(c) Results for 100 m train loading cases

Maximum live load bending in mainspan stiffening truss (kNm)

Option	0 (Base Case)	1	2	3	4	5	6
	BSALL 4 lanes Unrestricted (Base Case)	No traffic + 2 LRT	BSALL 2 lanes Reduced + 1 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT
1/8 span	110570	87870	96170	138870 (+26%)	= 3	= 3	= 3
1/4 span	106430	84710	92690	133430 (+25%)	= 3	= 3	= 3
1/2 span	97880	79970	86400	124680 (+27%)	= 3	= 3	= 3

Maximum live load truss deflection (m)

Option	0 (Base Case)	1 2 3			4	5	6
	BSALL 4 lanes Unrestricted (Base Case)	No traffic + 2 LRT	BSALL 2 lanes Reduced + 1 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT
Main Span	3.64	1.48	2.46	3.12	= 3	= 3	= 3
Side Span	2.31	1.18	1.74	2.31	= 3	= 3	= 3

Maximum dead and live load tension in main cable (kN)

Option	0 (Base Case)	1 2 3			4 5 6		
	BSALL 4 lanes Unrestricted (Base Case)	No traffic + 2 LRT	BSALL 2 lanes Reduced + 1 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT
DL	116300	115488	118533 (+2%)	121375 (+4%)	119040 (+2%)	117214 (+1%)	125435 (+8%)
DL+LL	135050	118990	128833	133435	131100	129274	137495 (2%)

100 m train cases (continued)

Maximum live load change of slope (rads)

Option	0 (Base Case)	1	2	3	4	5	6
	BSALL 4 lanes Unrestricted (Base Case)	No traffic + 2 LRT	BSALL 2 lanes Reduced + 1 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT
Main span at towers	0.018	0.012	0.015	0.019 (+5%)	= 3	= 3	= 3
Side span main tower	-0.023	-0.013	-0.018	-0.020	= 3	= 3	= 3
Side span side tower	0.020	0.009	0.015	0.018	= 3	= 3	= 3

Maximum live load total change of slope ('crank angle') (rads)

Option	0 (Base Case)	1	2	3	4	5	6
	BSALL 4 lanes Unrestricted (Base Case)	No traffic + 2 LRT	BSALL 2 lanes Reduced + 1 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT	BSALL 2 lanes Reduced + 2 LRT
Main span at towers	0.029	0.019	0.024	0.030 (+3%)	= 3	= 3	= 3

6.3.4 Review and Conclusions

(a) Bending in the girder

The single track schemes show decreased live load girder moments for 50 m and 100 m trains. For the twin track schemes with traffic 50 m long trains show only nominal increased moments, but 100 m trains show noticeable increased moments - the significance of which requires review in ongoing studies.

Based on bending in the girder, single track options appear to be viable whilst twin track options may also be considered if the train length is limited to 50 m as proposed.

(b) Deflection

All schemes show a reduction in deflection relative to the BSALL base design.

Based on deflections, all options could be studied further.

(c) Rotations

All options show rotations that are similar or less than the BSALL results.

Based on rotations, all options could be studied further.

(d) Cable tension

All schemes, excluding Option 6, show a decrease in cable tension under combined dead load plus live load. In the case of Option 6, the increase is only 2% and 1%, respectively, for the 100 m and 50 m length train conditions.

Based on the cables tension, all options could be studied further.

6.4 Transverse Behaviour

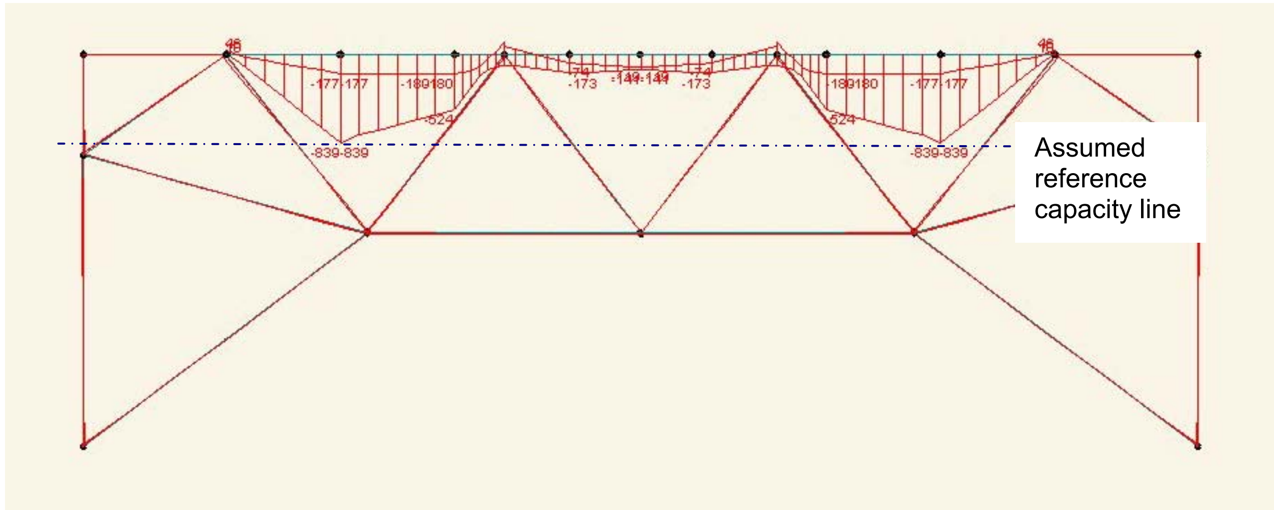
It is understood (ICE Report - ref 1) that the bridge was designed to carry 45 units of HB loading in combination with HA loading. The HB vehicle weights 1800 kN and a single HB axle load carries 450 kN. This is significantly higher than the axle loads associated with a light rail or tram system.

In order to make a qualitative comparison between the various options, the bending moment effects on a typical transverse frame have been determined for the original HB loading. These are plotted in the figure 'Case 0' following. Given that it is believed that the plate thicknesses do not vary along the length, it is reasonable to assume that the capacity of the top transverse beam will not be less than the peak value as shown.

Three other cases, Options 2, 3 and 1 are compared for reference. In all cases, four lanes of restricted BSALL traffic loading have been modelled to reflect the possibility of a local break down (for instance). The rail loads have also been increased using a Dynamic Amplification Factor of 1.20.

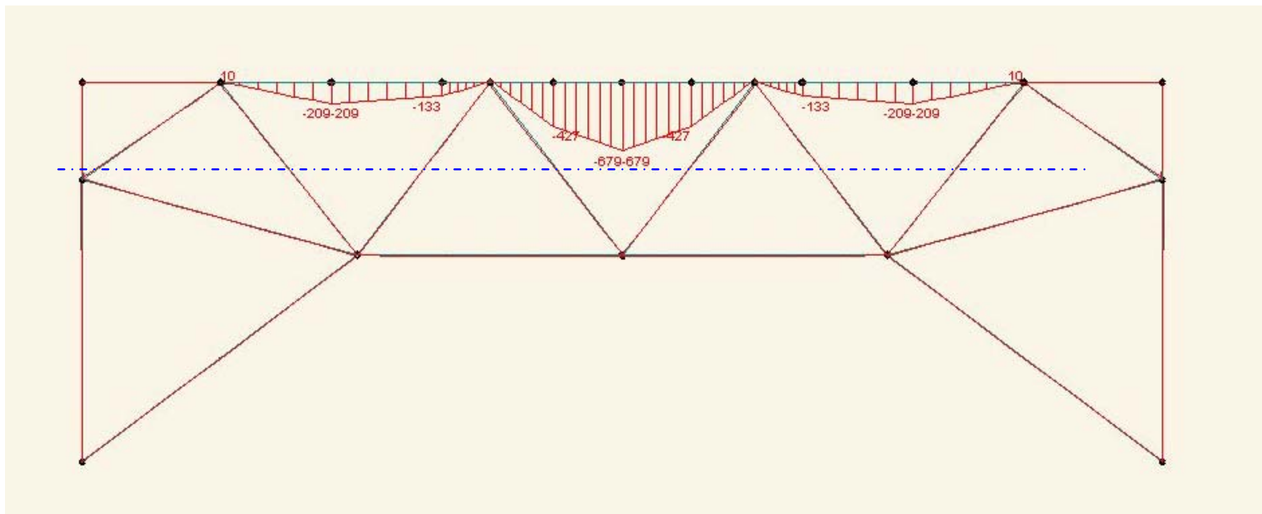
It can be seen that there is a reasonable certainty that the transverse beams (assuming that they still have a similar level of integrity as originally intended) are capable of carrying the LRT loads proposed.

Combination 1: Reference Design: DL + HB45 units + HA (to BS153- 1964)



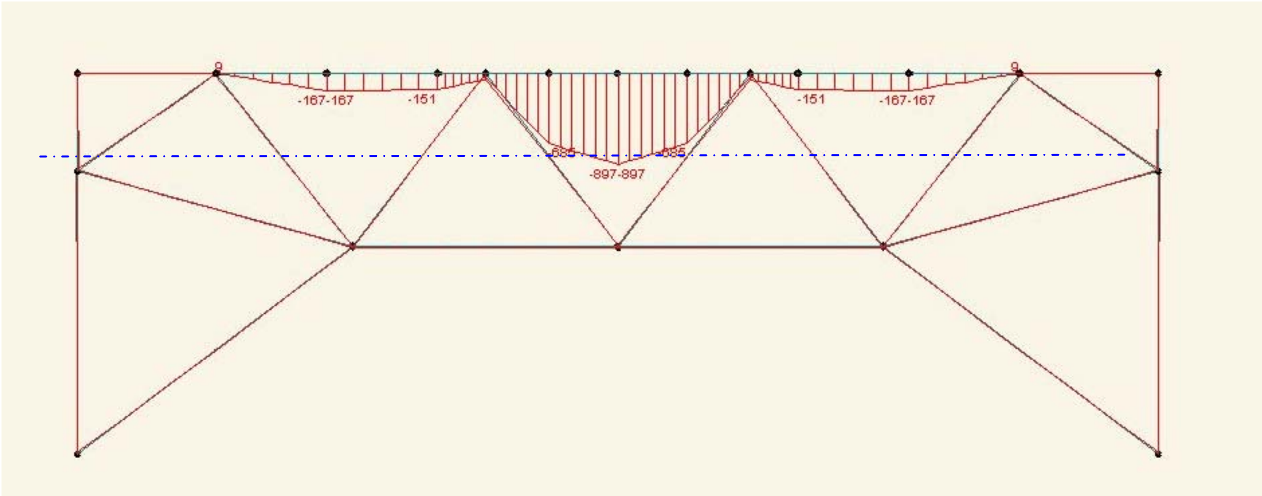
Maximum Bending Moments (kNm)

Combination 2: Single Track LRT & 2x6m Carriageways: DL + LRT+BSALL 4L (max 2axles)

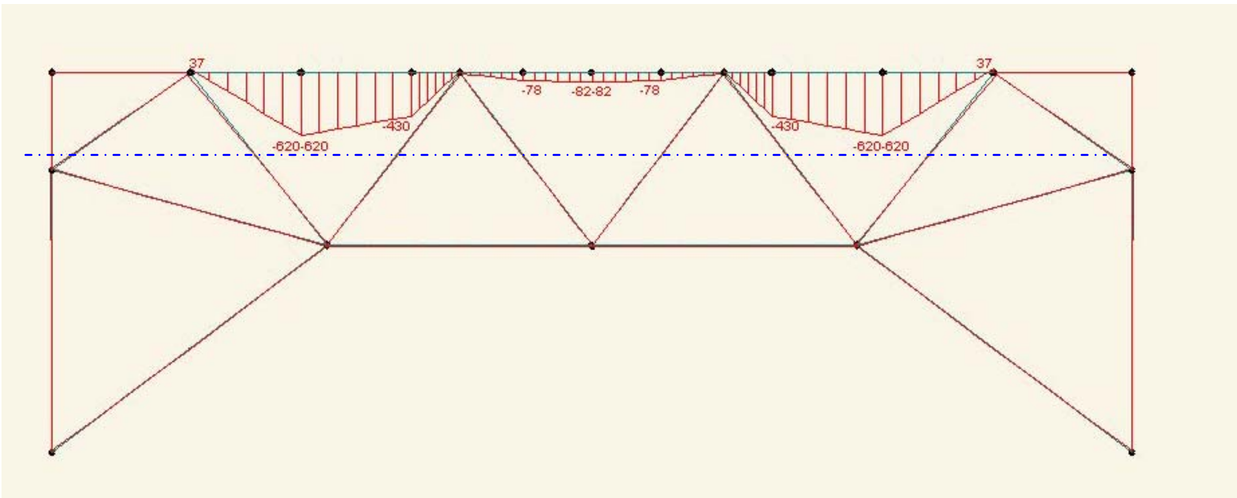


Maximum Bending Moments (kNm)

Combination 3: Twin Track LRT & 2x5.2m Carriageways: DL +2LRT+BSALL 4L (max 2axles)



Maximum Bending Moments (kNm)



Maximum Bending Moments (kNm)

6.5 Approach Viaducts

The spans of the approach viaducts vary between 34 and 54 m in length. Details of the construction are sketchy. However, we can compare for each option the change in dead load due to the reconfiguration combined with the live load as an indicator of the likely effect.

The smallest loaded length of the adjusted BSALL available at present is for 100 m. This should give a fair comparison of the maximum sagging and minimum hogging demands on the girders compared to the base loading case (4 lanes of BSALL all inclusive + footpath). The comparison considers two lanes of the reduced BSALL UDL plus footpath loading in association with one or two tracks of railway UDL. The KEL's have been excluded for simplicity.

Option	BSALL All inclusive	BSALL Restricted	Light Rail	Change in Dead Load (kN/m)	Live Load (kN/m)	Relative Total (kN/m)
0	4 lanes	n/a	n/a	0.0	47.3	47.3 **(base)**
1	n/a	n/a	2 track	-1.2	40.0	38.8 **(82%)**
2	n/a	2 lanes	1 track	-2.3	37.7	35.4 **(75%)**
3	n/a	2 lanes	2 tracks	+3.6	57.7	61.3 **(130%)**
4	n/a	2 lanes	2 tracks	+3.3	57.7	61.0 **(129%)**
5	n/a	2 lanes	2 tracks	+2.7	57.7	60.4 **(128%)**
6	n/a	2 lanes	2 tracks	+0.9	57.7	58.6 **(123%)**

The % ratio in the last column is a fair indication of the relative load effects before and after based on the current assessment loading. Note: It does not factor in the initial dead load which is not known at present. If we assume, for instance that the original dead load is in the order of 300 kN/m (250 kg/sq.m of steel work, 0.25 concrete deck plus, say, 50 kN/m for the superimposed load) then the total increase for option 3 is (300 + 61.3) / (300 + 47.3) = 4%

Thus: for the worst case, the total increase in load is less than 5%.

This simple comparison indicates that, at worst, some minor strengthening and modification of the viaduct structures for live load effects may be required for the twin track options with highway loading, but this would need to be confirmed against a more detailed assessment when the details of the as-built construction are established. Single track options, or those without traffic should not require strengthening.

7 The Rail Movement Joint

7.1 The issue

The largest movement joint on the Forth Road Bridge (footway to main span) is described in the ICE report as providing for 6 ft (1830 mm of longitudinal movement). It is understood that this includes allowance for plan rotation as well as vertical rotation and axial movement components.

With the original design loading, the joint at the main towers was required to accept, in addition, around 0.044 rads (0.022 main + 0.022 side) in elevation and 0.033 rads (0.028 main + 0.005 side) in plan.

Additional study work has indicated that the rotations may be in a similar order for Light Rail operations.

Whilst the rotations are tolerable for road traffic, they require a special joint for railway use. There is around 8 m of space available to account for this change in slope.

7.2 Evidence of Other Existing Bridges

A useful summary table is contained in the East Corridor HCT report (ref 5 in the appendix), to which is here appended the predicted Forth Bridge values:

Movement	I-90 Bridge	Tagus Bridge	Sky Train Bridge	Forth Bridge
Longitudinal displacement	1250 mm	**3050 mm**	670 mm	**2130 mm ***
Horizontal rotation	+/- 0.019 rads	not known	not known	+/-0.033 rads**
Vertical rotation	+/- 0.038 rads	**+/-0.060 rads**	+/- 0.013 rads	**+/-0.030 to 0.038 rads*** **

*Estimated. A figure of 6 ft (1830 mm) is quoted in the ICE report and is assumed to be the total range of movement at the main span side at the outer edge of the footway. An allowance for side span movement (mainly thermal plus deck rotation) has been added to this figure. It is understood that the ICE figure includes allowance for plan rotation as well as vertical rotation and axial movement components. The rail joints, which are located close to the centre of the bridge, are not as sensitive to the axial effect resulting from plan rotations.

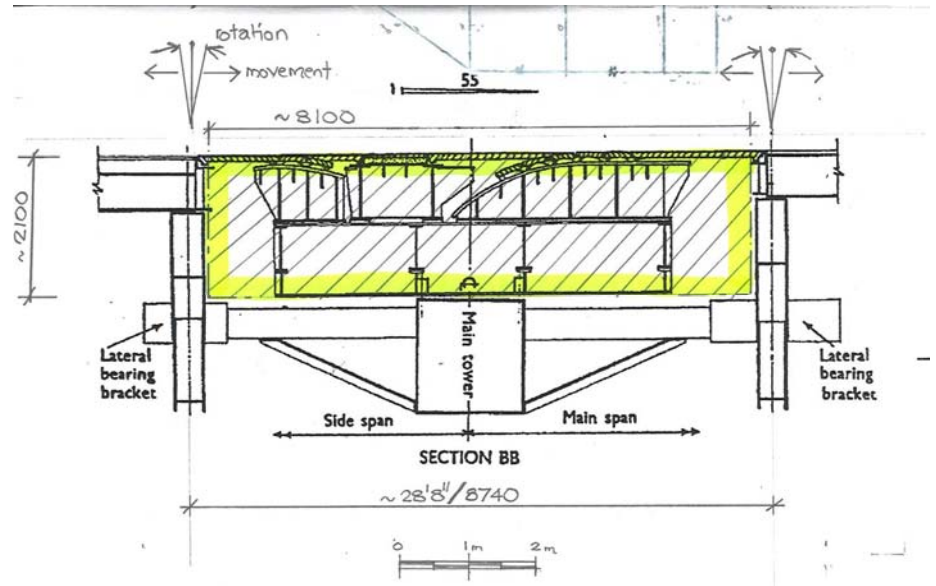
** Based on ICE report

*** Lower figure for single track; higher figure for twin track rail loading

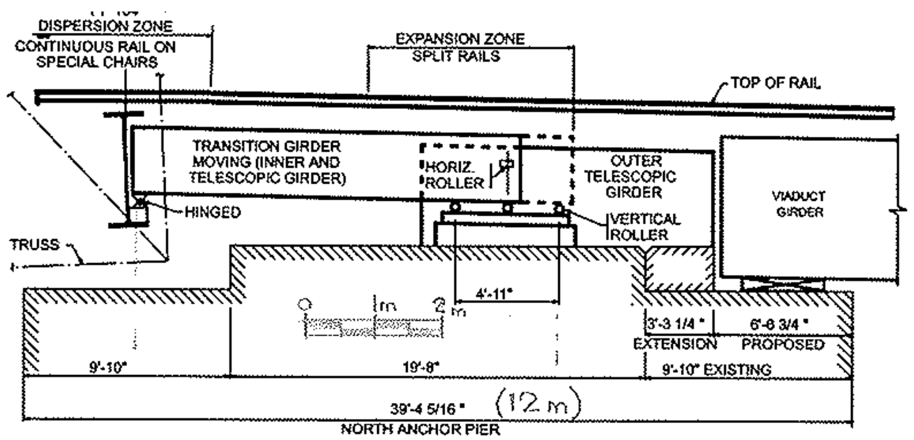
This comparison indicates that the order of magnitude of axial movement and rotation required can be achieved with a rail joint system. At the Tagus Bridge, approximately 8.5 m between joints on the main bridge and approach span was available. A similar space is available at the Forth bridge - so a solution seems entirely possible.

The Forth Joint and Tagus Joint are compared in the following diagrams:

Forth Joint: approximately 8.7 m space available



Tagus Joint: approximately 8.5 m space provided



7.3 Conclusion

Sufficient space is available to accommodate the joint. Existing precedent, particularly that of the Tagus bridge, would indicate that the technical issues associated with a rail movement joint can all be addressed. The joint would require development and testing in the normal way - but is entirely feasible.

8 Conclusions

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8.1 Summar y

The comparison has been made comparing the actions under BSALL and rail loading.

1. For the purpose of this report, the study has been limited to cases in which either one or two rail tracks are provided with footway loading, and with or without reduced highway applied to one lane in each direction. This selection is judged sufficient, within the present study, to justify whether or not a multi modal scheme for the bridge is feasible or not.
2. Whilst all of the proposed options are geometrically viable, only two of the options (2 and 6) can be classified as complying fully with the ideal of a single carriageway width of 6.0 m minimum. These are the single track option of DRG 021 and the twin track option of DRG 061. The latter option does, however, infringe on the outer air vent spaces and requires a reduction in width locally at the main towers.
3. Under dead plus live load combinations, the cable tension for all the options is less when compared to the BSALL base case, except for Option 6 which shows a nominal increase of 2%.
4. The bridge girders are sensitive to the short loaded lengths associated with train loading. The single track options are generally acceptable, but the twin track options with traffic indicate larger increases in girder moments. However, twin track options appear viable with shorter train lengths operating in conjunction with the reduced traffic configuration.
5. For the options studied, only the twin track options show any increase in load for the approach viaducts and even in these cases less than 5% increase is projected. It is likely therefore, that at worst only minor strengthening work will be required to the approach viaduct for the options presented.
6. Modification will have to be made to the movement joints, in particular those located at the main towers. Evidence exists (Tagus Bridge) that indicates a solution will be feasible in the space available. The joint would require development and testing in the normal way - but is entirely feasible.

8.2 Recommendations

1. All of the Options 1 to 6 presented have a positive potential and should be studied further.
2. The performance of the bridge is sensitive to the intensity of railway/ tram loading that is to be accommodated. Early consideration should, therefore, be given to specifying the type and characteristics of the light rail / tram vehicles that are anticipated to be employed on the bridge. It is tentatively recommended that an upper load intensity of 20 kN/m length, be considered. This is broadly consistent with many of the current light rail specifications in the UK. Lighter loads may be applicable for tram type loading.
3. The performance of the bridge is sensitive to the length of railway/ tram loading that is to be accommodated. Early consideration should, therefore, be given to specifying the type and characteristics of the light rail / tram vehicles that are anticipated to be employed on the bridge. It is tentatively recommended that a 50 m length, similar to that proposed for the Edinburgh Tram system, and others in the UK, be considered.
4. The present study is limited to a comparison of the effects of actions on the bridge under proposed changes of loading relative to the effects of actions under the current BSALL loading. An early understanding of the actual capacities of the bridge elements is therefore necessary.
5. A review of the requirement for 6.0 m width carriageway should be made accepting a possibility of narrow carriageways. This may unlock the other alternative options presented.
6. Additional studies should also investigate the possibility of using unrestricted traffic or twin lanes in a breakdown condition in combination with the various rail scenarios.

8.3 Ongoing study

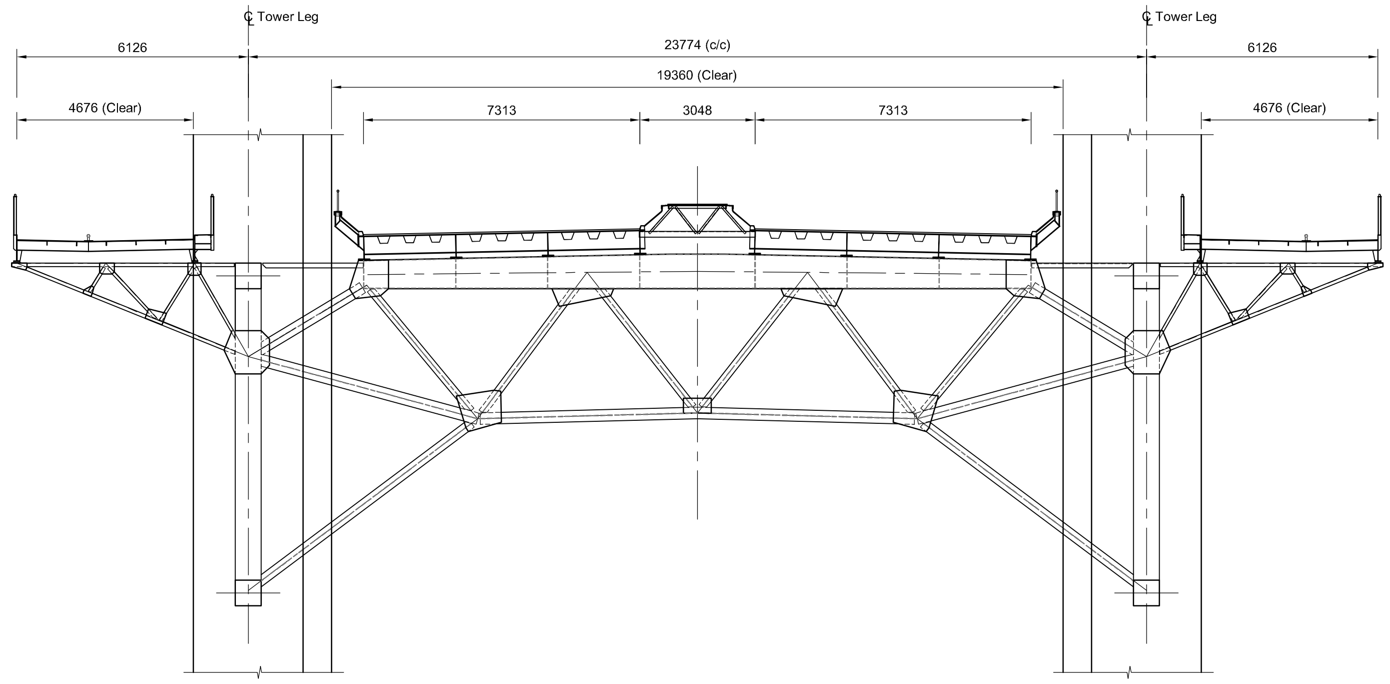
The following topics should be considered for review in subsequent studies:

1. Obtain as built / modified bridge details.
2. Review assessment reports for current state of bridge and the assessment loading when available to indentify the critical members based on actual rather than relative capacity.
3. Draw up a project specific design statement to cover rail and road loading and ongoing assessment methodology.
4. Further study of the rail joints to be carried out. In particular, accommodation in the space available.
5. Further study of aerodynamic behaviour.

Appendix A - Drawings

- FRC/C/052/FRB/001 Existing Layout
- FRC/C/052/FRB/011 Twin track/OLE/ Emergency Walkway
- FRC/C/052/FRB/021 Single track/OLE/ Emergency Walkway/2 x 6000 Carriageways
- FRC/C/052/FRB/031 Twin track/No OLE/Minimum Clearance/2 x 5187 Carriageways
- FRC/C/052/FRB/041 Twin track/OLE/Minimum Clearance/2 x 4817 Carriageways
- FRC/C/052/FRB/051 Twin track/OLE/ Emergency Walkway/2 x 4537 Carriageways
- FRC/C/052/FRB/061 Twin track/OLE/ Emergency Walkway/2 x 6000 Carriageways
- FRC/C/052/FRB/071 Rail on Footways

Drawing number / Rev
FRC/C/052/FRB/001



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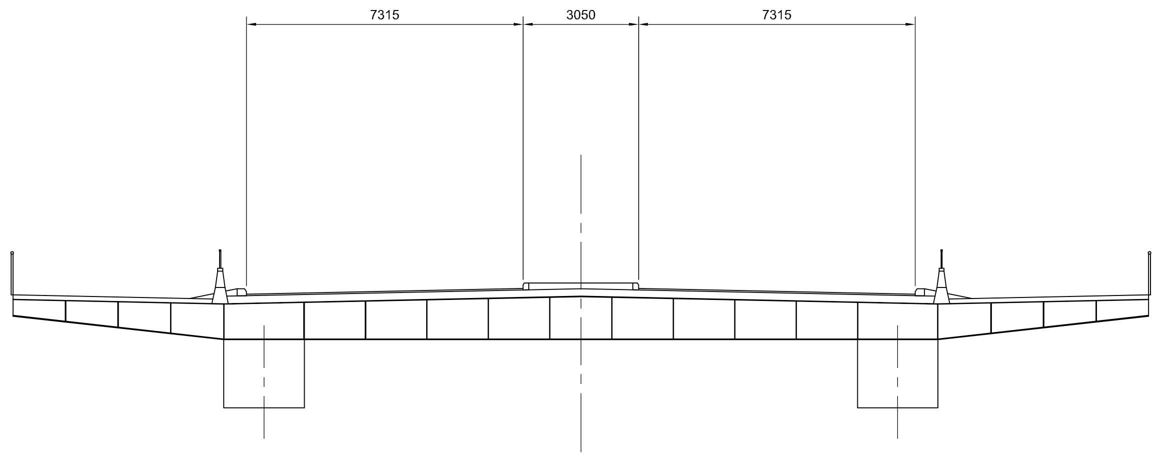

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NOTES

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Reviewed	Approved
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Client

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Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE
EXISTING LAYOUT

Drawing status
PRELIMINARY

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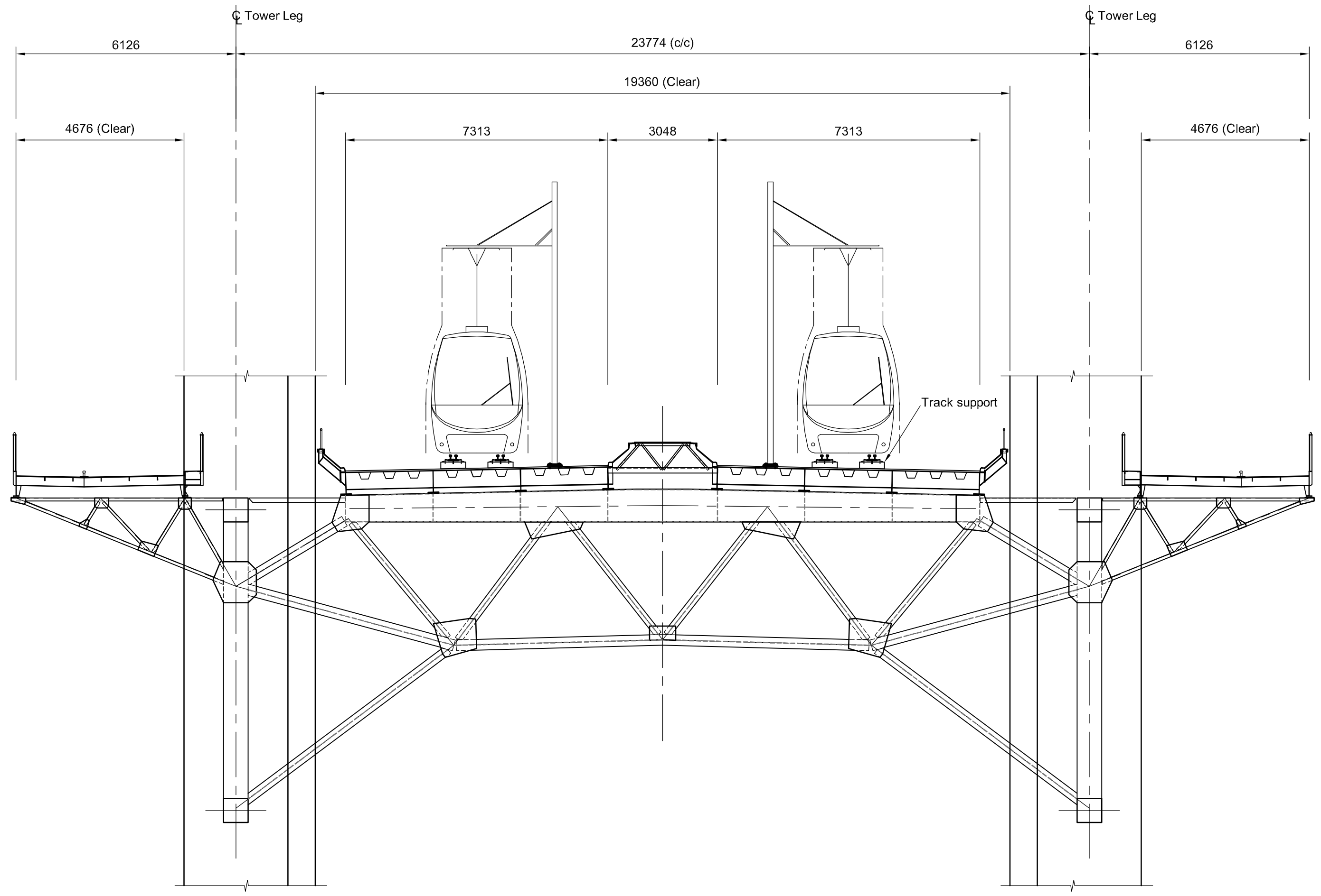
Drawing number: FRC/C/052/FRB/001
Rev: 0

Drawing number / Rev
FRC/C/052/FRB/011



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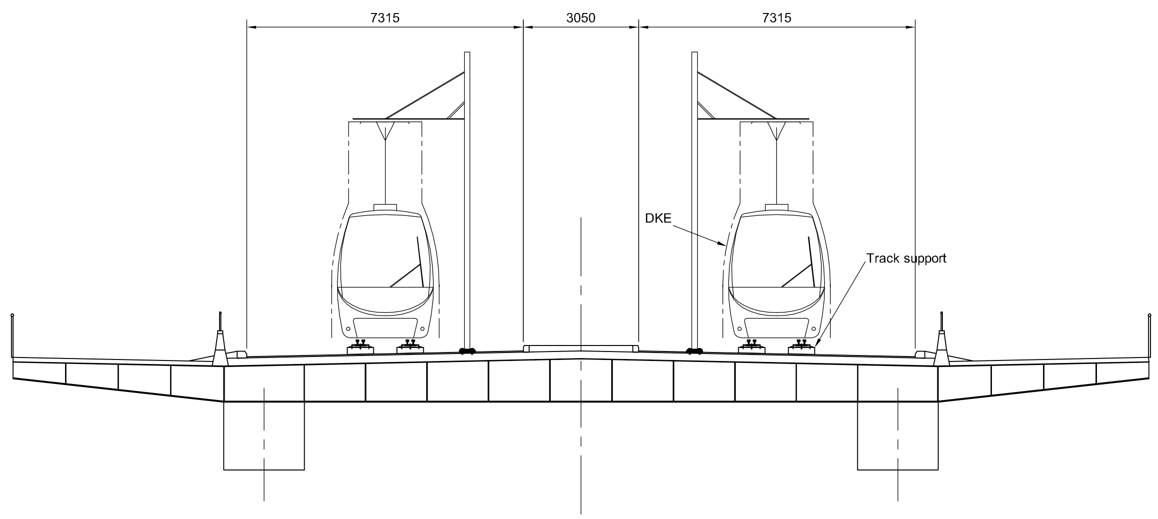

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Project

FORTH REPLACEMENT CROSSING

Drawing title

EXISTING FORTH ROAD BRIDGE TWIN TRACK RAIL OLE EMERGENCY WALKWAY

Drawing status

PRELIMINARY

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Drawing number: FRC/C/052/FRB/011

Rev: 0

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Drawing number / Rev
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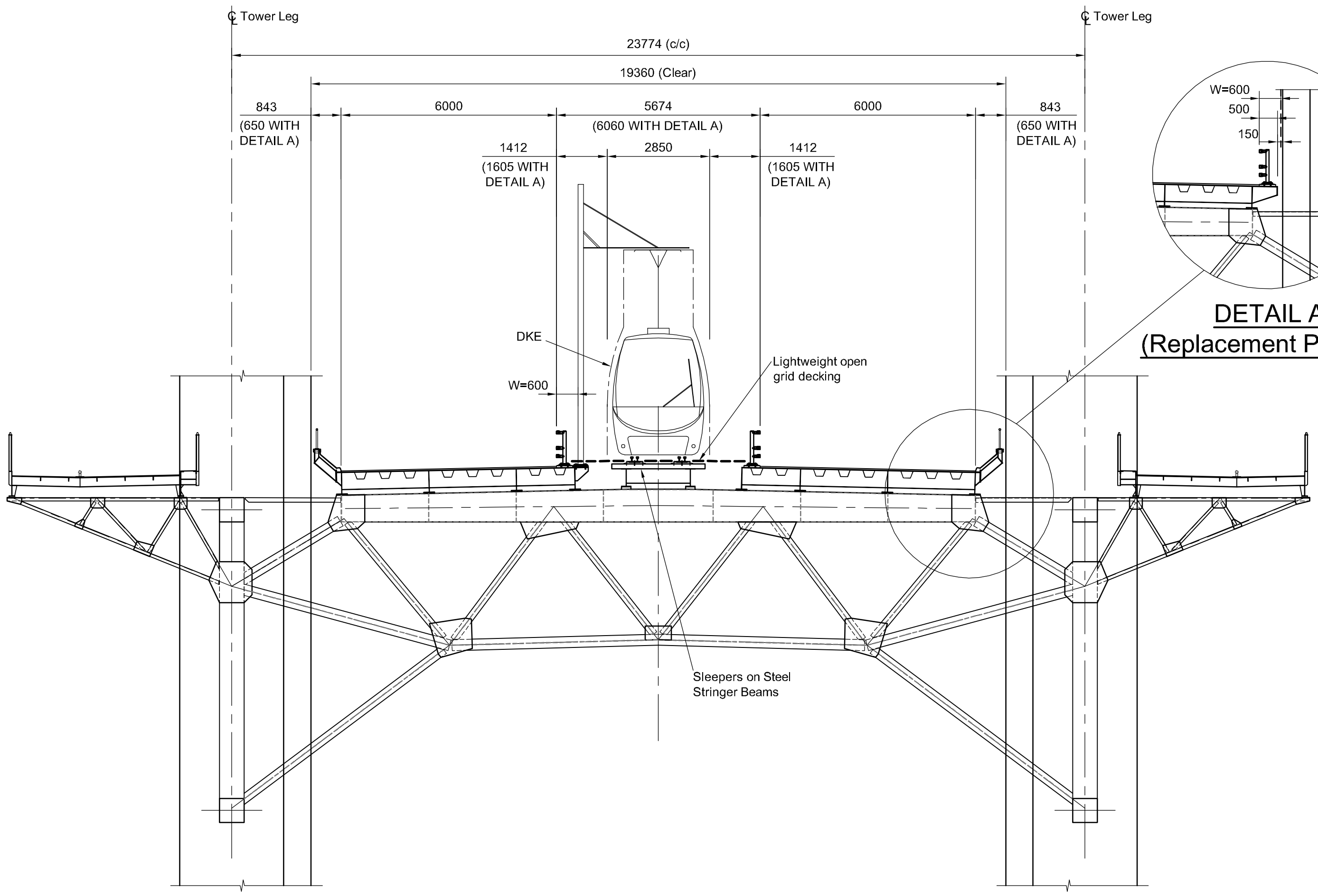

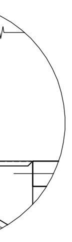

DETAIL A
(Replacement Parapet)

SUSPENSION BRIDGE
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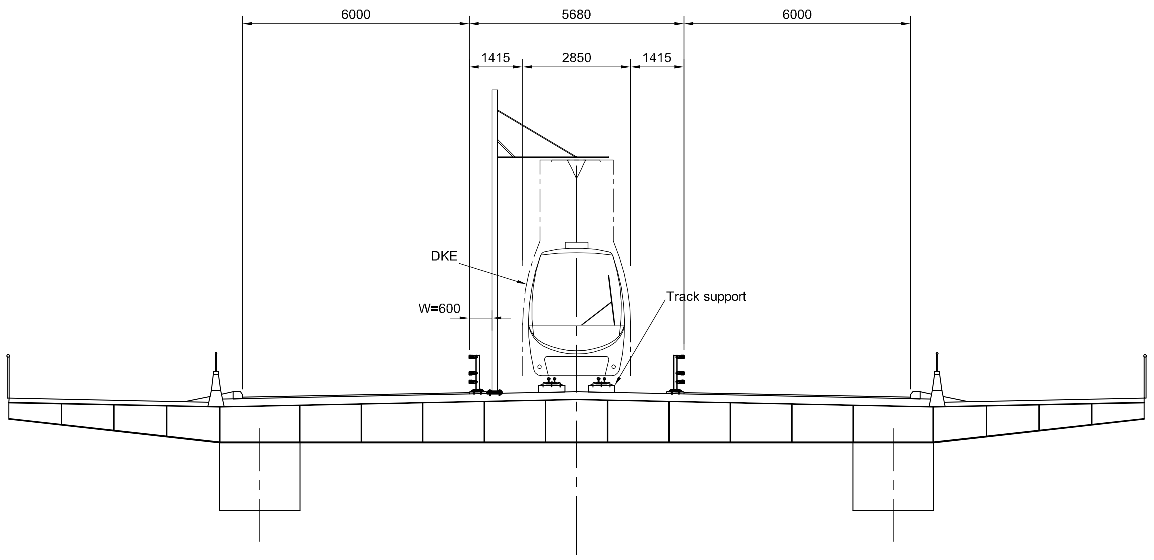

APPROACH VIADUCT
SCALE 1 : 100

OPTION 2

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Reviewed	Approved
0						

Client

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Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE
SINGLE TRACK OLE
EMERGENCY WALKWAY
2 x 6000 CARRIAGEWAYS

Drawing status
PRELIMINARY

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Drawing number
FRC/C/052/FRB/021

Rev
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Drawing number / Rev
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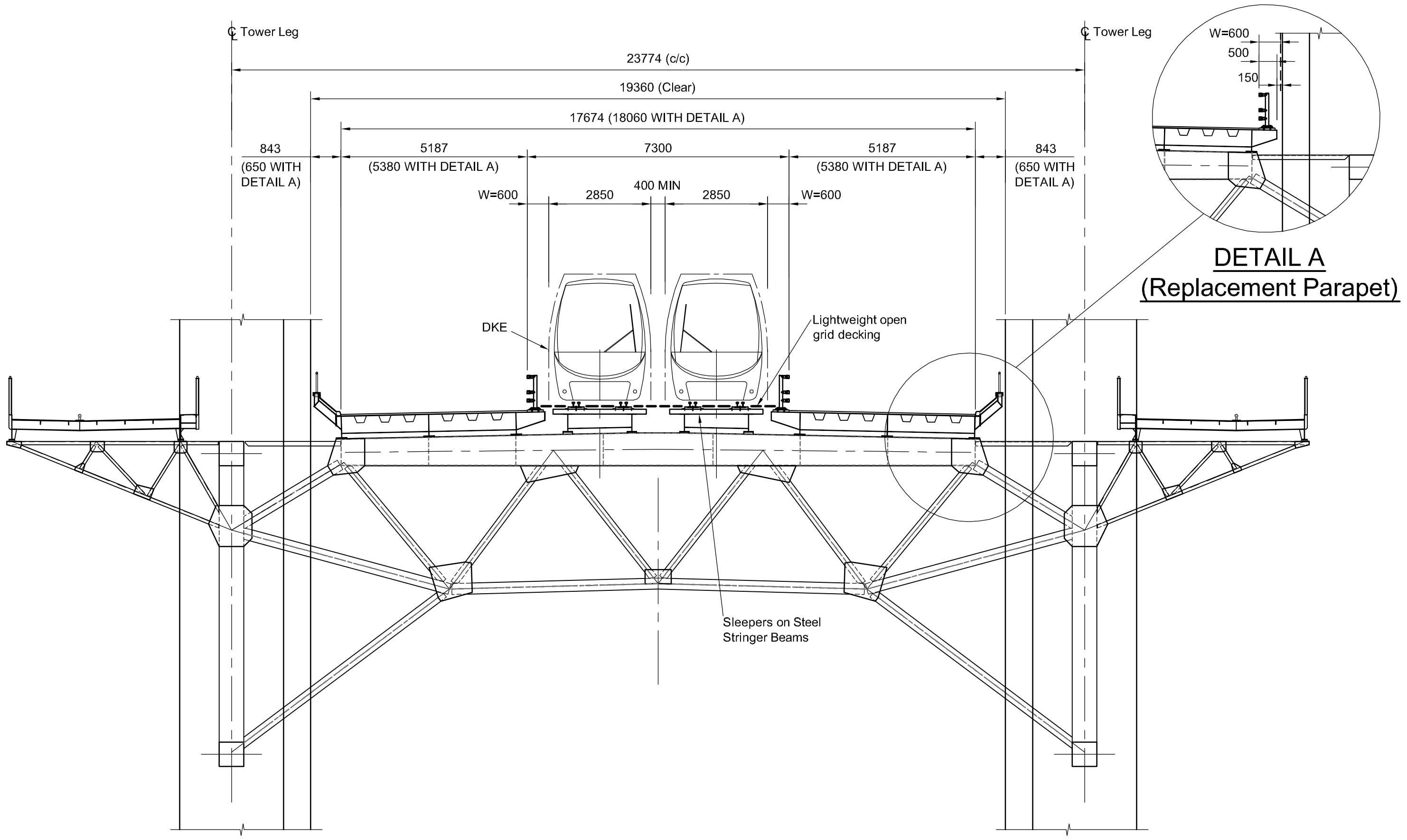

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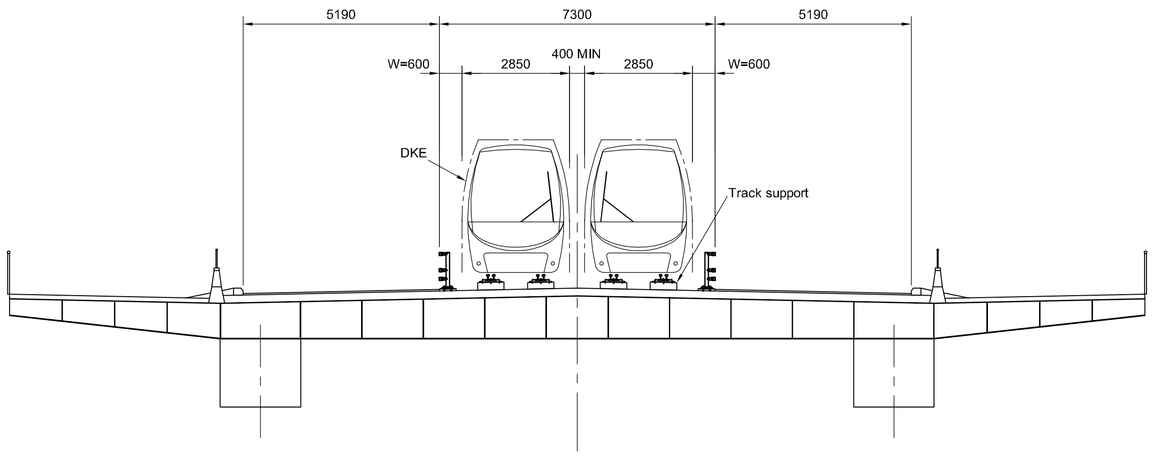

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OPTION 3

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Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE
TWIN TRACK NO OLE
MINIMUM CLEARANCE
2 x 5187 CARRIAGEWAYS

Drawing status
PRELIMINARY

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Rev: 0

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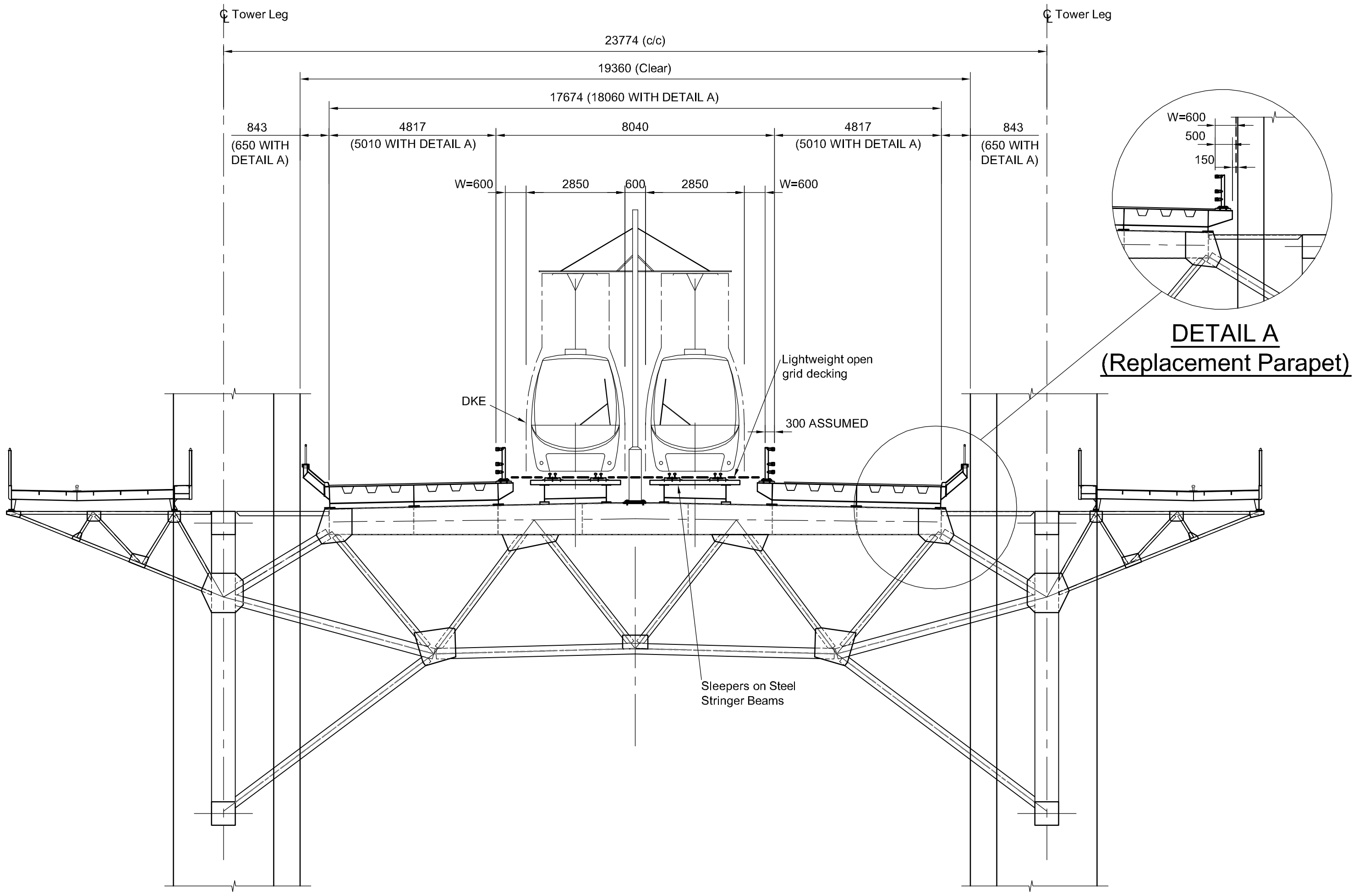

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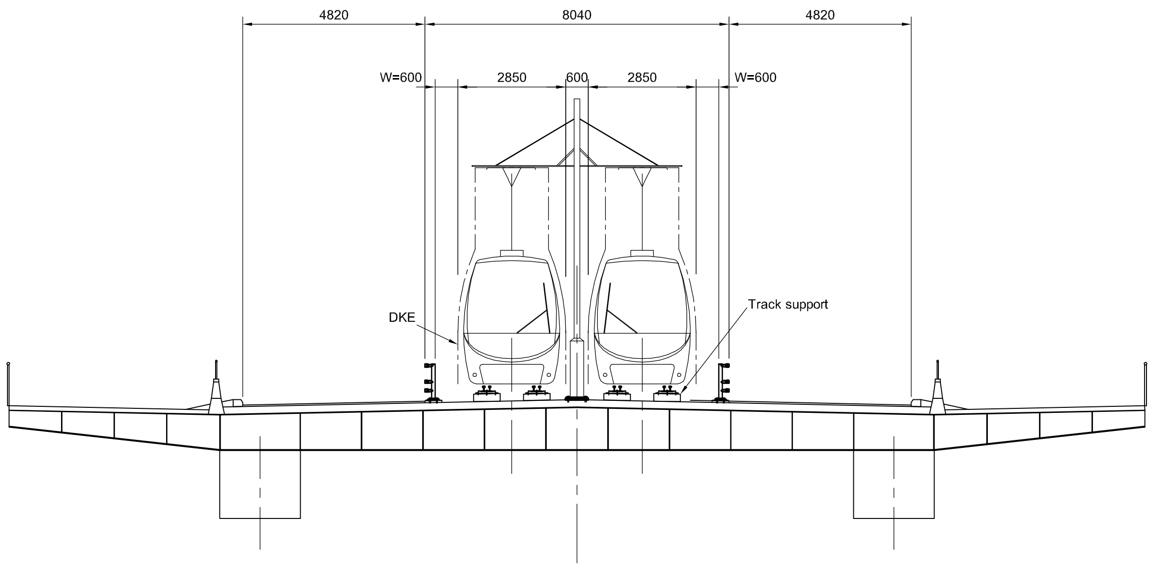

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OPTION 4

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Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE
TWIN TRACK RAIL OLE
MINIMUM CLEARANCE
2 x 4817 CARRIAGEWAYS

Drawing status
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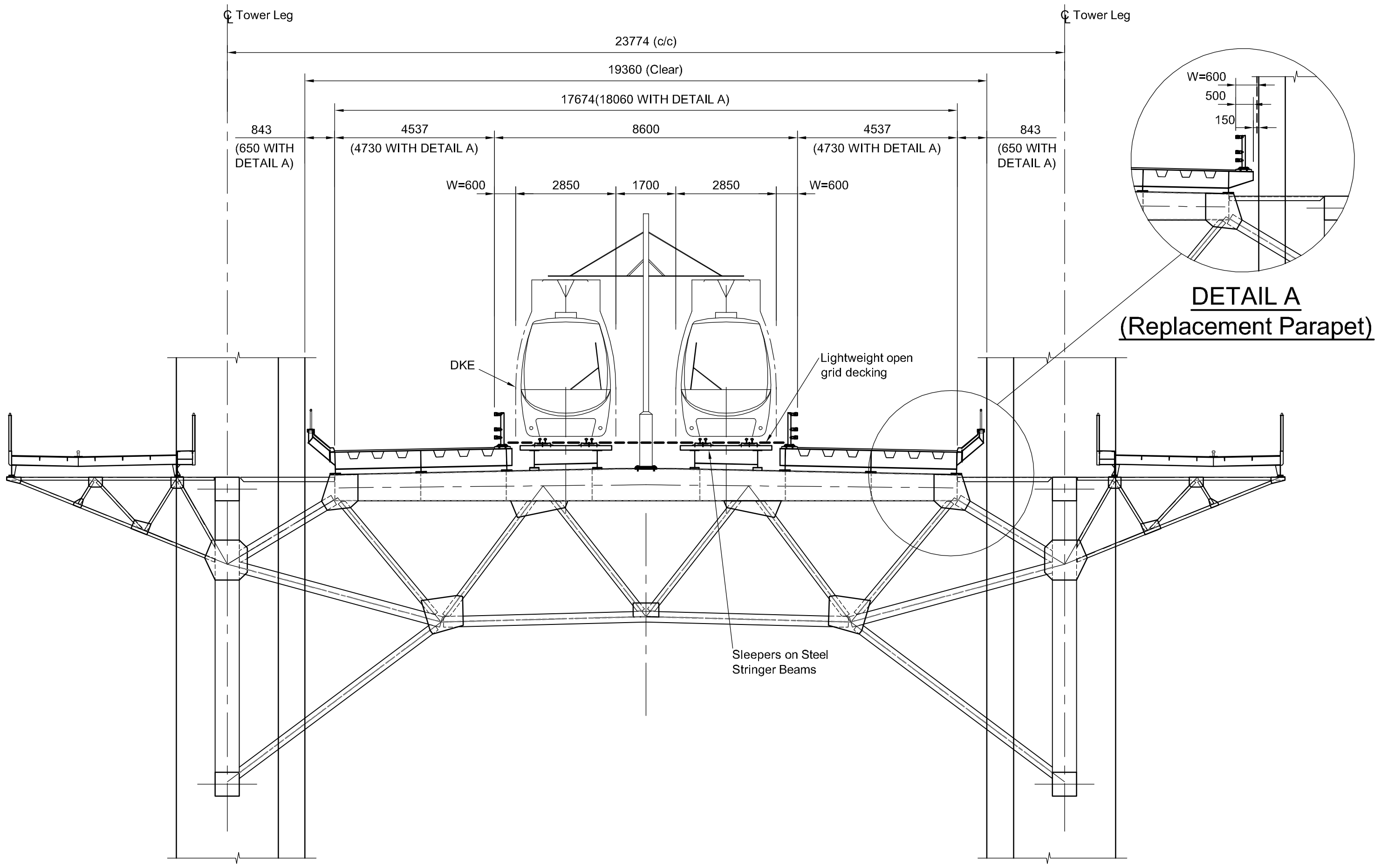

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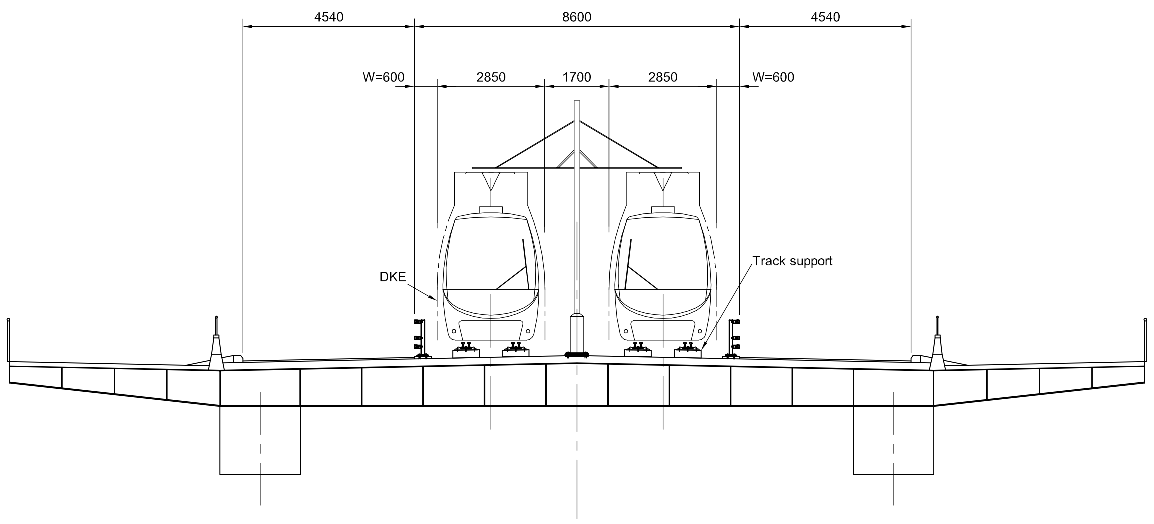

APPROACH VIADUCT
SCALE 1 : 100

OPTION 5

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Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE
TWIN TRACK RAIL OLE
EMERGENCY WALKWAY
2 x 4537 CARRIAGEWAYS

Drawing status
PRELIMINARY

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Client no.	RD 001675	

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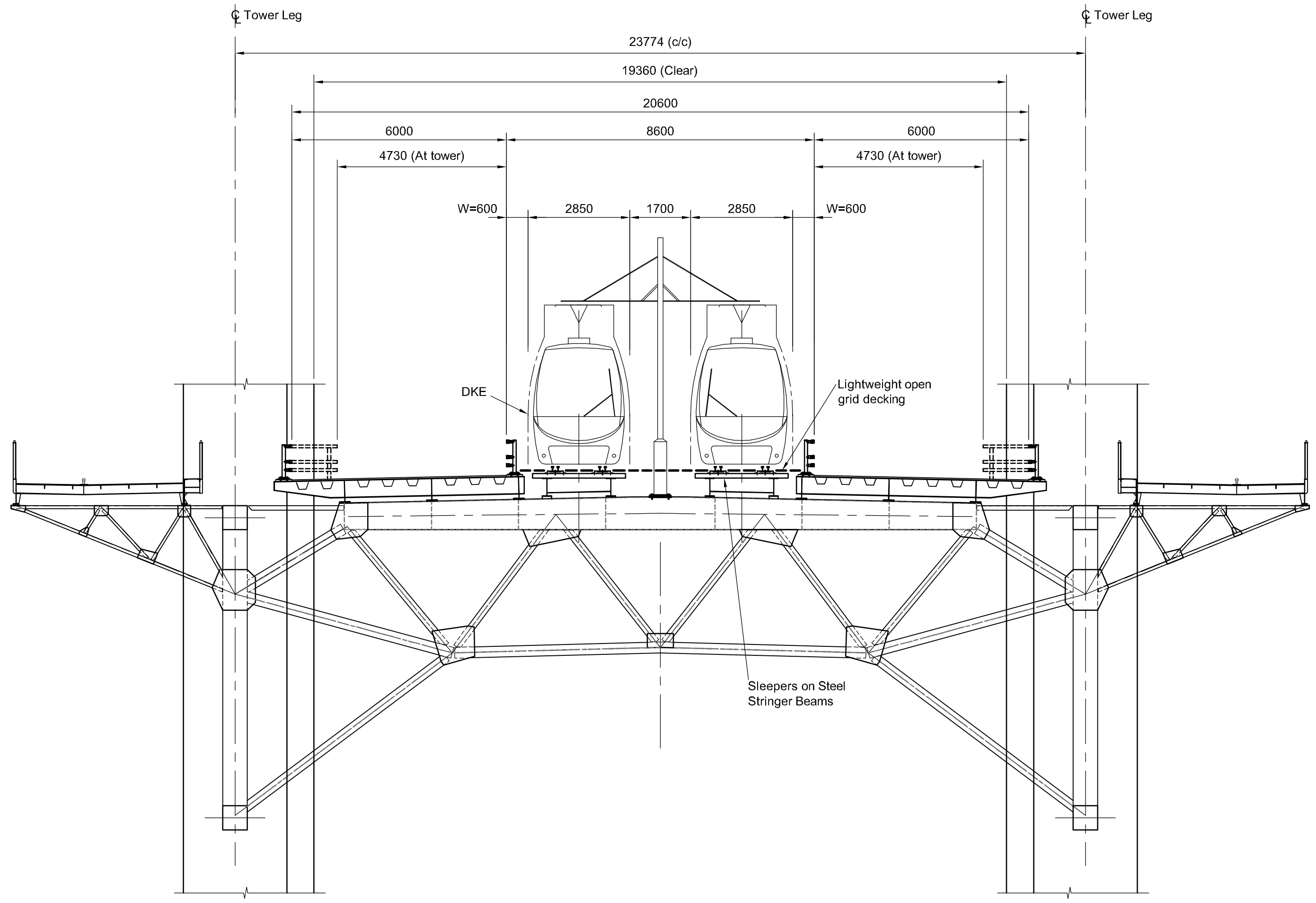
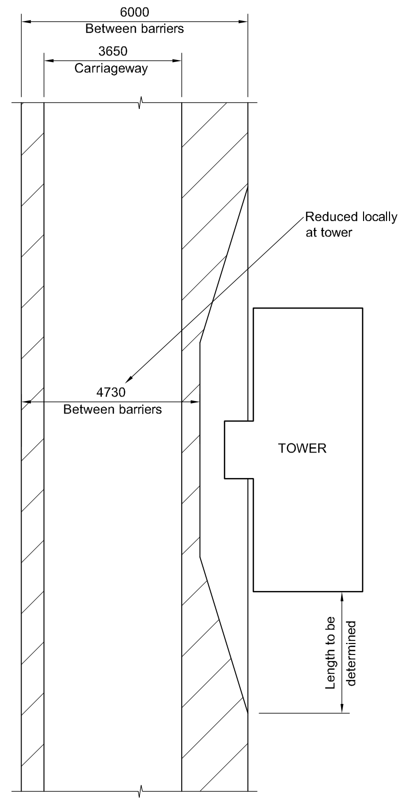


SUSPENSION BRIDGE

SCALE 1 : 100



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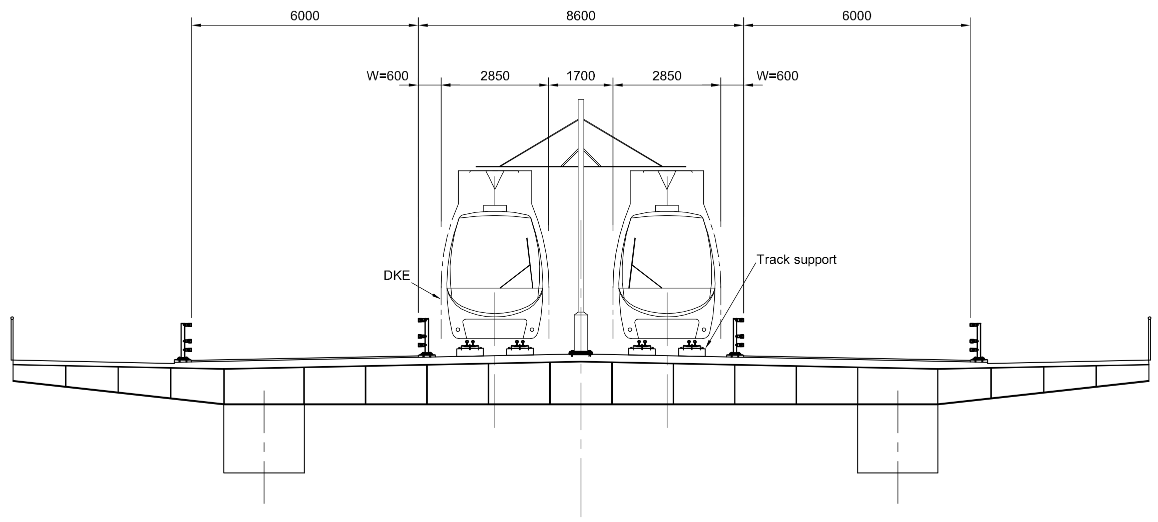

APPROACH VIADUCT

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OPTION 6

NOTES

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Reviewed	Approved
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Client

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Project

FORTH REPLACEMENT CROSSING

Drawing title

EXISTING FORTH ROAD BRIDGE
TWIN TRACK RAIL OLE
EMERGENCY WALKWAY
2 x 6000 CARRIAGEWAYS

Drawing status

PRELIMINARY

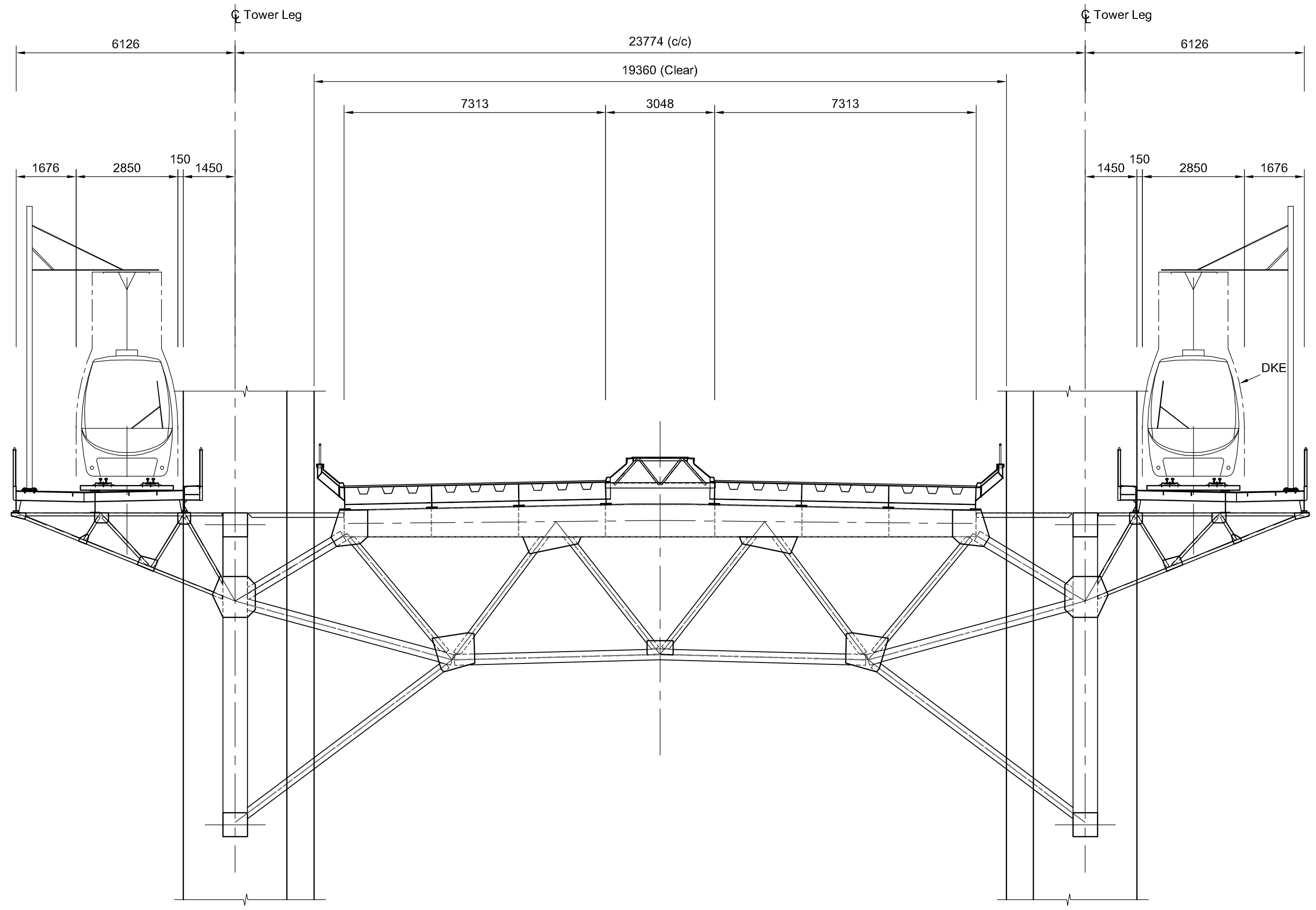
Scale	1:100@ A1	DO NOT SCALE
Client no.	RD 001675	

Drawing number: FRC/C/052/FRB/061

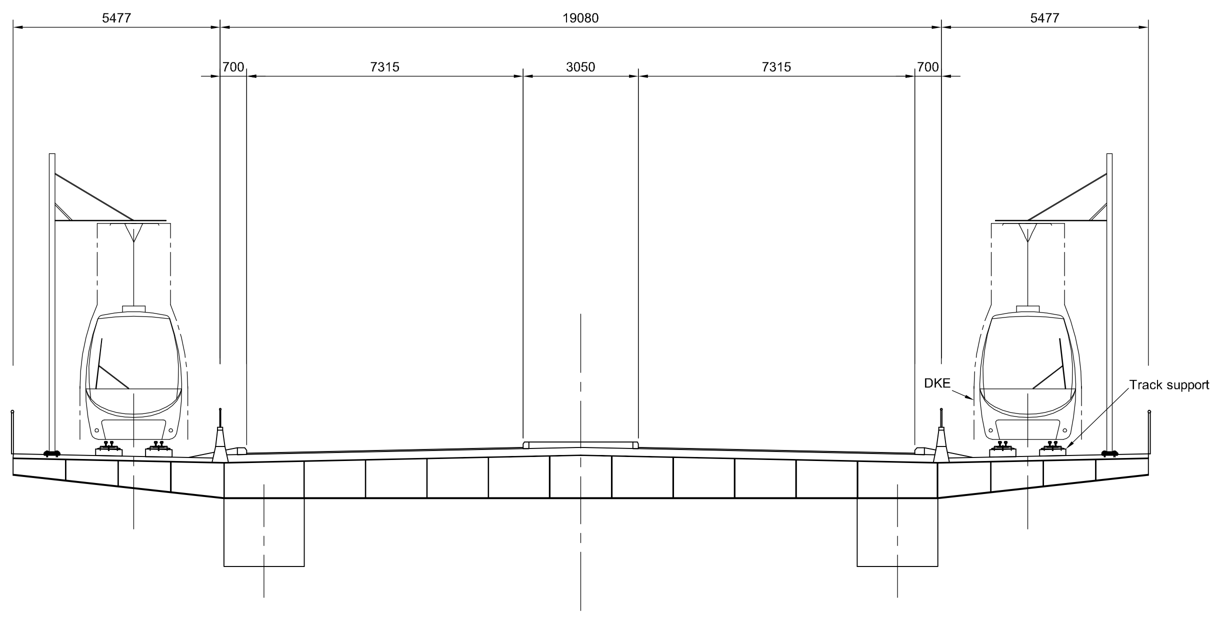
Rev: 0

Created by : ARUP File: J:\125000\125101-00\4 LG Project Data\11 Drawings\Existing Bridge\FRC-C-052-FRB-061.dwg Date: Sep 30, 2008 - 12:21pm Plotted by: len.griffin

Drawing number / Rev
FRC/C/052/FRB/071



SUSPENSION BRIDGE
SCALE 1 : 100



APPROACH VIADUCT
SCALE 1 : 100

OPTION 7

NOTES

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Reviewed	Approved
0						

Client
TRANSPORT SCOTLAND
An agency of The Scottish Government

JACOBS ARUP

Project
FORTH REPLACEMENT CROSSING

Drawing title
EXISTING FORTH ROAD BRIDGE RAIL ON FOOTWAYS

Drawing status
PRELIMINARY

Scale	1:100@ A1	DO NOT SCALE
Client no.	RD 001675	

Drawing number: FRC/C/052/FRB/071
Rev: 0

Created by : ARUP   File: J:\125000\125101-00\+ILG Project Data\11 Drawings\Existing Bridge\FRC-C-052-FRB-071.dwg   Date: Sep 30, 2008 - 12:21pm   Plotted by: len.griffin

Appendix B - References

1 Forth Road bridge
ICE Paper No. 6890
Anderson et el.
1965

2 Forth Road Bridge - Maintenance challenges
Andrew and Colford
c 2003

3 Forth Estuary Transport Authority
Forth Road Bridge
2006 Bridge Specific Assessment Live Loading Report
W.A.Fairhurst & Partners
April 2008

4 Transport Scotland
Forth Road Bridge
Highway Traffic Loading
Traffic Control Options and Potential Effects
Flint and Neill Partnership
May 2007

5 East Corridor HCT - Summary of I-90 Floating Bridge (Homer Hadley) Studies
Parsons Brinkerhoff & Douglas, Inc.
2006

6 Design of Continuous Welded Rail on a Suspension Bridge
Rao and Sanghvi
Parsons Transportation Group
c 2000

7 Jacobs / Faber Maunsell (for Transport Scotland) Drg 49550 B / XDR / 01 Rev 1