,000,000}{60,000} = 583 \text{ sq. ins.}
\]
AVERAGE CHORD:

The average chord of the stiffening truss will occur at the mid-point of the span.

Influence Line for Moment.

In this diagram we have for \( x \):

\[
\begin{align*}
H/ & \quad y = 0.003756x - 0.00002370x^2 \\
V/ & \quad y = 0.002570x \\
\sigma & = 0.001166x - 0.0000237x^2 \\
x & = \frac{0.001166}{0.0000237} = 492 \text{ ft.}
\end{align*}
\]

Total Area

Parabola/ \( A = \left(0.001166x^2 - 0.00002370x^3\right)_0 \)

\[= (4641 - 3085)\]

\[= 1556\]

Triangle/ \( A = \frac{-2.028 \times 1576}{2} = -1598\)

Total \( = -43\).
LIVE LOAD MOMENT:

Side Areas

Parabola/ \[ A = (0.00128x^2 - 0.0000073x^3) \text{ in}^2 \]

= (451 - 94) = 357

Triangle/ \[ A = -\frac{492 \times 2.025 \times 492}{2} \]

= -316

Total = 441

ve/ Total Live Load Area = -43 - 2 x 41 = -125

Moment = 125 x 6,600 x 194.045 = 16,000,000 lbs/ft.

Area of chord = \[ \frac{16,000,000}{40 \times 25,100} \]

= 155.2 in. Steel

+ ve/ Total Live Load Area = +41

Moment = 41 x 6,600 x 194.045 = 5,250,000 lbs/ft.

Area of chord = \[ \frac{5,250,000}{40 \times 25,100} \]

= 50.4 in. Steel

TOTAL AREA = 213.6 in. Nickel Steel.

allowing 10" for minor stress.

----------------------------------------
**AVERAGE WEB:**

The average diagonal will be assumed to occur at the centre of span.

52 panels at 30.31' = 1576' approximately.

sec. $\theta = \frac{50.2}{40} = 1.255$

Shear at centre $= \frac{6600 \times 1576}{8} = 1,300,000$ lbs.

Allowing for complete reversal,

Area of diagonal $= \frac{1,300,000 \times 1.255}{26,100} \times 2$

= 125" Nickel Steel.

**VERTICALS:**

Say 19" Carbon Steel

**WEIGHT OF STIFFENING TRUSS:**

Chords (2) $= 2 \times 3.4 \times 204 = 1365$ lbs/ft.

Diagonals $= 3.4 \times 30.31 \times 125 = 704$ lbs/ft.

Verticals $= \frac{4}{3} \times 3 \times 3.4 \times 19 = 45$ lbs/ft.

Details 55%

2132 lbs/ft

1170 lbs/ft

3302 lbs/ft

------------------
WIND SYSTEM:

Areas exposed per ft.  
Floor \(\frac{1}{2} \times 5\) = 7.5 sq. ft.

Truss \(= \frac{2}{50} (2 \times 50 \times 3 + 50 \times 2\) = 27.5 sq. ft.

Load \(= 27.5 \times 30\) = 825 lbs/ft.

Train Load = 300 lbs/ft.

1125 lbs/ft. of bridge.

Then average chord stress

\[
\frac{1125 \times 1576}{12 \times 93} = \frac{2,375,000}{25,100}
\]

= 91 sq. ins. Nickel Steel.

Average area of combined chord

WEIGHT OF WIND SYSTEM:

Weight \(= 1.65 \times 3.4 \times 91\) = 572 lbs/ft. of bridge (85% details).

WEIGHT OF CABLES:

Weight \(= 3.4 \times 563 \times 1637\) = 2060 lbs/ft. of bridge.

SUSPENDERS:

Weight = say 240 lbs/ft. of bridge.
DEFLECTION AT MID POINT:

Live Load.

Moment of Inertia of Stiffening Truss

\[ I = \frac{5}{394} \times \frac{1}{1^2} \left( \frac{p}{p} - \frac{8FH}{1^2} \right) \]

\[ = \frac{5}{394} \times \frac{1576^4}{29,000,000 \times 208,000} \times \frac{8 \times 194.045 \times 8,940,000}{1576^2} \]

\[ = 13.28 \text{ ft.} \]

Temperature.

With highest temperature,

\[ H = -212,000 \text{ lbs.} \]

Now \( H = -\{E_h \times \frac{l_t}{100} \} \)

Also \( H = \{E_h \times \left( \frac{I \times L_t}{D_{52}} \right) \} \)

---------- (Johnson, Bryan & Turnbull, Vol. II).

Hence \( \frac{I \times L_t}{D_{52}} = F_k(l - y) = 580 \times .056 = 20.85 \)

or \( \frac{L_t}{D_{52}} = 20.85 \times 208,000 = .0001002 \)

Then \( \frac{l_t}{D_{52}} = \frac{50 \times 194.045 \times 1576^2 \times .0000061 \times 60 \times .0001002}{48} \)

\[ = 1.84 \text{ ft.} \]

Total Live Load + Temperature = 15.12 ft.

On an Exact Method, taking into account the deformations of the Stiffening Truss, we have:

Live Load = .84 x 13.28 = 11.17 ft.

Total Live Load + Temperature = 12.72 ft.
In order to fully appreciate the significance of the value allotted to temperature deflection at the centre of the bridge, it is necessary to investigate the statical conditions of the structure.

The cable CABD is stressed primarily by the dead load of the structure, which is so arranged during erection that the cable takes all the dead load, whilst the stiffening truss is unstressed. Hence for all conditions of stress we have the basic fact that the cable has an initial stress and an initial strain of large proportions before the application of the load.

Live load on the channel span now increases the stress in the cable, as measured by the horizontal component $H$, and thus produces a further sag in the cable, amounting to a maximum of 13.25 ft. at E. This deflection is calculated on the assumption that the stiffening truss is very rigid or that its deformations have no effect on the form of the structure as a whole. In order to determine the exact deflection at E it would be necessary to know in detail the sectional areas of the truss members and of the cables, and with other statical data which would necessitate a big staff and a long time to properly determine.

If we now assume that there is no live load on the bridge, but that the temperature rises by 60° F, there are two aspects of this problem. In the first place, the cable between A and B tends to increase in length and thus tends to sag considerably. This tendency now acts in such a manner as to throw a proportion of the dead load upon the stiffening truss, thereby relieving the cable of a certain amount of stress. This effect is demonstrated by the negative sign given to $H$. 
for temperature (\( E = -212,000 \text{ lbs.} \)). The cable, now relieved of some of its dead load, tends to contract and the centre to rise. Hence we have two counterbalancing effects produced by the temperature rise, the sum total being a small downward deflection at \( E \) for a rise, and a small upward deflection for a fall in temperature. The deflection for 60° \( F \) rise in temperature is 1.24 feet.

If the cable is rigidly fixed to the tops of the towers, the towers must move under the action of temperature, either in bending, or by rotation about a hinge at the base. It is important to regard the movement of the tower tops as an effect of the deflection of the structure, and not as cause of it. With suspended side spans the tower tops move outwards for a rise in temperature, contrary to first glance expectations. This movement of the tower tops has no bearing on the deformation of the cable.

The corresponding deflections for the Manhattan Bridge (calculated on similar assumptions) for a live load of 16,000 lbs/ft. on four trusses are:

\[
\text{Live Load} \quad 15.03 \text{ ft.} \\
\text{Temperature} \quad 2.12 \quad (\text{55°F}) \quad 15.03 \quad 2.12 = 7.41
\]

**SYDNEY HARBOUR BRIDGE** 12,000 lbs/ft on two trusses

\[
\text{Live load} \quad 13.28 \text{ ft.} \\
\text{Temperature} \quad 1.84 \quad (\text{60°F}) \quad 13.28 \quad 1.84 = 7.25
\]

These two bridges are similar in all respects, save that the Manhattan Bridge has a shallower and less rigid stiffening truss with a smaller span.

The suspension design for the Quebec Bridge was of a different type, in some respects less satisfactory. The stiffening trusses here were very deep (100 ft.), but were continuous over the towers and hinged at the centre, forming themselves an indeterminate system. Owing to the conformation of the stiffening truss it was able to take up a considerable portion of the live load, and the centre deflection under the live load was only 2 ft. Under temperature,
however, the indeterminate stiffening truss itself deflected considerably and the compensating effect mentioned above did not occur to such a large extent. Hence the deflection under temperature was 5 ft., giving a total of 7 ft. for live load and temperature.

The vertical movement would entail heavy maintenance charges and though the bridge would carry the railway traffic it would not do it as economically or as safely at high speeds as a cantilever or an arch bridge would, and for this reason a cantilever or an arch bridge was decided upon.

There are various important points to be noted in regard to the relation of designed live load to present existing live load for those bridges above already in service. The Brooklyn Bridge is now subjected to a very much greater load (2960 lbs. per lin. ft.) than it was designed for, viz. 1750 lbs., but this load in every case approximates to a uniform live load spread over the whole length of structure. The Bridge trains and trolley cars run respectively at 700 ft. apart in the clear and 100 ft. centre to centre, producing thus a distributed load over the bridge; and the objectionable wave in the floor will thus not be produced, particularly as the loads themselves are very light. The Williamsburg Bridge carries the full live load it was intended to, consisting of uniform live load due to trolley cars and roadways, with the addition of two light elevated railway tracks, whose load bears only a small proportion to the total.

On the Manhattan Bridge the provision for two of the trolley-car tracks has been converted into a separate roadway, and the two light elevated railway tracks carry six-car suburban trains at a spacing of 500 ft. clear, a very different thing to concentrated main line railway loading.

For the Delaware River Bridge now under construction at Philadelphia, for many years to come the provision for two suburban electric train tracks will not be taken advantage of, the loading will be mostly highway loading, consequently the loads applied to the structure will be of the nature of a uniform load and for this reason the bridge has been chosen of the suspension type.

The proposed Detroit River Bridge is for vehicular and tram traffic only.
ARCHES: Long span steel Arch Bridges are of two types, viz., Three-hinged and Two-hinged. Three-hinged arches are not generally used for medium span railway bridges because they are less rigid than two-hinged arches, but for long span bridges they have advantages for erection purposes.

The statical action of an Arch is the direct inversion of the action of the Suspension Bridges. Loads are transferred from the floor to the arch rib and transmitted direct to the abutments - the rib itself being in direct compression. For this reason the arch is the most rigid of all types of structure; the Simple Span and the Cantilever both act in bending, and more flexure is produced in this way than by the effect of direct compression.

The largest arch span yet proposed was for a bridge across the Hudson River, New York, designed by Max am Ende, in 1860, span 2650 feet, rise 440 feet. When the Forth Bridge was under consideration Max am Ende also designed, in 1880, an arch bridge of 1640 feet span with a rise of 395 feet.

As an alternative to the cantilever design for the Quebec Bridge, Mr. Charles Worthington of New York, proposed a voussoir arch of 1900 feet span; the foregoing proposals were never carried into effect.

The most notable Arch Bridge yet erected is the Hell Gate Arch at New York, with a span of 997.5 feet, carrying four railway tracks for heavy steam freight service. This bridge under full live load of 24,000 lb. per ft. deflects only 5.82 inches at the crown, and under minimum temperature sinks a further 5.30 inches.

A two-hinged or three-hinged braced arch is the best type for railway traffic when the abutments permit of sufficient rise, which will usually be the case when the arch type of bridge proves to be the proper solution. A two-hinged or three-hinged arch is more rigid and less subject to vibration than any other type of bridge, and has the advantage of easier erection as each
half can be erected as a cantilever arm held back by suitable temporary anchorages until the centre connection is made. The Arch possesses another advantage over other types, because for live and dead loads the web stresses are relatively small, but high web stresses are involved in the erection. Consequently sections designed for the requirements of erection automatically provide for heavy concentrations of loading due to or in excess of specified requirements.

Preliminary investigations on a two-hinged Arch Span of 1,550 feet with a rise of 310 feet, with a rib depth at crown of 60 feet showed that the deflection at quarter point with live load covering half span was approximately 8\(\frac{3}{8}\) inches. The maximum deflection at centre/half loaded was 7 inches, and the rise or fall at centre, with a temperature variation of 60 degrees F., was approximately 7\(\frac{3}{8}\) inches.

As an Arch Bridge either two or three-hinged is very suitable for heavy railway traffic, and various firms asked to be allowed to tender for and were prepared to guarantee the erection of an Arch Bridge, the author prepared and included an alternative to the Cantilever Bridge design for a two-hinged Arch Bridge of 1,650 feet span, but tenderers could tender for a three-hinged arch if they so desired.

**CANTILEVER BRIDGES:**

The Cantilever Bridge, compared with the Suspension Bridge, is rigidity itself. This type of bridge consists of two rigid steel frames, supported on the main piers at the ends of the channel span, anchored to massive anchor piers at the extreme ends of the structure, and cantilevered out over the channel. The free ends of these frames support an ordinary simple span - "the suspended span". Plate No. 61. By this system the loads applied to the main span are transferred vertically to the foundations, downwards at the main piers, and upwards at the anchor piers, which will be smaller than those required for the Suspension Bridge. The Cantilever Bridge is statically determinate, and on account of the high rigidity this system is adopted where possible for structures carrying heavy...
Examples of notable Cantilever Bridges are:

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Span (ft)</th>
<th>Open to Traffic</th>
<th>Year</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forth Bridge</td>
<td>1710</td>
<td>Open to Traffic</td>
<td>1863</td>
<td></td>
</tr>
<tr>
<td>Loading</td>
<td>2 railway tracks</td>
<td>4400 lbs/ft.</td>
<td></td>
<td>Plate 62.</td>
</tr>
<tr>
<td>Quebec Bridge</td>
<td>1800</td>
<td>Open to Traffic</td>
<td>1917</td>
<td></td>
</tr>
<tr>
<td>Loading</td>
<td>2 railway tracks</td>
<td>10,000 lbs/ft.</td>
<td></td>
<td>Plate 63.</td>
</tr>
<tr>
<td>Blackwell's Island Bridge</td>
<td>1162</td>
<td>Open to Traffic</td>
<td>1909</td>
<td></td>
</tr>
<tr>
<td>Loading</td>
<td>Present Traffic</td>
<td>5,150 lbs/ft.</td>
<td></td>
<td>Plate 64.</td>
</tr>
</tbody>
</table>

The critical point of the relative economy of Cantilever and Suspension Bridges is somewhat difficult to decide. However, for railway traffic Cantilever Bridges are probably more economical for spans between 700 and 1,700 feet; whilst if rigidity is taken into account the Cantilever Bridge, though not the most economical, is the better type to use up to spans of 2,000 to 2,800 feet, whilst above this limit the suspension type is economically the only practicable type. Even so, the most economical Suspension Bridge is one in which the sag of the cables is 1/8th of the span, and the depth of stiffening truss, to keep the local deviation of grade of railway to less than 1 in 100, is \(\frac{1}{30}\) times the span. This depth of stiffening truss is unsightly and undesirable, and modern Suspension Bridges have on this account been designed with trusses of smaller depth, as the Manhattan Bridge of 1,470 feet with 24 feet depth of truss and the New Delaware River Bridge of 1,750 feet span, and a truss depth of 28 feet. Utilising a shallower stiffening truss decreases the economy of the structure, and probably raises
"Our history has traced a steady growth...the telegraph and telephone, the aeroplane, the continuous progress of land and sea travel."
the economical limit of Cantilever Bridges to 1,800 feet. In any case, if any other type than the Suspension Bridge can be built, the more rigid structure is to be preferred for fast heavy railway traffic, on account of the greater vibration of the Suspension Bridge, and its weak resistance to lateral and upward forces due to wind.

Cantilever Bridges are of two types, one without a suspended span, and the other with a suspended span. The Blackwell's Island Bridge is the most notable example of the first type, and the Quebec Bridge of the latter type.

There is no advantage in omitting the suspended span, on the contrary such a structure differs only from a true continuous girder bridge over several supports by the introduction of a hinge at the centre of the main span which transmits shears but not moments. The vibrations and deflections of each portion are transmitted through the hinges to the other portions, and as the stresses depend on the deflections there is an uncertainty in the calculations.

In the second type with the suspended span, the length of the main span is usually determined by local conditions. With the Sydney Harbour Bridge the requirements of navigation and economy of foundations determine the length of the centre span at 1,600 ft. The general dimensions to be fixed by the designer are, therefore, the length of the suspended span, the length of the anchor arms where these are not determined by local conditions, and the depth of the trusses; the traffic conditions usually determine the distance apart of the trusses centre to centre.

The length of the suspended span depends upon practicability of erection rather than the most economical distribution of material for carrying the dead and live loads after the bridge is completed. Were the latter the only consideration, a span of 800 ft. would, for the centre span of the Sydney Harbour Bridge, be more economical than the 600 feet chosen. But to lift a span of 800 feet weighing in the vicinity of 8,500 tons
by floating into position or by cantilevering out would, if not impossible, be risky and costly.

The cantilever method of erecting a suspended span of even moderate length always requires additional material to take care of the erection stresses, both in the cantilever arms and in the suspended span; the longer the suspended span in relation to the length of total main span the greater will be the additional material required, so that whether the method of erecting the suspended span is by cantilevering out, or by lifting into position, the length of the suspended span is limited, not by the economic considerations of the finished bridge, but either by the excess of material required during erection by the cantilever method and the difficulties arising therefrom, or by the difficulties attending the lifting of a very long and heavy span into position, and these difficulties increase rapidly with the length of span to be lifted. In lifting into position the various members will not be subjected to any greater stress during erection than they would be in a simple span of the same length resting on two piers, and it is, therefore, possible to design the suspended span as economically as to weight as a well designed simple span should be. The importance of economy in this respect is exemplified in the Quebec Bridge, where every pound of weight uniformly distributed over the suspended span needs 3 pounds of metal added to the bridge to carry it or 4 pounds in all. This accounts for the curved top chord of the suspended span and the use of nickel steel in the trusses thereof.

In the Sydney Harbour Bridge, aesthetics had to be given more than ordinary consideration; the trusses of the suspended span will be constructed of high grade steel, and were designed with parallel flanges so as to line up with the harbour arms of the cantilever to make a pleasing outline. The depth was kept at 1/6th of the span for economy, but economy was sacrificed to some extent to appearance, as a curved chord would have reduced
the weight. Having fixed the centre span at 600 feet each of the cantilever arms becomes 500 feet, and the anchor arms were fixed at the same length for appearance and to obtain less costly anchor piers than if the anchor arms had been made shorter. It must not be forgotten that the shorter anchor arm increases the pier re-actions as well as the steel in the anchorages, so that with a shorter anchor arm the anchor piers would have been more expensive.

While as shown above an addition of dead load in the main span will require several times its weight of metal to carry it, an addition of dead load in the anchor arms requires no increase in metal to carry it when there is a downward or negative re-action on the anchor pier, because any load placed between the main piers increases all moments and shears over all the spans, while any load placed in the anchor arms, if the re-action in the anchor pier is negative, decreases that re-action, and consequently the moments in the anchor arm, but it has no effect on the main span. For this reason carbon steel is mostly used in the anchor arm, and the additional weight of steel as necessitated by its use is a source of economy when the relative prices of carbon and nickel steel are considered.

The limiting span with a Cantilever Bridge i.e., the span at which the structure can just carry its own weight, has been calculated to be 5,600 feet, whilst the maximum practicable span with carbon steel i.e., the span requiring members of maximum practicable section is 2,000 feet. Up to 1,650 to 1,700 the cantilever or suspension types will be relatively of equal cost.

Dr. Waddell in his "Economics of Bridgework" taking an average site and cost figures, from actual value, considers that for Suspension or Cantilever Bridges of equal cost the limiting span for a double-track railway bridge would be 2,570 feet, whilst with a four-track railway bridge also carrying a highway the limiting span would be 2,200 feet. Above these spans the Suspension Bridge would be cheaper.

It must be remembered that those are American conditions, where steel is comparatively cheap, and in Australia the Suspension Bridge of 1,650 feet would be about equal in cost to
a Cantilever Bridge of the same size.

**SUMMARY:**

The length of spans which may economically be used for the various types of bridges in the light of our present knowledge of steel and its alloys and loadings possible are as under:

- **Simple Spans.**
  - Up to 800 feet.

- **Arch Spans.**
  - Up to 2,800 feet.

- **Cantilever Spans with suspended girder.**
  - 700 feet to 2,200 feet.

- **Cable Suspension Bridges.**
  - 1,500 feet to 3,200 feet.

Spans longer than this up to 5,000 feet are feasible. The relative economic considerations of Cantilever and Suspension Bridges begin at about 1,500 feet. Arch spans can only be used where the natural conditions are suitable, or where ornamental bridges are required, and when considering Cantilever or Suspension Bridges between 1,500 and 2,200 feet span, each type should be investigated. If the bridge is for highway traffic only the Suspension Bridge will be the most economical and quite suitable, but if heavy railroad traffic is to be carried, the Cantilever Bridge will be much more rigid and up to spans of 1,800 feet in Australia as cheap a structure, whilst the life and ultimate usefulness of a Cantilever Bridge will be greater than the Suspension type.

A Cantilever Bridge of 1,600 feet span or an Arch Bridge of 1,650 feet span, to meet traffic requirements is perfectly feasible, and each is at least as cheap as, if not cheaper than, a Suspension Bridge of the same span with a much greater rigidity and greater life of ultimate usefulness than the Suspension Bridge. Plates 65, 66, 67.

The Arch Bridge, which is 650 feet longer in span than the longest Arch Bridge yet erected, was submitted as an alternative to give tenderers every latitude and to secure the most rigid bridge combined with economy. The Arch Bridge requires 14,500 tons less steel.
of similar grade of steel than the Cantilever Bridge requires.

Two types of Cantilever Bridge are possible:

(a). With an inclined lower chord.

(b). With a horizontal lower chord.

A bridge of the first type would be much cheaper than the latter type, in that the main piers would be reduced to the minimum height; it would be much simpler to erect, as the traveller could traverse the bridge at deck level, and in constructing the cantilever the traveller could build up and down, so there would only be half the vertical lift required at the centre post. Consequently the traveller would be smaller in size, and the erection problems safer, simpler, and cheaper. The headway, however, would be considerably curtailed, as the headway of 170 feet could only be given over the central 600 feet of bridge, whilst the sloping cantilever would hamper the view of masters of shipping and be an element of danger. The harbour, over-seas, and interstate shipping traffic would be concentrated within the central 600 feet whether up or down traffic. Plate 68 illustrates a bridge with the headway above.

The shipping of Sydney is now exceeded only by four ports in the United Kingdom - London, Liverpool, The Tyne, and Cardiff - and to build a bridge now, which would concentrate that traffic in the years to come over 600 feet of waterway would be short-sighted and ill-advised, whilst the sloping arms of the Cantilevers would also obstruct the view for navigation purposes.

Within 50 years the commerce of Sydney will at least have trebled, and the deep-sea boats will load at Sydney and ply to the various ports of the world without calling at any other Australian port for cargo. The magnificent terrain of New South Wales ensures this.

Again, a Cantilever Bridge with sloping arms could not be as handsome a bridge and as suitable for its surroundings as the bridge with the horizontal lower chord.
The bridge with sloping bottom chords is from the purely engineering point of view the most suitable, but when the claims of commerce, shipping, aesthetic considerations of the city, and the safety of the bridge against collision from a leviathan of the future are taken into account, the design adopted with the horizontal lower chord fully justifies the increased cost of £600,000. It is just as useful a bridge for the traffic to be carried as the bridge with sloping bottom chord, has the advantage of giving much greater facilities for shipping, is free from all danger of collision, and has a much better appearance.

The vertical live load deflection of the Cantilever structure designed for the Sydney Harbour Bridge is 13\textfrac{1}{2} inches.
CANTILEVER BRIDGE.

Dead Load.

In the design of a bridge of the magnitude of the Sydney Harbour Bridge the most particular consideration and accuracy is required to estimate the weight of the finished structure correctly, as an under estimation of weight simply courts disaster. The traffic on the bridge can be regulated so that the live load stress can never be exceeded and the wind stresses likewise can be determined with assurance, for should an exceptional storm strike the Bridge the members thereof need not be stressed beyond their elastic limit; but if the finished weight of the bridge exceeds the dead load estimated, when calculating the stresses, the traffic across the bridge must be regulated, and limited for all time.

Accurate estimates of the weight of the floor system and of the lateral and transverse bracing can be made, and it is in the weight of the main trusses where an underestimation of weight may occur particularly in the percentage of detail required to the theoretical section.

In the original Quebec Bridge the dead load was considerably underestimated, which fact materially contributed to the disaster. The earliest and gravest mistake in the construction of this bridge was made in adopting an artistic outline for the cantilever arms, involving the use of curved compression chords and resulting in a reversal of stresses in certain of the web members. As a result of this reversal of stress, elongated pin holes could not be used in them and it was found impossible to assemble the truss members in the field with butt riveted joints in full contact for the whole depth of the member. It is considered that this "open joint" erection was the direct cause of the failure of the bridge when nearly half finished.

The second mistake made in connection with the construction of the original Quebec Bridge was the underestimating the weight of the details of the truss members. An
accurate estimate was arrived at of the weight of the floor system and of the transverse and lateral bracing, but the weights of the steelwork dead load on which the stresses were calculated were too small and, as the anchor arms were designed and manufactured before this error in dead load weight was discovered, the anchor arm stresses were underestimated. All the dead load stresses of the completed structure were from 10% to 20% in excess of the calculated amounts.

In Simple Spans and in Suspension Bridges after the preliminary trials the dead load may be fixed with sufficient accuracy so that in the final trial, the error, if the dead load is taken out as uniform, will be small. The dead load due to the floor will be uniform while that due to the stiffening truss in a Suspension Bridge is a maximum at about the quarter point, the weight per foot at the centre being approximately the average over the channel span; the dead load of hangers and main cables increasing towards the main towers.

With a Cantilever Bridge the dead load stresses must be most accurately determined. On account of the large connections, there is a danger that the percentage assumed for details may be too small and it is only after repeated trials that the final dead load stresses will approach those in the completed structure.

In the Quebec Bridge as built the design was completed entirely before any work was put into the shop, this involved a large delay in the design of the anchor arms which were the first truss members to be manufactured, but the final result was very satisfactory as the dead weight between the main piers checked within one per cent.

The calculated weight, the finished weight and the percentage of detail, i.e., the percentage of difference between the calculated and shipping weights which represents the weight of gussets, stiffeners, rivets, etc., of the member for the Quebec Bridge are of particular interest:-
### Percentage of Detail on Trusses of Quebec Bridge.

<table>
<thead>
<tr>
<th></th>
<th>Stress Sheet Weight</th>
<th>Shipping Weight</th>
<th>Percent of Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anchor Arm.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Post</td>
<td>7,537,200</td>
<td>9,656,156</td>
<td>28</td>
</tr>
<tr>
<td>Bot. Chord</td>
<td>8,140,400</td>
<td>11,182,070</td>
<td>37</td>
</tr>
<tr>
<td>Diag. Comp.</td>
<td>5,696,420</td>
<td>9,292,559</td>
<td>58</td>
</tr>
<tr>
<td>Diag. Tens.</td>
<td>3,495,960</td>
<td>4,372,432</td>
<td>25</td>
</tr>
<tr>
<td>Vert. Comp.</td>
<td>1,970,024</td>
<td>1,163,876</td>
<td>66</td>
</tr>
<tr>
<td>Vert. Tens.</td>
<td>2,157,600</td>
<td>2,788,606</td>
<td>29</td>
</tr>
<tr>
<td>Sub. Members</td>
<td>500,960</td>
<td>807,803</td>
<td>61</td>
</tr>
<tr>
<td><strong>Total Anchor Arm (Built)</strong></td>
<td><strong>29,600,264</strong></td>
<td><strong>41,199,452</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td><strong>Cantilever Arm.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bot. Chord</td>
<td>7,626,960</td>
<td>9,893,552</td>
<td>41</td>
</tr>
<tr>
<td>Diag. Comp.</td>
<td>4,810,244</td>
<td>8,130,278</td>
<td>69</td>
</tr>
<tr>
<td>Diag. Tens.</td>
<td>2,881,180</td>
<td>3,747,936</td>
<td>30</td>
</tr>
<tr>
<td>Vert. Comp.</td>
<td>2,110,276</td>
<td>2,512,742</td>
<td>62</td>
</tr>
<tr>
<td>Vert. Tens.</td>
<td>1,638,252</td>
<td>2,327,032</td>
<td>42</td>
</tr>
<tr>
<td>Sub. Members</td>
<td>634,272</td>
<td>911,889</td>
<td>44</td>
</tr>
<tr>
<td><strong>Total Cantilever Arm (Built)</strong></td>
<td><strong>19,101,184</strong></td>
<td><strong>28,423,039</strong></td>
<td><strong>49</strong></td>
</tr>
<tr>
<td><strong>Total Cantilever &amp; Anchor Arms.</strong></td>
<td><strong>48,701,448</strong></td>
<td></td>
<td><strong>43</strong></td>
</tr>
<tr>
<td>Including Back</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Including Top Detail</td>
<td>2,099,265</td>
<td>71,721,756</td>
<td>47</td>
</tr>
<tr>
<td>Including Top Chord Trusses</td>
<td>1,163,615</td>
<td>72,685,371</td>
<td>50</td>
</tr>
<tr>
<td>Including Grillage</td>
<td>1,939,402</td>
<td>74,824,973</td>
<td>54</td>
</tr>
<tr>
<td>Including Main Anchor less Bars &amp; Pins</td>
<td>1,266,864</td>
<td>76,065,819</td>
<td>56</td>
</tr>
<tr>
<td><strong>Suspended Span.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top Chord &amp; E. P.</td>
<td>1,877,272</td>
<td>2,792,860</td>
<td>45</td>
</tr>
<tr>
<td>Web Members (Built)</td>
<td>1,018,684</td>
<td>1,888,640</td>
<td>66</td>
</tr>
<tr>
<td><strong>Total Sus. Span (Built)</strong></td>
<td><strong>2,895,956</strong></td>
<td><strong>4,412,500</strong></td>
<td><strong>53</strong></td>
</tr>
<tr>
<td><strong>Grand Total Built Truss Members.</strong></td>
<td><strong>51,597,404</strong></td>
<td></td>
<td><strong>58</strong></td>
</tr>
</tbody>
</table>

207
### Percentage of Detail on Trusses of Quebec Bridge. (Contd.)

<table>
<thead>
<tr>
<th>Eyesbar.</th>
<th>Stress Sheet Weight</th>
<th>Shipping Weight</th>
<th>Percent of Detail %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchorage Carbon</td>
<td>251,330</td>
<td>325,410</td>
<td>29</td>
</tr>
<tr>
<td>Anchorage &amp; A-12</td>
<td>1,253,910</td>
<td>1,429,692</td>
<td>14</td>
</tr>
<tr>
<td>M2 Carbon.</td>
<td>10,427,608</td>
<td>12,187,293</td>
<td>17</td>
</tr>
<tr>
<td>Top Chord Car.</td>
<td>1,650,824</td>
<td>1,935,695</td>
<td>17</td>
</tr>
<tr>
<td>Sus. Span &amp; C-12</td>
<td>13,833,672</td>
<td>15,878,090</td>
<td>97,484,783</td>
</tr>
<tr>
<td>M2 Hi.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fins Carbon</td>
<td>1,925,186</td>
<td></td>
<td>02.96</td>
</tr>
<tr>
<td>Fins Nickel</td>
<td>1,139,334</td>
<td></td>
<td>1.72</td>
</tr>
<tr>
<td>Sleeves C &amp; N</td>
<td>422,060</td>
<td></td>
<td>.65</td>
</tr>
<tr>
<td>Pin Caps</td>
<td>92,783</td>
<td></td>
<td>.14</td>
</tr>
<tr>
<td>Pin Bolts</td>
<td>47,050</td>
<td></td>
<td>.14</td>
</tr>
<tr>
<td>Fill Rings</td>
<td>24,877</td>
<td></td>
<td>.94</td>
</tr>
<tr>
<td>Brake</td>
<td>17,896</td>
<td></td>
<td>.93</td>
</tr>
<tr>
<td>Field Rivets, say</td>
<td>1,000,000</td>
<td></td>
<td>1.51</td>
</tr>
<tr>
<td>Field Bolts, say</td>
<td>30,000</td>
<td></td>
<td>.05</td>
</tr>
</tbody>
</table>

**Total Shipping Weight, Excluding Floor Laterals and Sway Bracing:**

| 4,688,986 | 102,183,769 | 56.80 |

The Forth Bridge weighs 2 tons per foot at the suspended span and 34.5 tons per foot at the tower. The Quebec Bridge weighs 8.7 tons near the suspended span and 55.5 tons per foot near the tower.

At the suspended span the Sydney Harbour Bridge weighs 11.6 tons per foot, while at the main pier the weight is 55.6 tons per foot.

Plate No. 69 illustrates the relative weights per foot of the Forth, Quebec, and Sydney Harbour Bridges.
Comparison of weights per foot of bridge

The Sydney Harbour Bridge

The Quebec Bridge

The Forth Bridge
The following is a comparison of the largest compression members of the Forth, Quebec, Sydney Harbour and Hell Gate Bridges:

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Member</th>
<th>Area, Sq. ins.</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forth</td>
<td>Bottom Chord</td>
<td>800</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>Quebec</td>
<td>Main Post</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom Chord - Cant.</td>
<td>1,904</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td>Arm</td>
<td>1,631</td>
<td>Nickel Steel</td>
</tr>
<tr>
<td></td>
<td>Bottom Chord - Anchor</td>
<td>1,903</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td>Arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney Harbour</td>
<td>Main Post</td>
<td>2,497</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td>Bottom Chord - Cant.</td>
<td>1,387</td>
<td>Nickel Steel</td>
</tr>
<tr>
<td></td>
<td>Arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom Chord - Anchor</td>
<td>1,766</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td>Arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hell Gate</td>
<td>Bottom Chord</td>
<td>1,384</td>
<td>Hard Carbon Steel.</td>
</tr>
</tbody>
</table>

The Forth Bridge member was tubular in section and is as near the ideal member it is possible to get from the point of view of the distribution of material, but the connections are very difficult, and it would be impossible to get skilled men for such work outside the shipbuilding centres of Great Britain.

The Hell Gate member was a single H Section and has plates 2 inches thick, but is not comparable with the members of the Sydney Harbour Bridge or Quebec Bridge.

The lower chord members of these bridges is a HH Section and the Quebec Bridge members are heavier than the Sydney Harbour Bridge members. On account of the truss outline and loading, the Sydney Harbour Bridge top chords, however, are heavier than those of the Quebec Bridge.

The main post sections of carbon steel are in the form of \[ \text{HH} \] That of the
Sydney Harbour Bridge will be much heavier than the main post of the Quebec Bridge, and when completed will be the heaviest bridge member ever fabricated.
WIND LOADS.

The Forth Bridge is designed for the very high wind load of 56 lbs. per sq. foot, corresponding to a wind velocity of 137 miles per hour. The Forth Bridge was designed just after the Tay Bridge disaster, which bridge failed during a terrific storm partly due to the wind load, and the then Board of Trade made assurance doubly sure by imposing the above wind load on the designers of the Forth Bridge.

Records of storms at Sydney during the past half century indicate that the severest storm blew from the South East, the wind attaining a velocity of 120 miles per hour, equivalent to a pressure of 45.2 lbs. per square foot, the next storm of the greatest magnitude reached a velocity of 92 miles per hour from W.N.W., equivalent to a pressure of 25.6 lbs. per square foot, whilst many wind storms of 60 to 90 miles per hour have been recorded.

Wind pressure on structures has been the subject of many experiments. During the building of the Forth Bridge Sir Benjamin Baker, the Designer, conducted a comprehensive series of experiments. He used a large gauge of 20 feet long by 15 feet deep, exposing 300 square feet of surface, a small fixed gauge with exposed surface of 1.5 square feet, and a small revolving gauge with exposed area of 1.5 square feet.

The revolving gauge was arranged so that it turned and faced the direction of the strongest wind; the large and small fixed gauges were arranged to face the direction from which the strongest winds blew.

The maximum results were recorded by a Westerly Wind, viz.:

- Large fixed gauge, average pressure 27 lbs. per sq. ft.
- Small fixed gauge, average pressure 41 lbs. per sq. ft.
- Revolving gauge, average pressure 35 lbs. per sq. ft.

The variations in these results were typical of all readings, and show conclusively
that the average pressure over a large surface is much less than over a small surface.

Wind pressure is conveniently expressed by the formula:

\[ P = KV^2 \]

where

- \( P \) = pressure in lbs. per sq. ft.
- \( V \) = velocity of wind in miles per hour.
- \( K \) = a constant.

From many extensive series of experiments, "\( K \)" has been found to vary from 0.0027 to 0.0039, but from Hiffel's two hundred and more experiments, and from German experiments on electric cars, "\( K \)" has been found to be 0.003.

In designing the Sydney Harbour Bridge a wind pressure of 30 lbs. per sq. ft. was taken: this corresponds with a wind velocity of 100 miles per hour, that is, a violent hurricane. With a wind of this velocity there would be little, if any, traffic on the bridge, as empty freight cars and light passenger cars would be overturned, and vehicular and pedestrian traffic would be suspended.

Such storms are very rare, and gusts of the maximum velocity act on a small area and never over the whole area of such a bridge. Should, however, the improbable happen, and the whole area of the Sydney Harbour Bridge be subjected to double the wind pressure for which it is designed, that is a typhoon raging at 142 miles per hour, equivalent to a pressure of 60 lbs. per sq. ft., the wind stresses in the truss members would be less than the maximum live load stresses combined with the wind stresses of 30 lbs. per sq. ft., because no live load could traverse the bridge. The stresses in the laterals would be increased above the specified limits, but the stresses would be within the elastic limit of the material, and no injury should result.

In the Forth Bridge, designed for a wind of 56 lbs. per sq. ft. on the exposed surface of two trusses the lower chords transmit the wind pressure to the piers and the maximum stress
in these members is as follows:

\[
\begin{array}{lll}
\text{Dead Load} & 2222 & \text{British Tons} = 5112 \text{ units of 1000 lbs.} \\
\text{Live Load} & 1022 & \text{"} = 2289 \text{ "} \\
\text{Wind Load} & 8220 & \text{"} = 6541 \text{ "} \\
\end{array}
\]

Thus the metal provided to take care of the wind stresses is nearly three times that provided for the live load, and is 47 per cent of the total required.

The Quebec Bridge is designed for a wind pressure of 30 lbs. per sq. ft. on the exposed surface of two trusses, and the stress for which the bottom chord adjacent to the main pier is designed is as follows:

\[
\begin{array}{ll}
\text{Dead Load} & 14,000 \text{ units of 1000 lbs.} \\
\text{Live Load (including impact)} & 6,965 \\
\text{Wind} & 5,146 \\
\text{Minor Stresses} & 452 \\
\text{TOTAL} & 29,583 \\
\end{array}
\]

It is seen that the area provided to resist the wind stresses is 17% greater than that necessary for the live load stresses.

The Sydney Harbour Bridge is designed for a wind pressure of 30 lbs. per sq. ft. on the exposed area of two stresses. For primary stresses the members are designed for the maximum of the two following combinations, viz., full live load, one third wind and other coexisting primary stresses, or three quarters live load, full wind and other coexisting stresses.

For the bottom chord adjacent to the main post the two combinations are as follows:
<table>
<thead>
<tr>
<th>Description</th>
<th>Units of 1,000 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>15,860</td>
</tr>
<tr>
<td>Full Live Load (including impact)</td>
<td>6,254</td>
</tr>
<tr>
<td>One third Wind Load</td>
<td>1,767</td>
</tr>
<tr>
<td>Minor Stresses</td>
<td>376</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>24,257</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Units of 1,000 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>15,860</td>
</tr>
<tr>
<td>Three quarters Live Load</td>
<td>4,713</td>
</tr>
<tr>
<td>(including impact)</td>
<td></td>
</tr>
<tr>
<td>Full Wind Load</td>
<td>5,300</td>
</tr>
<tr>
<td>Minor Stresses</td>
<td>376</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>26,249</strong></td>
</tr>
</tbody>
</table>

The member was designed for a stress of 26,249 units, that is with a full wind load and three quarters live load.

It is certain that the live load will never exceed three quarters of the maximum live load when the wind pressure is 50 lbs. per sq. ft.

It is conclusive that the wind pressure allowed in the design of the Sydney Harbour Bridge is ample, and though a storm of double the pressure allowed were to stress the bridge over its entire length, - a disturbance of a most extraordinary character - the stresses in the chords would be less than those for which the Bridge is designed, and the stresses in the laterals would not exceed the elastic limit of the steel.
STRESSES AND WEIGHTS.

For the primary estimation of weights for the Sydney Harbour Bridge, accurate stress determinations were necessary in order to be able to evaluate the sections of members. It was considered sufficient for this purpose to consider only primary stresses, as it seemed highly probable that, with increased unit stress for secondary stresses, the sections of members would remain practically unchanged when secondary stresses were taken into account.

Primary stresses due to the various loads may be combined in two different ways to produce maxima co-existing stresses, viz:-

**Combination (1).**

- Dead Load.
- Live Load and Impact.
- Brake Force.
- Longitudinal Force (Traction).
- Centrifugal Force.
- One-third Wind, (a) and (c), or (b); i.e. Wind on Bridge and Train, or Longitudinal Wind.
- Temperature (a), (b), and (c); i.e., Uniform rise or fall of 60°F, Difference of 50°F between steel and masonry, and difference of 25°F between average temperatures of a chord exposed to the sun and of a shaded chord.

Torsion

and Friction.

**Combination (2).**

- Dead Load
- Three-quarters Live Load and Impact.
Brake Force.

Longitudinal Force.

Centrifugal Force.

Full Wind (a) and (c), or (b).

Temperature (a) and (b).

Torsion

and Friction.

Then the maximum primary stress on which any member is to be designed is given by one of these Combinations.

Live Load and Impact.

In main truss members and girders of approach spans, live load stresses are to be evaluated for a uniform load of 12,000 lbs. per lin. ft. of bridge, maximum loaded length 1100 ft., minimum load length 300 ft.; broken loads are not to be considered. There is also the deck system, including floor-beams and sub-members of the main trusses and approach girders, for which the following loading is specified:

- **Footway**: 100 lbs. per sq. ft.
- **Roadway**: 100 lbs. per sq. ft.
- **Railway**: Two coupled conventional electric locomotives, each 65 feet long overall and weighing 360,000 lbs., followed by a train 1000 ft. long weighing 2,200 lbs. per lin. ft., on each of the four tracks.

For other members of the deck system, such as flooring plates, transverse joists and stringers, the roadway loading is a conventional motor lorry, wheel base 12' x 6', overall length 24 ft., overall width 8 ft., space occupied 30' x 12'. Weight front axle 18,000 lb. back axle 36,000 lb. The remainder of the roadway to be covered with a live load of 100 lb. per sq. ft.
Impact allowance for the main system, excluding inner girders of approach spans, is 10% of the live load. Inner girders of approach spans are allowed 15% of the live load. Impact allowances for the deck system are:

**Railway Loading.**
- Stringers .......... 50%
- Floor-beams ........ 40%
- Other Members ...... 25%

**Roadway Loading.**
- Stringers, etc. ... 25%
- Floor-beams ...... 20%
- Other Members .... 10%

**Brake Force.**
A force of 220,000 lbs. for each truss is assumed to act between the suspended span and cantilever arm.

**Longitudinal Force.**
A pair of tracks on one side of the bridge is assumed to carry two similar trains of equal length, in similar positions travelling in the same direction. Then the traction, or braking, force exerted on the bridge by both these trains together is specified to be 650 lbs. per lin. ft. of loaded track.

**Centrifugal Force.**
On the northern approach spans, where the tracks are curved, provision is to be made for the centrifugal force due to a train on each of the two tracks on one side of the bridge travelling in the same direction. On the cantilever bridge the minimum radius of curve is 8 chains, speed 25 miles per hour, and on the arch bridge the minimum radius of curve is 18 chains, speed 50 miles per hour. The force is applied 5 feet above base of rail.
Wind.

(a) A wind load normal to Bridge of 30 lb. per sq. ft. of the exposed surface of two trusses and one and a half times the elevation of the floor, 150 lb. per lin. ft. on footway fence.

(b) A wind load parallel with the Bridge of 30 lb. per sq. ft. on one-half the area assumed for normal wind in (a).

(c) A moving wind load of 300 lb. per lineal ft. on the exposed surface of a train applied 7 feet above base of rail.

Temperature.

(a) A variation of 120°F in uniform temperature of the whole structure, normal temperature being 60°F.

(b) A difference of 50°F between the temperature of steel and masonry.

(c) A difference of 25°F between the temperature of a shaded chord and the average temperature of a chord exposed to the sun.

Torsion.

Due to differential deflections of the ends of the two trusses forming one cantilever arm, the stresses in the suspended span and its hangers have to be determined.

Friction.

Friction stresses are produced by rotation or axial sliding of a pin in its pinhole. Friction force in sliding is taken at 20% of the normal force on the pin.
CANTILEVER BRIDGE.

Live Load Stresses.

Main Members.

The most convenient method of obtaining live load stresses when the live load consists of a moving uniform load is the Method of Influence Lines. The structure is statically determinate, with the exception of a slight indeterminateness due to the two horizontal members near each main post. These members are added to the structure purely for the sake of appearance, and are of very light section, so that one is justified in neglecting them as regards live load stress. Therefore, influence lines can be drawn for all stresses and reactions due to the live loads. The stress in the member then is

\[ S = \text{Area of influence diagram} \times \text{load per lin. ft. per truss.} \]

It is convenient also here to evaluate the live load and impact stresses together. The live load per lin. ft. is 12,000 lb., or 6,000 lbs. per ft. per truss.

\[
\begin{align*}
\text{Impact 10%} & = 600 \text{ lbs. per ft. per truss.} \\
\text{Total} & = 6,600 \text{ lbs. per ft. per truss.}
\end{align*}
\]

All stresses were evaluated in units of 1000 lbs., so that the load on each truss is 6.6 units per ft.

Subsidiary Members and Floor.

Using the loads and impact allowances set out above for the deck system, the live load and impact stresses are easily determined in the floor details, stringers, floor-beams and subsidiary members.

Wind Stresses.

Normal Wind.

(a) Wind on Bridge.
The normal wind loads on the bridge are subdivided as follows:

(1) 30 lbs. per sq. ft. on the exposed area of two trusses.
(2) 30 lbs. per sq. ft. on one and one-half times the elevation of the floor.
(3) 150 lbs. per lin. ft. on footway fence.

Wind stresses naturally depend upon the system of wind bracing. The suspended span of the Sydney Harbour Bridge has upper and lower lateral systems of bracing, portal frames at the inclined end posts, and subsidiary sway frames at each vertical. Lacking a complete investigation into the relative displacements of the upper and lower lateral systems, it is taken that the upper laterals transmit the normal wind loads at the upper chord panel points through the portal frames to the point of suspension of the trusses. The loads on lower chord and intermediate web panel points are taken direct by the lower lateral system. Notwithstanding this method of distribution the sway frames were designed to transfer the whole of the upper chord panel point loads to the lower lateral system independently of the upper lateral system. The suspended span then imposes on the cantilever arm a normal reaction at the ends, and, due to the inclination of the portal, a downward vertical overturning reaction on the hangers for the leeward truss. The horizontal component of the portal post stress in the leeward truss is taken up in tension by the lower chord of the leeward suspended span.

The cantilever and anchor arms are not assumed to possess an upper lateral system, but strong sway frames at each vertical transfer the upper chord panel point loads to the lower laterals in the plane of the lower chords. This system of bracing transfers all wind loads to the lower laterals direct, and also imposes on the main trusses heavy overturning loads at each sway frame, acting vertically downwards on the leeward truss.
For stresses due to wind on trusses, we have a primary estimate of the depths of the various members, and knowing the geometrical lengths of members the normal wind loads on each truss due to wind on trusses may be found. The cantilever arm lower lateral system then forms a cantilever itself, bearing the normal reaction of the suspended span and the normal loads on the cantilever arm, a structure whose stresses in chords and laterals may be easily found. The main trusses also have to bear the vertical overturning loads and the vertical reaction from the suspended span. On the leeward truss these loads are vertically downward, and are treated as dead loads at the panel points. The stresses in main members other than lower chords are composed solely of overturning stresses, whilst lower chord stresses are combined of lateral and overturning stresses.

The stresses in the anchor arm lower lateral system are to be determined on two different premises:

(a) The main pier is rigid.

(b) The main pier is elastic in torsion.

In the first case, the normal loads on suspended span and cantilever arm do not affect the anchor arm laterals, and under the action of the normal loads on the anchor arm these laterals form a beam fixed at one end and simply supported at the other. This is an indeterminate system, and, as such, must be investigated on the general theory of indeterminate structures. Here, again, influence lines prove of particular value. The influence line for normal reaction at anchor pier is the graph of the deflection of the anchor arm lateral truss under unit normal load at the anchor, lateral support removed. This follows from Maxwell's Principle of Reciprocal Deflections. The Method of Elastic Weights might also be employed to advantage here, but on account of the simplicity of the K-bracing assumed in the lower lateral truss, it is more convenient to obtain the deflection line by means of a Williot Diagram.
After several trials, when the sections of the members become constant, the stresses in the lateral truss are finally obtained.

If the main pier is assumed elastic, the pier can rotate a certain amount under the action of the normal loads on the suspended span and cantilever arm, the amount of rotation depending on the moment on the main pier, the axial moment of inertia of the horizontal section of the pier and the modulus of elasticity of the pier in torsion. Thus, if the lateral support at the anchor is removed, unit load on the cantilever arm or suspended span would produce a deflection at the anchor, and loads on these parts of the bridge affect the normal reaction at the anchor. An influence line for this reaction is obtained in a similar way to that for pier rigid, and the lateral stresses in laterals and lower chords of the anchor arm are found. The overturning stresses in the anchor arm are found in a similar way to those in the cantilever arm.

Stresses due to wind on floor and fence may be taken together, as the loads are in the nature of a uniform load. Influence lines for stresses in lateral truss chords and laterals are of great assistance in obtaining these stresses. In the anchor arms the stresses are found for "pier rigid" and "pier elastic" as before. Due to the loads on the floor and fence being above the plane of the lower laterals, overturning stresses are produced in the main trusses. Combining the lateral and overturning stresses we have the total stresses due to wind on floor.

The sum of the stresses due to wind on trusses and wind on floor gives the stresses for wind on bridge. If, after the sections of members have been determined, the depths of members assumed are found to differ from the actual depths, the whole stress determination must be revised with the new wind loads to obtain the final stresses due to wind on bridge.
(c) **Wind on Train.**

Stresses due to wind on train are determined in a similar manner, with the exception that this load is a normal moving uniform load, for which case of loading the influence lines for lower laterals are extremely useful to obtain the lateral stresses. As the wind load on train is assumed applied 7 feet above the base of rail, and a considerably greater distance above the centre line of the lower laterals, there is produced also an overturning force, which produces stresses in the main truss members. These overturning stresses are a constant fraction of the live load stresses, and the sum of the overturning and lateral stresses gives the total stresses in the members. The sum of the stresses due to wind on bridge and wind on train gives the total wind stresses on all members due to normal wind.

(b) **Longitudinal Wind.**

The longitudinal wind panel point loads on the bridge are one-half of those for normal wind on trusses and floor, but without the loads on footway fence. The stresses due to these loads are best obtained graphically by a Maxwell Diagram, if the loads due to wind on floor are applied at the fixed points where the traction girders are placed. (See Longitudinal Force). Comparing the stresses due to normal wind with those due to longitudinal wind, the maximum value for any one member is taken as the wind stress in the member. Actually, the longitudinal wind stresses are found to be less than the normal wind stresses in all cases except in the horizontal sub-members near the main posts, and in the lower sub-chord at the ends of the cantilever arms. These latter members are to be computed for the stresses due to brake, longitudinal wind, traction force, and friction force in compression, reversing for brake and friction in tension. The horizontal reactions from the suspended span due to longitudinal wind and traction are assumed to have effect only on this sub-chord, and not on the other members of the cantilever and anchor arms, as it is taken that the action of the brake will embody these stresses in the other members, and the condition that the suspended
span touches the stops limiting its horizontal motion is a very rare one.

Brake Stresses.

A horizontal force of 220 units is specified as the action of a brake between the suspended span and cantilever arm. The most advantageous position for the brake will be at the points of connection of the suspended span lower chords with the ends of the lower sub-chords of each cantilever arm. The function of the brake is to retard relative motion between the two abutting chords due to the incidence of a load on the suspended span, horizontal wind or any other force.

The brake force is thus responsible for a stress of ±220 units in the suspended span lower chord, and for stresses in all the main truss members of the cantilever and anchor arms due to the moment in the vertical plane exerted by this force about the main shoe.

Longitudinal Force (Traction).

Traction force consists of 650 lbs. per lin. ft. of loaded tracks for both tracks on one side of the bridge, applied at base of rail. The stresses due to this force depend entirely on the positions of the expansion joints in the railway floor system and of the traction girders which transmit the force to the main trusses at various lower chord panel points. Expansion joints are so arranged that the maximum length of floor between joints is 500 feet, and traction girders are used, one on each truss for each complete unit of floor, one on anchor arm, one on cantilever arm, and two on the suspended span.

The force due to traction is applied at base of rail, which is above the level of the geometrical lower chord panel points, to which the forces are transmitted. Hence on each length of floor, the force resolves itself into a force parallel with the lower chord acting at a lower chord panel point and a vertical moment in the plane of the trusses.

Traction stresses on the suspended span due to the horizontal force are taken to be
embodied in those due to brake, viz., $\pm 220$ units in the lower chord. Due to the vertical moment stresses are produced in other truss members, and a vertical reaction is applied at the ends of the cantilever arm. If both sets of tracks are loaded in pairs in opposite directions, a moment in the plane of the suspended span lower laterals is produced, applying a normal force on the ends of the cantilever arms, and producing stresses in the lower laterals of the suspended span. Stresses in main truss members are computed for a loaded length equal to and in the same position as that for maximum live load stress in the member, and stresses in lower laterals are computed for a loaded length equivalent to that for maximum stress in member due to wind on train.

In the cantilever arm we have firstly the stresses due to the direct force, combined with those due to the lateral reaction of the suspended span. These stresses affect only the lower chords and laterals, but in some cases the maximum total traction stress in the member is produced by loads on the tracks near the other side of the bridge, so that both cases have to be watched. When the loads are on the tracks near the truss containing the member in question, the loaded length for main truss members is the same as that for maximum live load stress, and for laterals is the same as that for maximum stress due to wind on train.

The stresses due to the vertical moment of the traction force and the vertical reaction from the suspended span are easily obtained. The horizontal reaction of the suspended span is assumed to have effect only in the lower sub-chord, as noted above.

Stresses in the anchor arm are evaluated on the same principles, having regard when dealing with direct force and lateral reaction, to differentiate between "pier rigid" and "pier elastic". Total stresses in members are obtained by judicious combination of all the cases of stress.
The traction girders are designed to transmit traction and longitudinal wind forces from the sections of floor to the lower chord, and consist of cantilevered plate web girders connected to framed struts which are fixed to the lower flanges of the railway stringer bracing.

Centrifugal Force.

On the curved Northern Approach spans, centrifugal force comes into action, and consists of a uniform lateral load of the same nature as wind on train. The forces can be easily computed from the radius of curve and the speed of the train, and produce lateral stresses as well as overturning stresses.

Temperature.

(a) Stresses due to a uniform rise or fall of 60°F are not in the nature of primary stresses, but secondary stresses are produced on account of the distortion of truss members.

(b) If the steelwork of the structure and the masonry of the main pier have a difference in temperature of 50°F, there is a tendency, on account of differential expansion, for the main shoes to move upon the main pier. This motion is impossible, and hence relative deformations are produced in the structure, which give rise to stresses in the members.

There are three bracing systems abutting on to the main pier, viz:--

Anchor arm lower laterals,
Cantilever arm lower laterals,
Main post sway bracing.

The action of the differential temperature is to spread or contract the feet of these systems, but with K-bracing of the lower laterals these systems are not rigid against the action, and a lateral strut is introduced into the quadrilateral formed by the anchor and cantilever arm lateral diagonals at the main post. This strut does not run normal to the
axis of the bridge, as in this case it would take up all the stresses due to the expansion, and could not be made strong enough to do this, but runs parallel with the axis of the bridge, and thus limits the primary stresses to the lateral quadrilateral of which it is a member. The main post sway frame takes up the loads by bending of the main posts and stresses in the frame members.

These stresses are indeterminate and depend on the sections of the members, and thus can be obtained only after several trials.

(c) The anchor arm lower lateral system, as noted above, forms a beam fixed at the main pier and simply supported at the anchor. If one chord of this system is 25°F lower in temperature than the other, it tends to contract, and the whole frame tends to bend in a circle, displacing the end at the anchor pier, if the lateral support be removed. Hence, there is produced at the anchor a normal reaction which tends to replace the structure in position, and stresses are set up in the lateral system. The normal reaction is different for the two cases - "pier rigid" and "pier elastic" - and thus the stresses must be found for both cases. These stresses are indeterminate and are obtained only after several trial designs have been computed.

Torsion.

Under unsymmetrical loading of the two anchor and cantilever systems, it will be found that the end of one cantilever arm truss is depressed below the other, while on the other arm the opposite effect is produced, thus allowing two diagonally opposite corners of the suspended span to fall, and the other two, relatively, to rise. This effect is analogous to a twisting of the suspended span, and produces reactions on the suspended span hangers, equal and opposite to one another at the same end, whose magnitude depends on the elastic properties of the suspended span lateral system and portal bracing. Towards the
completion of the design of the structure the magnitude of these relative deformations can be determined, the reactions computed, and the stresses in the suspended span can be determined.

Torsion stresses are computed for the suspended span only.

Friction.

Upon the completion of the preceding investigations one is in a position to accurately determine the normal reactions on the pins at the ends of the suspended span lower lateral system, and at the anchors on the anchor arm lateral system. The end triangles of the lateral systems then are designed for a longitudinal force at the pin of 20% of the normal force on the pin. Friction stress is also taken into account in the lower sub-chord of the cantilever arm. The laterals and struts of the end lateral triangles are designed for wind, traction, temperature (c) and friction in compression, reversing for friction in tension.

Dead Load.

After the total stresses in the laterals and sway bracing have been determined, these members may be designed complete and their sectional areas obtained, due regard being paid to the bending stress due to the weight of the member. A percentage of detail, based upon the form of the member, its lacing system and the type of connections is allotted to the member, and the weights of bracing are determined. The floor can be accurately designed at the start, and the complete weights are known.

Dead load stresses in main truss members due to weight of floor are then computed on an analytical method.

Dead load stresses due to weights of truss members and bracing then remain to be determined. For the suspended span it is necessary to make initial assumptions of weight,
determine dead load stresses and design the members for their total stress. The weights of members are run out with approximate allowances for details and second trial dead loads are obtained for each panel point. This process is repeated in a number of trials, until the final reaction does not vary from the trial reaction by more than 0.5%. Summaries of total co-existing stresses are made and the members finally designed.

Considerable importance attaches to the percentages of detail allowed on each truss member. For very exact work it is necessary to draw sketches of the make-up of the member and compute its "shipping weight". The excess of "shipping weight" over its "stress sheet weight", expressed as a percentage of the "stress sheet weight" is the percentage of details. Its value depends on the type and form of member, its sectional area, and the nature of its connections and lacing, splice plates and rivetting.

When final weights are obtained, 2% overrun is allowed on all weights to give the extreme panel point loads.

Stresses in the cantilever arm can be obtained direct by analytical method, working inwards from the end of the cantilever arm to the main post. The anchor arm, however, is of a similar nature to the suspended span in that several trial dead load stresses must be computed before accuracy can be obtained.

Maximum total stresses for which the members of the main bridge were designed, and the sectional areas of the members are shown on Plan Nos. 70, 71 & 72.

**Cantilever Bridge Weights.**

The weights of the Cantilever Bridge steelwork are:

**Trusses, Bracing, Shoes, Pins and Details.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended Span</td>
<td>3,600 tons</td>
</tr>
<tr>
<td>2 Cantilever Arms and Main Posts</td>
<td>21,160 tons</td>
</tr>
<tr>
<td>2 Anchor Arms</td>
<td>18,370 tons</td>
</tr>
<tr>
<td>Approaches</td>
<td>4,070 tons</td>
</tr>
<tr>
<td></td>
<td>47,200 tons</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
</tr>
<tr>
<td><strong>Trusses, Bracing, Shoes, Pins and Details</strong></td>
<td></td>
</tr>
<tr>
<td>c/d.</td>
<td></td>
</tr>
<tr>
<td><strong>Floor.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
</tr>
</tbody>
</table>
CANTILEVER ARM
MAXIMUM CO-EXISTING STRESSES

* Denotes Compression
- " Tension

Stresses are in units of 1000 lbs
Bending Moments are in units of 1000 ins lbs.
Figures in Red denote Sectional Area of Members in sq. ins.
ANCHOR ARM
MAXIMUM CO-EXISTING STRESSES

* Denotes Compression
- "" Tension

Stresses are in units of 1000 lbs.
Bending Moments are in units of 1000 ins. lbs.
Figures in Red denote Sectional Area of Members in sq. ins.
SUSPENDED SPAN
MAXIMUM CO-EXISTING STRESSES

+ Denotes Compression
- " " Tension
Stresses are in units of 1,000 lbs.
Bending Moments are in units of 1,000 ins.lbs.
Figures in Red denote Sectional Area of Members in sq. inches.
Live Load Stresses.

A two-hinged arch is a structure indeterminate in the first degree, the indeterminate quantity being the horizontal thrust. With crossed diagonals in the centre panel a redundant member is added, the structure becoming still more indeterminate. If the areas of section of all members are initially assumed, an influence line for horizontal thrust can be obtained on the Method of Elastic Weights, using Maxwell's Principle of Reciprocal Deflections, and thus the influence lines for stress in any member can be drawn. When the design is completed upon these assumptions, further trials must be performed with the new sectional areas and the process repeated until the final sections remain constant for every member.

Live load and impact stresses are computed together for a uniform load of 6.6 units per ft. of truss for main members, equivalent to a panel point load of 330 units.

Stresses in hangers are found using the loads specified for deck system, and live load stresses in the floor.

Wind.

Normal Wind.

(a) Wind on Bridge.

Normal panel point wind loads for the first trial are estimated; for other trials the actual loads are used. The wind-bracing system for the two hinged arch bridge consists of an upper lateral frame continuous between end posts, and strong portal frames transferring the forces to the hinges, a lower lateral system continuous between hinges, with a portal bay where the floor penetrates the plane of the lower laterals. The floor system is supported underneath the arch on hangers with hinges in the transverse vertical planes, so that the floor also re-
quires a lateral bracing system. On account of the necessity of an expansion joint in the length of floor, this bracing cannot be made continuous, but is of the form of a cantilever bridge in the horizontal plane. The floor expansion joint is arranged symmetrical about the centre line of the bridge with one hinge of the floor lateral system, the other hinge being placed at the expansion joint. The main pier of the cantilever system is represented by the panel point nearest the point where the floor intersects the plane of the lower laterals, and the portal frame on the end post represents the anchor pier. In addition there are sway frames arranged at verticals from the end post to one panel beyond the junction of floor and lower laterals. These sway frames are assumed to take the upper panel point wind loads independently of the upper laterals. The end portal frame transmits the reaction of the upper laterals and the negative reaction of the floor laterals to the main hinges.

The upper and lower laterals are investigated as simple spans, and the stresses in the laterals are corrected for the variation in slope of the plane of the bracing. This variation in slope then imposes horizontal and vertical loads at each of the upper and lower panel points, outwards and downwards respectively on the leeward truss. The horizontal thrust for these loads is evaluated on the theory of indeterminate structures and the stresses in the main truss members are then found by means of a Maxwell Diagram.

Wind on floor and footway fence is a uniform normal load applied to the cantilever system of the floor laterals. The stresses in the diagonals and chords of the floor laterals are then best obtained by influence lines, and the reactions on the main trusses are imposed on the main trusses in addition to the other normal wind loads above. Overturning stresses also must be considered, due to vertical loads on the main trusses.

(a) Wind on Train.

The wind on train is a moving normal load, and must therefore be treated accordingly. The stresses in floor laterals are found from the influence lines, but stresses in
truss members are to be computed for a length of train corresponding to that for maximum live load stress.

The stresses in main truss members are best obtained by first finding the stresses due to a normal unit load applied at one point where the floor intersects the plane of the lower chord. There will be certain stresses in the lower laterals, which will produce horizontal and vertical loads on the main trusses at the lower panel point. The stresses in main truss members can be found as above, when it must be noted that the stresses on the far half of the arch for a load on the near half correspond exactly to those on the near half for a load on the far half. Then for each member, with its corresponding loaded length, the reactions on the main piers of the floor laterals are found by means of the influence lines, and the final stresses computed. Special influence lines can be drawn for the shear in the lower laterals, and by this means the stresses in the lower laterals are obtained.

Overturning stresses due to wind on train are a constant fraction of the live load stresses in main truss members.

Combining stresses due to wind on bridge and wind on train we obtain the maximum stresses due to normal wind.

**Longitudinal wind.** (b)

Using half the panel point loads due to normal wind, acting horizontally, with half the normal load on the floor, the stresses in main truss members are found by first finding the horizontal thrusts and drawing a Maxwell Diagram.

**Longitudinal Force (Traction)**

Again the traction stresses are to be evaluated for the length of train giving maximum live load stress in the member, and the best procedure is to find the stresses in members due to unit horizontal force applied at base of rail above the panel point forming the main pier of the floor lateral system. Here the traction girders are placed on both halves.
of the bridge, and the traction forces are transmitted to the main trusses. Unit force at base of rail can be resolved into unit horizontal force at the lower chord panel point, and a moment in the plane of the trusses. If we determine the horizontal thrust due to the horizontal load, that due to the vertical moment is easily obtained, and the stresses in main truss members due to unit force at base of rail are found. The stresses on the far side of the bridge with load on the near side correspond to those on the near side for load on the far side. Combining the stresses produced by the actual loads on the two halves will give the maximum coexisting traction stress in the member.

**Centrifugal Force.**

The Northern Approach spans have to resist lateral forces due to wind on bridge, which produce lateral and overturning stresses on the spans, the forces being treated as a moving load.

**Temperature.**

(a) If the uniform temperature of the structure varies by 60°F, there is produced a horizontal thrust at the hinges, which gives rise to primary stresses in all the truss members.

(b) When there is a difference of temperature of 50°F between the steelwork and the masonry of the abutments, there results a spreading or closing action on the two frames abutting at the hinges, viz.: the lower lateral system, and the end post portal frame. This is assumed to produce stresses in the members of both frames only as far as the floor level, and the stresses are determined in both frames due to reactions at the hinges, whose magnitude depends on the elastic properties of the frames. The lower lateral frame has two redundant members in addition, and the portal frame one redundant member, and the stresses are found on the ordinary theory of redundant members.

(c) If one lower chord of the bridge is 25°F lower in temperature than the other, there is no primary statical action upon the lateral systems as for the Cantilever Bridge, but the
only result is a fall of the truss whose lower chord is lower in temperature, and secondary stresses set up thereby.

**Dead Load.**

The Arch Bridge is erected on the cantilever system and closed at the crown, where a temporary hinge is inserted. After the floor beams and stringers of the floor have been placed in position, the arch is closed at a mean temperature, and the chords in the centre panel are rivetted up, completing the two-hinged structure. Thus the stresses due to truss dead load and part of the floor dead load are to be determined as for a three-hinged arch, and for the remainder of the floor as for a two-hinged arch.

The three-hinged arch is statically determinate, and the horizontal thrust is easily found. Influence lines for horizontal thrust are of advantage on account of the number of trials necessary to determine final dead loads. Having a series of dead loads at each panel point of the structure, the horizontal thrust is determined, and the stresses in the parabolic lower chord are found for this thrust. If the dead load were uniform, giving the same horizontal thrust, these would be the only stresses in the structure. But as the load is not uniform, the bracing system has to take up stresses due to the difference between the actual loads and the panel point loads due to this uniform load. These stresses may be calculated by ordinary analytical methods as for a simple span, as the horizontal thrust is already fully accounted for.

The floor dead load stresses for the two-hinged arch are found from the influence lines.

When, after a number of trials, the final stresses reach stability and the sectional areas of all members are known, the weights of various members can be computed, with exact regard for percentages of details on the same principles as the Cantilever Bridge. The forms
of the various members are widely different in these two bridges, and the percentages of
details in the members of each bear no relation to one another. For the Arch Bridge, the
maximum total stresses and sectional areas of members obtained on the completion of the
second trial are shown on Plan No. 73. The third and final trial at date of entry was not
complete.

**Arch Bridge Weights.**

The weights of steelwork in the Arch Bridge are:

<table>
<thead>
<tr>
<th></th>
<th>Trusses, Bracing, Shoes, Pins and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main arch</strong></td>
<td>27,600 tons</td>
</tr>
<tr>
<td><strong>Approaches</strong></td>
<td>7,800 tons</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong> 35,400 tons</td>
</tr>
<tr>
<td><strong>Floor</strong></td>
<td>11,100 tons</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>46,500 tons</strong></td>
</tr>
</tbody>
</table>
ARCH BRIDGE

MAXIMUM CO-EXISTING STRESSES

(2nd Trial)

+ Denotes Compression
- Denotes Tension

Stresses are in units of 1000 lbs.
Bending Moments are in units of 1000 ins. lbs.
Figures in Red denote Sectional Area of Members in sq. ins.
DESCRIPTION OF BRIDGES.

In the Cantilever design, Plate 65, the main Bridge consists of steel cantilevers spaced 93'6" apart centre to centre, with Shore and Harbour arms each 500 feet long; the Harbour arms supporting a central span 600 feet long. The clear span from centre to centre of main piers is 1,600 feet, the three approach spans on either side of the main span are each about 200 feet long; the remainder of the approaches will consist of concrete arches masonry faced.

The main piers, located on Dawes' Point and Wilson's Point, will be founded on solid rock about 20 feet below mean sea level, the Harbour being crossed in one clear span without any pier in the fairway, so that for all time navigation will be as free and as unrestricted as at present. An area of 10 acres has been reserved at the site of each pier against mining.

Headway for shipping of 170 feet above high water is provided under the centre 600 feet of Bridge; this headway being 12 feet less at the piers. The headway is 20 feet greater than that provided by the Forth Bridge or the Quebec Bridge, and 35 feet greater than that provided under the four bridges across the East River, New York, the Brooklyn, Williamsburgh, Blackwell Island, and the Manhattan Bridge, and is ample to meet present and future requirements.

A view of the approach spans, anchor arms, anchor pier and main pier of the Bridge at Dawes' Point, as these will appear to a passenger on a ferry boat rounding Fort Macquarie is shown by Plate No. 74. The main piers will be prominent features in the seascape of Sydney Harbour. They will be constructed of concrete with granite masonry facing, and every effort has been made to secure a design which, in its massive ruggedness, will be
simple and dignified.

Plate No. 75 illustrates the arch-approach spans on the City side; the avenue in approach to the Bridge, 120 feet wide, will be flanked by buildings as shown. The view from such buildings would be unsurpassed.

As it will be the year 1930 before the Bridge can be opened for traffic, the Chief Railway Commissioner requires four lines of railway to be provided across the Bridge.

In addition to the four railway tracks, there will be a roadway 57 feet wide, providing for six lines of vehicular traffic, and two footways each 10 feet wide. The wearing surfaces of the roadway and footways will be the best Seyssel Mastic Asphalt. Plate No. 50.

Plan No. 76 shows the portals of the Bridge. It is fitting that the Bridge should have dignified portals at either side in keeping with the magnitude of the main structure.

The Arch Bridge, Plate No. 66, consists of two-hinged steel spandrel braced main trusses set in a vertical plane spaced 98' 6" apart centre to centre and having a clear span of 1650 feet centre to centre of hinges, the cross girders are spaced 50 feet apart longitudinally. The rise of the centre line of the bottom chord above the horizontal line through the centres of hinges is 370 feet, the depth of the arch centre to centre of chords at the crown is 60 feet and at the abutments 130 feet. The abutment towers are to be constructed of reinforced concrete, granite masonry faced, whilst the ordinary piers and abutments are of concrete masonry faced.

There are 14,500 tons less steel in the arch design than in the cantilever design but the granite masonry is more expensive whilst the arch bridge may be somewhat more difficult to erect, the cost of pontoons etc. for floating out the centre span so that it can be lifted into position will be avoided. The reflection of the cantilever bridge
under live load is 13\(\frac{1}{2}\) inches whilst that of the arch bridge is 7 inches, and on the northern side of the harbour the radius of the curves leading up to the arch bridge will be 20 chains as against 8 chains with the cantilever bridge. This is because the railway cannot begin to curve before the anchor pier of the cantilever bridge is passed, whereas with the arch design the railway can curve at the main abutment tower and thus easier curves can be obtained.

The cost of the arch bridge should be from £400,000 to £500,000 less than the cantilever bridge.

Plan No. 77 shows a view of the southern abutment pier and portal of the arch bridge and Plate 78 a cross section of deck.
ARCH BRIDGE AT CROWN
METHOD OF ERECTION.

CANTILEVER BRIDGE.

The Cantilever Bridge including the suspended span can be erected across the Harbour without any falsework by cantilevering out until the Bridge meets in the centre. Additional members would be required during construction, which would add to the cost of the work; when the Bridge is completed these members would have no part in the finished structure.

The method, which will probably be adopted if the tender for the Cantilever design proves lowest, is by floating out the centre span and lifting it in position. The pictures will make this clear, and it will be seen from them how the bridge can be constructed without interfering in any way with the shipping and ferry traffic. The main and anchor piers will first be constructed and later the approach piers and the steel trusses, shown on the left of Plate No. 79, of the approach spans will be proceeded with.

Plate 79 shows a further stage in construction. On the Milson's Point side the "Shore-Arm" of the Cantilever is shown completed, but still resting on the false-work (or staging). This "shore-arm" is attached to the "anchor pier", and the weight of this half of the cantilever and the anchor pier, will more than balance half the span from main pier to main pier, as it is built over the waterway.

As the floor of the Bridge is built out, a large bridge-erecting "travelling-gantry" will be erected, as shown, for the purpose of lifting the massive bridge members into position. As each piece - weighing many tons - is placed in position, it will be connected securely to the main structure, so that at all times during construction the completed portions will be absolutely safe. On the Dawes Point side, the approach spans are shown completed and the floor system of the cantilever shore-arm can be seen resting on temporary falsework.

Plate No. 80 also shows the main cantilever arm on the Milson's Point side completed, and
the falsework or staging removed from beneath the shore-arm. The cantilever arm on the
Wilson's Point side is now ready to carry the suspended span as will be described later.

On the Dawson Point side, the view shows the shore-arm completed, but with the
temporary staging used for its construction still in position.

The Harbour arm of the cantilever is shown nearing completion, also the "travelling
cracking gantry", which lifts the bridge members into position after they have been towed
from the fabricating works.

When the last member of the Harbour arm is placed in position, this travelling-
gantry will be dismantled and removed; the further operations in connection with the erection
of the suspended centre span being conducted from the ends of the cantilevers.

Plate No. 80 shows the suspended span, 600 feet long, 100 feet high, and weighing
some 5,000 tons, resting on falsework after fabrication on the harbour foreshore at Lavender
Bay. When completed, it will be carried on pontoons and towed out to the bridge site.

Plate No. 81 shows both arms of the cantilevers completed with the suspended
span 600 feet long being towed to the bridge site.

The lifting of this span into position is a work of great magnitude requiring the
utmost care and engineering skill. Every movement has to be accurately planned, and all the
lifting gear specially designed.

Plate No. 82 shows the centre span as it will be suspended prior to lifting. The
pontoons have been floated away clear of the Bridge.

The lifting of the span is accomplished by means of eight hydraulic jacks, two at
each corner of the span. These jacks, arc, of course, operated in unison, and to guard
against accidents will be followed up by heavy screw jacks. The work is carefully watched
throughout, and every man employed has his duties scheduled on a predetermined plan. The
lift of the jacks gives a two-foot rise to the suspended span. This again is secured by heavy pins, and the lifting jacks adjusted for the next lift, also of two feet.

Slowly - inch by inch - the great load of some 5,000 tons rises through the height of 170 feet, until at last it is connected to the main structure by specially designed pins.

Making use of that well-known physical property of water - its incompressibility - the operation of lifting is a simple one; the hoisting chains are pinned to the lifting girder when the hydraulic jacks are in their lowest position. The jacks are slightly raised to release the lower pins, which are then withdrawn and the jacks pumped up until the next pin-hole comes opposite a hole in the lower diaphragm. Plates Nos. 33 and 34.

On the extreme upper ends of the cantilever arms of the main bridge are placed heavy erection-girders, supported on specially designed rocker-bearing, to equalise the load on the suspension bars carrying the jacking girder.

On this jacking girder, which is rigidly connected to the erection girder overhead by the suspension bars, are placed the 1,000 ton hydraulic jacks, with the rams down to the lowest point. Both the jacking and the lifting girders are provided near each end with double diaphragms through which the hoisting chains (or bars) pass. With the jacking girder connected to the suspended bars, it will be evident that the lifting girder is free to move upwards.

In commencing operations the lifting chains (or bars) are pinned to the lifting girder, the lower ends of the chains being, of course, attached to the suspended span. The pin-holes (12 in. diameter) in the chains are spaced two feet apart.

The pins connecting the lifting chains to the rigid jacking girder have to be withdrawn to accomplish which the jacks are slightly pumped up.

Hydraulic jacks are pumped up to the full capacity of the ram - two feet - and the lifting girder raised a corresponding distance, carrying the lifting chains, which are at this
Erection Girder

Suspension Bar

Lifting Girder

1000 Ton Hydraulic Lifting Jacks

Working Platform

Jacking Girder

Lifting Chains

End of Cantilever Arm of Main Bridge

End of Suspended Span

Length 600 ft  Weight 6000 Tons.
Erection Girder on Cantilever Arm

Suspension Bars

Ready for 2 ft Lift

After 2 ft Lift Completed

Platforms

1000 Ton Jack

Lifting Chains

Enlarged Detail of 12 inch Dia. Pin
time free to move through the diaphragm of the jacking girder until the next hole comes up into line. When this occurs, the lower pins are pushed into position, and the gain of two feet secured.

The upper pins are then withdrawn and the ram of the jack, with the lifting girder, run back ready to repeat the operation.

The eye-bars of the main permanent structure are arranged between the suspension bars of the temporary lifting gear. Corresponding eye-bars are also attached to the suspended span. When the lift is completed and the pin holes of these upper and lower sets of eye-bars come into line, the permanent pins are pushed into place, thus permanently securing the suspended span to the main bridge.

When the centre span is in position the erection of the bridge is practically completed. The construction of the railway tracks and roadways has then to be undertaken, and the decking and simpler details attended to; the difficult work, however, is through when the suspended span is secured in its final position.

ARCH BRIDGE:

The Arch Bridge will be erected by cantilevering out from either pier until the end meets at the centre, when the final rivetting up will take place. Each half of the Arch will be securely anchored and tied to the shores on either side until the central connection is made.
PROVISION FOR TRAFFIC DURING ERECTION OF BRIDGE.

During construction, the railway passenger traffic using the existing Milson's Point Station will be diverted to the station constructed some years ago along the foreshores of the harbour near Lavender Bay, and the goods traffic will be diverted from Milson's Point to its final location at North Sydney Station.

To enable the goods traffic to be so diverted the author began the construction of the railway approach to the Bridge from Bay Road Station to North Sydney Station on July 30th last.

A compressor house has been erected at the site of North Sydney station, and a second between Eureka Street and Anorun Street. Three compressors have been installed, electrically driven, each by a 75 HP motor operating on three-phase current, 25 cycles at 440 volts. Each compressor cylinder is 14" diameter, 12" stroke, and working at about 200 revolutions per minute; each machine induces 464 cubic feet of free air per minute from the atmosphere, compresses it to 100 lb. per square inch, and delivers it to the air-receivers, from whence it is conducted by 3" pipes to the air-driven jack-hammers, which drill the holes in the rock preparatory to blasting.

In the transformer house alternating current at 6600 volts is transformed to 440 volts before it is led to the motors.

A gyrating stone crusher electrically driven has been installed and the hard sandstone will be broken into concrete metal and used in constructing the concrete retaining walls and tunnel lining.

In less than two months after construction was authorised some 34 houses were vacated, sold and demolished and the plant installed, and on September 19th Miss Butler
switched on the current to No. 1 compressor, Plate 85, and set the machinery in motion to begin the construction of this great work.

The land so made available at Milson’s Point will be utilized by the Contractor as a yard for building the bridge, in fact it would be almost impossible to build the bridge without the area of land in question. Plate No. 86 shows the position of the new station and the area of land available.

By June 30th, 1924, the present Milson’s Point Station will cease to exist, and the Railway traffic will be terminated at the new Station on the foreshores of Lavender Bay. The shunting necessary to marshal the trains will be mainly carried on adjacent to and in front of the Station which will be reconstructed so that the railway passengers will walk off the platforms to the ferry on the level, as at the present Milson’s Point Station. The railway passengers will suffer no inconvenience when the new station is again in operation, and will not have to climb up and down the steps as was necessary before, when this station was in operation in 1915.

The tramway traffic will also be diverted to the new station and connected with the ferry there. A short length of tramway will be constructed from Alfred Street along Dind Street and will terminate on the cliffs above the new station. To connect the tramway with the ferry, a bridge 30 feet wide on a grade of 1 in 10 will be provided, the harbour end of this bridge will terminate near the ferry wharf, but 35 feet above the wharf. To negotiate this 35 feet to and from the ferry, three escalators of the latest pattern will be provided. Each escalator will be 4 feet wide, of the reversible type; will be driven by an electric motor; will have a travelling speed of 90 feet per minute, and will have a capacity of 9,000 to 10,000 passengers per hour. In the morning rush hour, the main traffic will be from the tram to the ferry and two of the escalators will be used to convey passengers in that direction, the other escalator will take them up from the boat to the tram. In the evening
rush the conditions will be reversed, and two escalators will be used to convey the passengers up from the boat to the tram, the third conveying them down.

In addition to the escalators there will be stairways for those who prefer walking, and there will be a lift for aged people and others who would prefer not to use the escalators and could not use the stairways. The lift will also be used to convey luggage, mails, etc., between the tram, ferry and train. Railway passengers from the trains will have direct access to the trams, and will not have to walk up Alfred Street as was necessary when this station was in operation before. Plate No. 87 shows the arrangement of the escalators and stairways and the tramway diverted to the new station.

A new vehicular ferry is to be opened between Dawes’ Point and McMahon’s Point and consequently the volume of vehicular traffic using the Milson’s Point route will be about half of what it would otherwise be.
THE TOWN PLANNING ASPECT.

In designing this great work every possible opportunity has been taken to improve the conditions that exist. The Author has recommended that the Harbour foreshores from Lavender Bay to Wilson's Point, now used for railway purposes, should eventually be made into a Park (see Plate No. 88), and no more beautiful or more suitable site can be found in North Sydney.

Grassed lawns, with a little statuary on the water front, the cliffs covered with creepers, bougainvillia, and shrubs, to provide masses of colour as a background, would transform the present wilderness into beautiful gardens in the style may be of the celebrated Italian Gardens, The Boboli, The Pamphilj, The Doria, or the Villa de Medici.

The area above the ornamented cliffs made rich by masses of green and garden bloom, could also be entirely remodelled. Residential flats and other buildings in Italian renaissance to harmonise with the gardens below could be constructed here in charming surroundings, with fine arcaded walks on the edge of the cliffs overlooking the waters of the harbour. Treated broadly, these walks could be made most picturesque spots, and most delightful resorts for the residents during the long summer evenings.

Portions of the walks could be covered in with Pergola roofs supported by dark hardwood timbers and plain white rough-cast arches to harmonise with the buildings in the background and in keeping with the scheme of ornamentation in the gardens below. Plate No. 89.

This is not a visionary scheme for the beautification of the northern shores of the harbour, but a practical proposal which the North Sydney Council or other authority could well carry out with substantial profit to the promoters of the enterprise.

On the City side between the eastern side of the arched viaduct and York Street North, there is an area of ground, where the high bank now is, which will be trimmed off and formed into a Park. (See Plate No. 75).
Proposed Treatment of Roseberry Lavender Bay

Utilizing Existing Railway Area for Ornamental Gardins
An area of land of about half an acre will be added to the Girls' High School grounds; the Observatory Park being kept intact. Watson Road will be continued to the main avenue, thus affording direct access for vehicular and pedestrian traffic from Miller's Point to the bridge. Between the railway viaduct and Trinity Avenue there is a piece of land 48 feet below the railway and 27 feet above the street level, of an area of one acre, including the space under the arches. It is proposed to give access to this area by steps, and convert it into a children's playground.

At the bridge head Catherine Crescent will connect the main avenue from the bridge with York, Clarence, and Kent Streets; as shown on Plate No. 90, the Author has recommended that the areas flanking the Crescent be turned into beautiful Parklets.

When the Bridge and City Railway are constructed it will be necessary to widen certain streets to carry the traffic, which must develop.

By Catherine Crescent, York, Clarence, and Kent Streets can be most satisfactorily connected to the bridge approach, and when the Sydney Harbour Bridge and the bridge to Balmain are constructed the crescent will distribute traffic along these high-level streets as efficiently as possible.

Sydney to-day may be divided broadly into three zones; the eastern zone, from Macquarie Street to Elizabeth Street - the professional and residential; the central zone, from Castlereagh Street to George Street - the shopping; and the western zone, from York Street to Darling Harbour - the warehouse and shipping zone.

The professional zone, including as it does the Houses of Parliament, Law Courts, Public Libraries, Sydney Hospital, Royal Society, and various clubs, will always be preferred by doctors, barristers, solicitors, dentists, and other professional men requiring a quiet location near the centre of their activities; the fact that one side of Macquarie Street
and one side of Elizabeth Street is flanked by park lands renders these streets more valuable for professional than for shopping purposes.

The shopping zone embraces Castlereagh Street, Pitt Street, George Street, and Elizabeth Street South, with Liverpool Street and Oxford Street as east-west avenues. With the advent of the City and Suburban Electric Railways and the Sydney Harbour Bridge land in this zone will rapidly increase in value.

Sydney is going skyward, for these streets now flanked by two, three, and four storey buildings will have to be fronted by much higher buildings for the owner to get an adequate monetary return; already there is evidence there is evidence of the advent of the tall building. And what will the traffic then be like? To-day vehicular traffic is allowed in one direction only in Pitt Street and in Castlereagh Street, whilst the footpaths are far too narrow. The footpaths will have to be increased in width, by arcing the shop fronts, or by narrowing the widths of the roadways, or by straight-out resumptions, and the trams must be removed from these streets or placed underground, and vehicular traffic allowed to proceed in both directions. In some of the busiest shopping areas, as the block bounded by King, George, Market, and Pitt Streets, an upper level footpath, above the street level, will without doubt be constructed in the future, as it will be required to give the necessary shopping facilities. George Street will be the main shopping thoroughfare, and will be flanked by tall buildings from the Quay to the Broadway.

**SUBURBAN GOODS STATIONS.**

The warehouse and shipping zone is and always will be occupied by warehouses, by produce merchants, as in Sussex Street, and similar commercial establishments, which must of necessity be close to the wharves and the railway goods yard. With the advent of the system of City and Suburban Railways there will be railway goods stations probably at North Sydney, Mosman, Manly, Narrabeen, Balmain, Bondi, Randwick, Daceyville, etc., and the produce and goods which
now arrive at Darling Harbour by train and along the sea-front by boat, instead of being distributed through the streets of the city and suburbs, as at present, will be carried to the suburbs by railway, except in the warehouse area in the city and in Pyrmont, where it will be taken, as at present, by vehicular traffic using the streets. With the inevitable increase of vehicular traffic to and from the railway goods yard and the wharves it is essential that adequate means should be provided to cope with this traffic.

Here it will be interesting to note the traffic counts of vehicles made on July 2nd, 1925, between the hours of 7 a.m. and 6 p.m., the numbers given being the average daily traffic in both directions. At the Fort Macquarie ferry, 1776 vehicles; at Dawes' Point ferry, 472 vehicles; at the intersection of Boomerang and College Streets, 3650; William and College Streets, 2484; Oxford and College Streets, 10,580; Elizabeth Street and Eddy Avenue, 23,752; Central Railway Square, 17,112; and Pyrmont Bridge, 15,106 vehicles - a total of 80,934 daily in both directions.

The return herewith furnished by the Inspector-General of Police showing the volume of traffic passing over various points during eight hours of any one day is instructive. There were sixty-one checking points, and the totals for the whole of those points represent:-

**MOTORS.**

- 105 steel-tyred wagons above 3½ tons.
- 6,635 wagons with solid rubber tyres above 3½ tons.
- 15,539 wagons with solid rubber tyres under 3½ tons.
- 1,379 trucks with pneumatic tyres above 3½ tons.
- 16,393 trucks with pneumatic tyres under 3½ tons.
- 50,333 motor-cars.

**HORSE-DRIVEN.**

- 29,603 four-wheeled vehicles with steel tyres.
GROSS TOTAL OF HORSES.

61,496 horses, whether included in above figures or not.

MISCELLANEOUS VEHICLES.

14,603 wheel traffic, not included in the foregoing figures.

The number of pedestrians where the count could be taken totalled 99,661. Pedestrians were counted at 44 points in the city, but at 17 points no count was taken, as the great number of foot passengers rendered it impossible to check them with any reasonable degree of accuracy. It is considered, however, that the pedestrian traffic was probably more than double that recorded.

The grand total of vehicles, motor and horse-drawn, horses, and pedestrians, as well as miscellaneous vehicles, is shown to be 345,001.

The density of the tramway traffic, particularly during the morning and evening rush, when the headway on George, Pitt, and Elizabeth Streets is 17 seconds per tram in one direction, and the headway on one track in each street at the intersection of King and George Streets is six seconds, greatly increases the difficulty of satisfactorily handling the vehicular traffic of the city, and this traffic is now assuming very serious proportions, as the figures above, given by Superintendent Brack, indicate.

At Central Station the passenger traffic is very heavy between the hours of 4 p.m. and 6:30 p.m. In those 2½ hours on May 9th, 1920, 58,122 passengers entered and 10,372 passengers left the station, the maximum hourly traffic being between 5:10 p.m. and 6:10 p.m., when 37,200 passengers entered and 5760 passengers left the station. Based on the traffic statistics of other cities, this represents a daily traffic of 250,000 passengers - i.e. 125,000 passengers in and out of the station daily. Liverpool Street Station, London, has a daily traffic of 200,000; Gare Saint Lazare, Paris, 250,000 per day; and South Station, Boston, 270,000 per day; so that
the passenger traffic at Central Station is equal to, if not greater than, any other station in the world. Central Station is a tram terminus as well as a train terminus, and is a transfer point rather than a terminal station. Sydney Central will not always be the only terminal in the metropolis; a terminal station to deal with the northern and north-western traffic will probably be situated at St. Leonards in the years to come.

The construction of the City Railway, with its five projected stations in the heart of the city—viz., Town Hall, Wynyard Square, Circular Quay, St. James', and Liverpool Street—involves the reclamation of Darling Harbour. (Plan No. II.) Twenty-three acres of water are now being filled in and the area added to the railway goods yard; a road 100 ft. wide is being constructed around the foreshores of the harbour, from Jones Bay to Bathurst Street, with a bridge over the railway tracks to Union Street; access to the new goods yard will be obtained from Barker Street, which is to be widened to 60 ft., whilst the Harbour Trust is constructing a road along the foreshores of Darling Harbour from Bathurst Street northwards. When the reclamation and these roads are complete Pyrmont Bridge will be removed.

Traffic in this vicinity at present is badly catered for, and with the growing traffic to the goods yard and the wharves the congestion will rapidly become worse. Present conditions force the traffic along the narrow north-south streets parallel to the harbour, and thence into or across George Street to reach the northern, eastern, or western suburbs. To relieve George Street of this traffic, especially from Market Street via Railway Square to the University corner, the Conference has adopted the proposal made by the author to construct a new road from the intersection of Dixon and Liverpool Streets, thence on viaduct across the low-lying land reclaimed when Cockle Bay was filled in, and over the Darling Harbour Railway, reaching the surface at Harris Street. From Harris Street to Wattle Street the road would be continued along MacArthur Street, which street would be cut down and regraded to a ruling grade not steeper than 1 in 30,
whilst Bulwara Road and Jones Street would be carried by bridge over the cut of regraded Macarthur Street. From Wattle Street the new roadway would be on the surface, following the route shown, and would junction with the Broadway beyond Glebe Point Road; Dixon Street to be widened and extended to the new avenue, so that the traffic from this busy commercial area would have ready access to the avenue.

On the western side of the viaduct, a low-level street between Dixon Street and Little Quay Street would connect the cross streets, whilst William Henry Street would take the traffic from this low-level area across the railway to Harris Street. From the intersection of the new avenue and Broadway a new road to be constructed through Victoria Park to Cleveland Street. A roadway was provided for some two years ago in the agreement arrived at between the City Council and the University Senate, the University exchanging some 7½ acres of land, including the ornamental lakes, for a similar area of land owned by the City Council.

The facilities proposed should effectively relieve George Street of its present congestion from Market Street to Broadway.

FORECAST OF A SECOND HARBOUR BRIDGE.

In endeavouring to provide for the traffic of the future, the vehicular traffic in the central or shopping zone must as far as possible be confined to the vehicular traffic legitimate to that zone, and all extraneous vehicular traffic compelled to traverse the eastern and western zones. With the advent of the Sydney Harbour Bridge, and probably for 25 years thereafter, all the traffic which now uses Macquarie, Elizabeth, or other streets in the eastern zone to proceed via the ferry to Milson's Point will of necessity be compelled to use the western zone, as the vehicular ferry from Fort Macquarie to Milson's Point will cease to run.

About twenty-five years after the first bridge is completed a second bridge will be required; it will probably be a suspension bridge carrying vehicular and pedestrian traffic,
located between Kirribilli and Fort Macquarie; when the second bridge is constructed Macquarie Street will again carry traffic to and from North Sydney.

**FUTURE OF THE CROSS STREETS.**

Upon completion of the Bridge now in contemplation, the traffic from the eastern, south-eastern, and southern suburbs will endeavour to reach the main bridge approach by the roads having the easiest grades, and the heavier and slower-moving vehicles will attempt to cross the city immediately north or south of the Town Hall; the choice of street lies between Goulburn, Liverpool, Bathurst, and Park Streets. One of these streets must be widened. Goulburn Street is narrow, crooked, has steep grades, and has no direct access to Taylor Square, which is the focal point of the eastern suburbs traffic, nor is the street axial to the traffic to and from the railway goods yard and the general scheme of wharfage. From a town planning aspect it would be highly desirable to remodel Goulburn Street. The property is of a poor class; it is a second-class residential district, which must become a commercial area. From Taylor Square the traffic would probably be best served by following Campbell Street to Riley Street, thence along a new road to be constructed through the centre of the area already resumed by the City Council for remodelling purposes to the intersection of Goulburn and Commonwealth Streets, and thence the traffic could travel along Goulburn Street to the new avenue.

Liverpool Street via Oxford Street has good access to the eastern suburbs, but it also is not axial to the goods and shipping traffic, whilst the advent of two busy passenger stations under Hyde Park, with entrances from Liverpool Street, will throw a heavy pedestrian traffic along and across Liverpool Street, making it desirable to minimise the vehicular traffic in Liverpool street if possible.

Park Street has good grades, and connects with York Street, which is one of the best graded north-south streets in the city; but the right-angle crossing of the heavy vehicular and
tramsway traffic in George Street, also the right-angled turn from Druiit Street into York Street would seriously reduce the efficiency of this route as traffic avenue, would unduly congest the traffic, and would be a constant source of danger and confusion, whilst via this route there can never be any adequate connection with the goods yard and wharves, as the grades in the east-west streets are too severe.

There now remains Bathurst Street. It has good grades, has direct access to the railway and shipping, and will accommodate the traffic better than any of the other mentioned streets. It has the disadvantage, however, that it is not a through street, but by connecting it with Oxford Street and with William Street and Faig Avenue by two diagonal roads through the Hyde Park it will become a better traffic than any of these streets.

NORTH SOUTH TRAFFIC.

After deciding on the widening of Bathurst Street and the diagonal roads through Hyde Park, the north-south traffic must next be considered in relation to the bridge, the shipping, and the railway goods yard. This north-south traffic must be diverted from the shopping zone if possible. In the eastern zone, Macquarie Street and Elizabeth Street have been widened, and will accommodate much more traffic than they are called upon at present, whilst the abandonment of the vehicular ferry from Fort Macquarie to Wilson's Point will throw this traffic into the western zone in the near future.

In the western zone three streets require consideration—viz., York Street, Clarence Street, and Kent Street. The two first named have better grades than Kent Street, but are open to the very serious objection that they are dead-end streets, effectively blocked from future extension by the Town Hall itself, and there is the further fatal objection that the traffic to and from the Darling Harbour goods yard and the wharves would have to negotiate the very steep side streets, viz., Druiit Street, Market Street, King Street, and Erskine Street, or proceed
via Bathurst Street into George Street, and thence into York or Clarence Street.

Kent Street, on the other hand, although it is not as well graded a street as York Street or Clarence Street, can be regraded satisfactorily, can be extended through to George Street, and can be connected with the road across the reclamation at Darling Harbour, with a widened Bathurst Street, and with the new high-level road proposed from Dixon Street to the Glebe, much better than any other north-south street in the city can. It can also be satisfactorily connected with the avenue in approach to the Sydney Harbour Bridge, and was, therefore, recommended to be widened to provide for six lines of vehicular traffic and two footpaths, each 12 feet wide - i.e., 61 feet in all.

The widening of York Street to 61 feet from Grosvenor Street to Wynyard Street can readily be done at the present time, as the Scots' Church is about to be rebuilt; the Government owns the land at the corner of Margaret and York Streets; the remaining land is portion of Lang and Wynyard Square Parks, some Government land in the Rocks area, and a strip from St. Phillip's Church, which is necessary to realign York Street on the western boundary.

Watson Road will form an adequate getaway for the traffic wishing to reach Miller's Point and the Quay.

Minor street alterations necessary to facilitate traffic are the widening of the roadway to 76 feet at the Registrar-General's corner and Hyde Park. The City Council has approved of extending Elisabeth Street to Kent Street.

When the City Railway is constructed at the Quay Barracks Street will be closed, but Alfred Street will be extended to George Street, whilst Pitt Street will be widened as shown.

The crescent connecting the avenue from the bridges can be treated architecturally, whilst the two areas of land available on either side of Clarence Street can be formed into two beautiful parklets. These would more than compensate for any land taken from Wynyard.
Square and Lang Parks, whilst the crescent could be made one of the beauty spots of the city.

Plan No. 91 shows the new streets and the street widening decided upon. Those tinted in red have been adopted as the policy of the City Council, and were originated by the Author.
THE FINANCIAL ASPECT.

The complete cost of the Sydney Harbour Bridge will be about £6,000,000 sterling, of which two-thirds or £4,000,000 - the cost of providing four lines of railway across the Bridge, including the approaches from Bay Road Station to Wynyard Square Station is the railway portion of the cost, and is to be added to the Railway Capital Debt - whilst the remaining one-third, viz., £2,000,000 - the cost of providing the main roadway, and footways, is the Municipal portion of the cost - and is to be defrayed by a tax of one half-penny in the £, imposed on the unimproved capital value of the lands situated in the City of Sydney, in the Municipalities of North Sydney, Mosman, Manly, Lane Cove, and Willoughby, in the Shires of Ku-ring-gai and Waringah, and in that portion of the Shire of Hornsby directly served by the railway system.

Assuming the railway can be opened for traffic on 1st January, 1931, the Chief Railway Commissioner estimates that, after paying interest at 5½ per cent on £4,000,000 and all working expenses and maintenance, the revenue derived from the passenger traffic across the Bridge for the first twelve months would yield a surplus of £262,826, charging a fare of 3d. for the run from Kirribilli Station to Wynyard Square Station, a distance of over 1½ miles.

At present for this distance, allowing the passenger to walk 18 chains to the boat on the North Sydney side, the fare is by tram 2d., by ferry 1 1/3d., season ticket, or 2d. ordinary fare, making the total fare either 3 1/3d. or 4d., whilst the time of journey will be reduced by at least twelve minutes.

The Act provides for the Municipal portion of £2,000,000 to be defrayed by a tax on the unimproved capital value of the land in the City of Sydney, and the Shires
and Municipalities on the northern side of the Harbour, vis., part of the Shire of Hornsby, and the Shires of Ku-ring-gai and Warringah, the Municipalities of North Sydney, Mosman, Manly, Lane Cove, and Willoughby. The tax was imposed this year, 1923, and is paid to a special account. This account will be credited or debited with interest, as the case may be, at the average rate of interest paid by the State for loan money that year.

In 1901, the unimproved capital value of the City of Sydney was £20,207,812; in 1911, £23,940,030; and in 1921, £35,687,376. For the twenty-year period 1901-1921 the unimproved capital value increased at the rate of 2.92 per cent per annum, and for the ten-year period 1911-1921 at the rate of 4.19 per cent per annum.

In 1901, the unimproved capital value of the Shires and Municipalities on the northern side of the Harbour enumerated above, stood at £4,701,742; in 1911, at £7,247,436; and in 1921, at £16,523,208. For the twenty-year period 1901-1921 the unimproved capital value increased at the rate of 6.49 per cent per annum, and for the ten-year period 1911-1921 at the rate of 8.59 per cent per annum.

It has been shown by the experience of other countries that a very much greater increase may be anticipated with the construction of the Bridge.

The Rapid Transit Commissioner for Philadelphia in his Report of 1913 pointed out that while it is very difficult to estimate the exact amount of enhancement due to Metropolitan Railway Construction, the available figures for American cities show remarkable results. The accelerated increase in the land values of the section containing One Hundred and Thirty-fifth Street, New York, was about six times the cost of construction through this District. The assessed value of unimproved property in the 46th Ward, West Philadelphia, increased 546 per cent during the 12 years following upon the construction
of the Market Street Subway Elevated Line.

"This shows the enormous enhancement of value of land only, in outlying districts, due in large part to the Rapid Transit Lines, amounting in twelve years in this Ward to over 500 per cent to the great benefit of the owners, also of the City in point of increased assessable values and tax returns."

The report of the Special Sub-committee on the Passenger Transportation Problem of Manchester (1914) states, inter alia:--

"An enlightened policy as regards the carrying out of street improvements and improved transit facilities brings considerable benefits to the city in the shape of increased ratable values. As an illustration, the Whitworth Street improvements may be cited. After the completion of the works, the ratable value of the property in the immediate vicinity showed an increase of 245 per cent."

In determining the taxation, the author assumed that the Unimproved Capital Value of the City would increase at the rate of 4% per annum and the suburbs on the northern side of the Harbour at the rate of 3% per annum on this basis.

Fifteen instalments of the tax if imposed in 1923 would yield a sufficient sum to liquidate the Municipal moiety and all interest charges, also lighting and maintenance for the first five years after the Bridge is completed, leaving a balance in hand, the interest on which would defray the upkeep, maintenance, and lighting of the Bridge for all time, as provided for in the Act.

If the tax were not imposed until after the Bridge was opened for traffic, accrued interest during construction, £22,234, would have to be liquidated as well as the Municipal portion of £2,000,000. In addition, the upkeep and lighting of the Bridge would have to be provided for, and for all time afterwards, and the taxpayers would be called upon to find at least £1,250,000 more than if the tax had not been imposed this year. It is clearly to the advantage of the taxpayers to impose the tax at once instead of waiting until the Bridge is opened for traffic, whilst the tax so raised will materially assist in financing the Bridge during the next three years.
CONCLUSION.

As required by the by laws, in concluding this thesis I certify that all the proposals herein contained and approved for construction were originated by me.

(a) The Metropolitan Railways as located.

(b) The extent of the electrification.

(c) The location of the City Railway partly elevated and partly underground, notwithstanding that the Royal Commission on the Improvement of the City of Sydney and Suburbs reported in favour of the wholly underground scheme put forward by the then Chief Commissioner, Mr. T. R. Johnson, who subsequently concurred with my location.

(d) The Bridge as located and designed from Dawes' Point to Milson's Point notwithstanding a Royal Commission on Communication between Sydney and North Sydney had reported in favour of three separate subways for railway, tramway, and vehicular traffic.

(e) The location and design of all stations on the City Railway, and on the railways proposed to the eastern, western and northern suburbs.

(f) The proposal to convert the Milson's Point Railway from Lavender Bay to Milson's Point into a Park, the proposal for Catherine Crescent at the Bridge head connecting the main avenue from the bridge with York, Clarence and Kent Streets and the parklets shown.

(g) The portion of the scheme of new streets and street widenings coloured red, necessary in connection with the future traffic of the City and recommended to the City Council.
The estimated cost of the above scheme at present day prices is in the vicinity of £50,000,000 sterling, and by degrees the whole of it should be carried into effect. At present the two principal proposals, the City Railway and the Sydney Harbour Bridge, are under construction by me; the estimated cost of these works is £11,000,000.

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