National Highways

SPATS2-T0314

Volumetric Concrete Mixer Load Comparison

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CONFIDENTIAL

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EXECUTIVE SUMMARY

In 2017, an investigation was undertaken to determine whether proposed Volumetric Concrete Mixer (VCM) vehicles fell within the assumptions for LM1 and HA (ALL) load models, and thus be able to use the national road network in a manner similar to vehicles complying with the Road Vehicles (Construction & Use) regulations.

The Department for Transport (DFT) has asked for an updated investigation using vehicle configurations that are permitted under the Vehicle Special Order (VSO). The assessment has been updated to investigate a proposed 4-axle vehicle (at 38.4T) and a 5 axle vehicle (at 44T).

The load effects were calculated using the same methods as the previous study and using the same procedure as that employed in the development of the of the short span bridge live load model published in BD37/01 and as implemented in CS 454. No statistical reductions have been applied to the axle loads in the 3-vehicle and 8-vehicle scenarios. An additional analysis has been undertaken to calculate the load effects for the 3-vehicle and 8-vehicle scenario with an increased vehicle spacing of approximately 5.2m (3m previously considered), as this represents a more realistic scenario considering the front and rear overhangs of the vehicles.

The moment and shear load effects for the proposed VCM vehicles have been compared against the load effects for BS EN 1991-2 LM1 and CS 454 ALL Model 1 and ALL Model 2. The overload factor has been applied to the VCM in accordance with BD 37/01, based on the same assumptions that were used when the load models within BD 37/01 were established. At present, there is not sufficient statistical data on the overall weight and individual axle weights of VCMs in use to justify the application of the CS 458 overload factors, which are typically lower than the BD 37/01 method.

The findings of the study are as follows:

- All vehicles have been found to cause theoretical overload when compared with CS 454 ALL Model 1, with a peak overload of 17%. This remains at 17% when the increased VCM vehicle spacing is considered.
- All vehicles have also been found to cause theoretical overload when compared with CS 454 ALL Model 2, with a peak overload of 28%. This reduces to 16% when the increased VCM vehicle spacing is considered.
- All vehicles fall within the load effects for BS EN 1991-2 LM1, this would generally only apply to structures designed after 2010.

Conclusion

This study shows that VCMs operating at higher weight limits will likely result in the overloading of existing bridges by 16-17% when compared to CS 454 assessment load models. It is expected that if VCM movements are allowed to continue at their higher weight limits, there is a risk that a large number of existing structures will require interim measures. If this risk is realised, significant resources and funding will need to be diverted to manage structures overloaded by the VCMs.

In addition, it is expected that similar serviceability limit state (SLS) overload factors are likely due to the VCM loading. This will likely result in increased wear and tear, and impact whole life durability of existing structures.

1 INTRODUCTION

In 2017, an investigation was undertaken to determine whether existing overweight Volumetric Concrete Mixer (VCM) vehicles fell within the assumptions for LM1 and HA (ALL) load models, and thus be able to use the national road network in a manner similar to vehicles complying with the Road Vehicles (Construction & Use) regulations.

The Department for Transport (DFT) has asked for an updated investigation using vehicle configurations that are permitted under the Vehicle Special Order (VSO). The assessment has been updated to investigate a proposed 4-axle vehicle (at 38.4 tonnes) and a 5-axle vehicle (at 44 tonnes). The moment and shear load effects for the proposed VCM vehicles have been compared against the load effects for BS EN 1991-2 LM1 and CS 454 ALL Model 1 and ALL Model 2. For reference, these VCM vehicles would normally be restricted to a weight limit of 32 tonnes if not operating under a VSO.

2 METHODOLOGY

2.1 VEHICLE PROPERTIES

The analysis used in the 2017 study has been updated to reflect the revised maximum authorised VCM gross vehicle weights (GVW) from the DFT, which are 38400kg for 4-axle vehicles and 44000kg for 5-axle vehicles.

For this study, the 4-axle vehicle has been revised by:

1) Distributing the difference between the GVW of 38400kg and the normally permitted maximum weight of 32000kg equally across the axles, and
2) Taking a scenario whereby the rear axles are loaded to the maximum permitted of 11,400kg and the remaining weight is spread across the front axles at a similar ratio to that in the previous study (0.52 / 0.48).

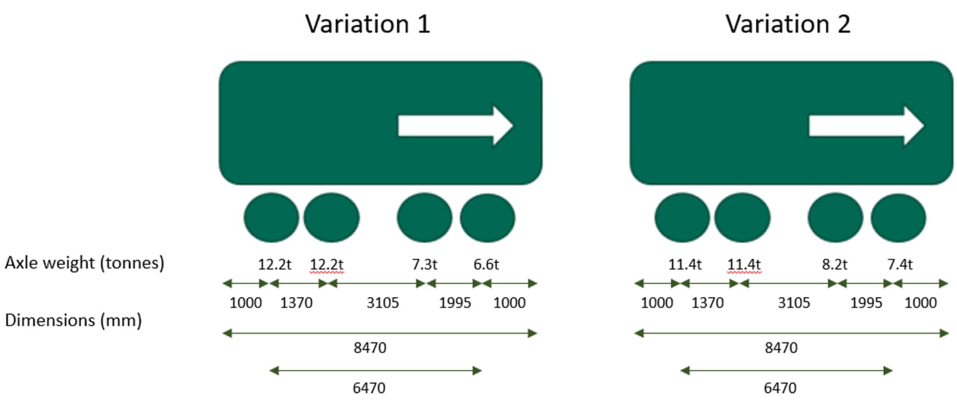

Figure 1: 4 Axle Volumetric Concrete Mixer Types

The 5-axle vehicle has been revised by:

1) Modelling the vehicle where axles 3 and 4 are loaded to the permitted 11400kg, and the remaining weight is spread across the remaining axles, and
2) Modelling the vehicle where axle 1 remains at 10t (based on real vehicle data sheets), increasing axles 3 and 4 to 11400kg and distributing the remaining weight equally between the remaining axles.

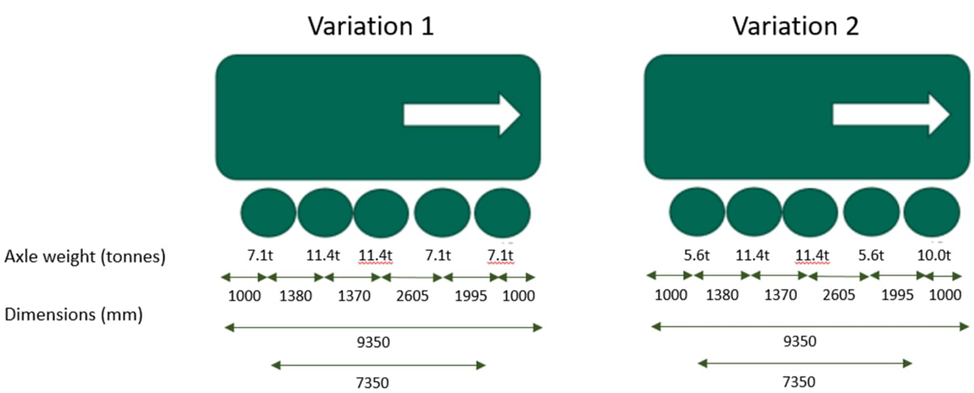

Figure 2: 5 Axle Volumetric Concrete Mixer Types

2.2 TRAINS OF VEHICLES

The following load effect scenarios have been analysed for the each of the revised VCM vehicles. The envelope of the potential load effects caused by these vehicles is calculated and compared against the Eurocode LM1 and CS 454 ALM1 and ALM2 load effects.

Eight scenarios have been considered:

Table 1: Load effect scenarios

Scenario	Load effect
1	Shear effect from single concrete truck
2	Shear effect from triple concrete trucks
3	Shear effect from eight concrete trucks
4	Shear effect from test plus two standard vehicles
5	Moment effect from single concrete truck
6	Moment effect from triple concrete trucks
7	Moment effect from eight concrete trucks
8	Moment effect from test plus two standard vehicles

The standard vehicle has been applied as per the previous study as a 24.4 tonne standard 3 axle vehicle.

The previous study and proposal included two shear effects for scenario. One at either end of the bridge. The results presented for shear in this study are the most onerous of the shear effects at both ends.

2.3 LOADED LENGTHS

The analysis has considered simply supported spans between 5 and 50m with 5m intervals between spans.

2.4 SPACINGS

As per the previous study, it is has been assumed that there is a 1.0m space between the rear of each vehicle and the front of the next; and there is a 1.0m front and rear overhang to each vehicle.

Following the initial analysis undertaken in this study, a further analysis was undertaken for increased spacing between vehicles to represent more realistic conditions. The increased spacing is described in Section 2.11.

2.5 IMPACT FACTOR

As set out in CS 454 an impact factor of 1.8 has been applied to one axle only and only to the single vehicle scenarios.

2.6 OVERLOAD FACTOR

As per the method used in the previous study, the overload factor has been applied in accordance with the method used to derive the BD37/01 load model, i.e. applied to all axles within the span. The overload factor has been applied as a factor on the total load effects as follows:

- 1.4 for span lengths up to 10m
- Linear interpolation between 1.40 and 1.0 for span lengths between 10m and 60m.

Table 2: Overload factors

Span	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m
Overload factor	1.4	1.4	1.36	1.32	1.28	1.24	1.20	1.16	1.12	1.08

It is noted that CS 458 applies overload factor of 1.2 to the critical axle and 1.1 to all other axles. However, these overload factors are derived on the basis that STGO and SO vehicles are subject to more rigorous management planning and supervision by hauliers to provide confidence that overloading will be unlikely. Hence, as there is not sufficient statistical data at present for VCMs load distribution, it is considered that the application of the CS 458 overload factors is not appropriate for this study currently.

2.7 WIDTH FACTOR

In CS 454 the width factor has been incorporated into derivation of the ALL Model 2 UDL and KEL in Table 5.19a. CS 454 ALL Model 1 does not apply a width factor, other than using different notional lane widths for the single vehicle and convoy situations.

A width factor has not been applied to the VCM load effects as it has already been applied to the CS ALL Model 2 values.

2.8 K FACTOR

In deriving the load effects for CS 454 ALL Model 2 a K factor of 0.91 has been applied in accordance with Figure 5.19a.

2.9 ULS EFFECTS

The extreme load effects used to derive the BD37/01 load model (and subsequently CS 454 ALL Model 2) were deemed to represent the ULS factored live load effect. CS 454 and the Eurocode presents load models that provide nominal/characteristic actions which are then multiplied by partial factors to give the ULS load effects. As such the load model published in BD37/01 was obtained by dividing the effects by a factor of 1.5. As the same method has been used to derive the load effects for the VCM, the load effects given in this study are considered to be ULS. These have been compared against ULS values from CS 454 and Eurocodes.

2.10 CALCULATION OF LOAD EFFECTS

Load effects have been calculated using an influence line method for moment and shear. These have been CAT II checked using a moving load analysis in LUSAS with enveloping of the results for moment and shear. The increment of the moving load was 0.5m. The results presented for shear in this study are the most onerous of the shear effects at both ends.

2.11 INCREASED SPACING

The previous study states in the text that they have assumed 3m spacing between the last axle of one vehicle and the first axle of the next vehicle, the initial analysis in this study has used the same spacings. The diagrams in the previous study however show that the vehicles have a front overhang of approximately 1.4m and a rear overhang of 2.8m. This would result in approximately 5.2m spacing between axles in adjacent vehicles.

This increase in spacing, over the 3m spacing previously used, is likely to result in reduced utilisations for the 3-vehicle and 8 vehicle scenarios. These scenarios have been re-run with the increased spacing, the results are presented in Section 3.7.

3 RESULTS

3.1 4 AXLE VEHICLE – VARIATION 1

Table 3: Utilisations by 4 axle vehicle, variation 1

4 - Axle Vehicle - Variation 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	421	497	536	547	552	543	532	518	504	488	kN
2	298	406	539	643	756	843	893	919	930	929	kN
3	301	409	542	648	761	856	950	1032	1103	1175	kN
4	289	410	518	610	696	744	769	797	809	811	kN
5	477	1160	1928	2651	3323	3953	4535	5071	5555	5994	kN.m
6	313	854	1632	2685	4111	5655	7168	8563	9852	11026	kN.m
7	313	854	1632	2687	4111	5691	7377	9288	11398	13541	kN.m
8	313	913	1778	2781	3980	5262	6601	7836	8971	10013	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.16	1.07	1.04	0.88	0.73	0.62	0.53	0.46	0.40	0.35	Ratio
2	0.82	0.88	1.04	1.03	1.00	0.96	0.89	0.81	0.74	0.67	Ratio
3	0.83	0.88	1.05	1.04	1.01	0.98	0.95	0.91	0.88	0.85	Ratio
4	0.80	0.89	1.00	0.98	0.92	0.85	0.77	0.71	0.64	0.59	Ratio
5	1.06	1.07	1.07	0.98	0.82	0.69	0.58	0.50	0.43	0.38	Ratio
6	0.69	0.79	0.90	0.99	1.02	0.98	0.92	0.85	0.77	0.70	Ratio
7	0.69	0.79	0.90	0.99	1.02	0.99	0.95	0.92	0.89	0.86	Ratio
8	0.69	0.84	0.98	1.03	0.98	0.91	0.85	0.77	0.70	0.63	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.12	1.11	1.08	1.02	0.90	0.77	0.66	0.55	0.52	0.49	Ratio
2	0.79	0.91	1.09	1.21	1.23	1.19	1.10	0.98	0.96	0.93	Ratio
3	0.80	0.91	1.10	1.21	1.24	1.21	1.17	1.10	1.14	1.18	Ratio
4	0.77	0.92	1.05	1.14	1.13	1.05	0.95	0.85	0.84	0.81	Ratio
5	1.01	1.04	1.04	0.99	0.86	0.75	0.64	0.54	0.51	0.48	Ratio
6	0.66	0.76	0.88	1.01	1.07	1.07	1.01	0.91	0.90	0.88	Ratio
7	0.66	0.76	0.88	1.01	1.07	1.08	1.04	0.99	1.05	1.09	Ratio
8	0.66	0.82	0.96	1.04	1.04	0.99	0.93	0.83	0.82	0.80	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.57	0.54	0.52	0.48	0.45	0.42	0.39	0.36	Ratio
2	0.39	0.47	0.57	0.64	0.71	0.75	0.75	0.74	0.72	0.69	Ratio
3	0.39	0.48	0.58	0.64	0.72	0.76	0.80	0.83	0.85	0.87	Ratio
4	0.38	0.48	0.55	0.60	0.66	0.66	0.65	0.64	0.62	0.60	Ratio
5	0.56	0.56	0.56	0.54	0.51	0.47	0.44	0.41	0.38	0.36	Ratio
6	0.37	0.41	0.48	0.55	0.63	0.68	0.70	0.70	0.68	0.66	Ratio
7	0.37	0.41	0.48	0.55	0.63	0.68	0.72	0.75	0.79	0.80	Ratio
8	0.37	0.44	0.52	0.57	0.61	0.63	0.64	0.64	0.62	0.59	Ratio

The 4 axle vehicle, variation 1 causes a theoretical overload at spans up to 35m relative to CS 454 ALL Model 1, with a peak overload of 16%. This occurs when looking at the shear effects for a 5m span, for the single vehicle scenario, and is driven by tandem axle loads of 120kN. These are 20% heavier than the heaviest tandem axles in CS 454 ALL Model 1.

Relative to CS 454 ALL Model 2, the vehicle causes theoretical overload at all span lengths, with a peak overload of 24%. This occurs when looking at the shear effects for a 25m span for the 8-vehicle scenario.

The vehicle does not cause overloads relative to the Eurocode Load Model 1 (LM1) as defined by the UK National Annex to Eurocode BS EN 1991-2.

3.2 4 AXLE VEHICLE – VARIATION 2

Table 4: Utilisations by 4 axle vehicle, variation 2

4 - Axle Vehicle - Variation 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	392.43	478.45	521.1928	533.2272	539.2768	531.6872	520.944	508.2308	494.2	479.2392	kN
2	279.45	393.89	525.3544	631.9104	744.1792	832.8212	884.544	912.05	923.384	923.4216	kN
3	282.254	397.53	528.5912	636.6888	748.48	845.0228	939.132	1022.08	1097.578	1165.266	kN
4	271.068	396.494	510.27	604.4016	691.9296	740.1932	771.996	798.9616	810.9696	812.5272	kN
5	444.22	1104.39	1859.664	2571.109	3235.533	3857.491	4432.536	4961.877	5440.747	5873.148	kN.m
6	291.30	818.076	1616.986	2672.723	4084.698	5622.606	7135.08	8530.083	9819.499	10993.1	kN.m
7	291.42	818.076	1616.986	2674.28	4084.698	5660.736	7365.648	9275.731	11374.50	13516.96	kN.m
8	291.26	865.676	1726.955	2727.754	3930.086	5230.357	6568.344	7804.25	8939.246	9981.868	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Max . Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.08	1.03	1.01	0.85	0.71	0.61	0.52	0.45	0.39	0.35	Ratio
2	0.77	0.85	1.02	1.01	0.99	0.95	0.88	0.81	0.74	0.67	Ratio
3	0.78	0.86	1.02	1.02	0.99	0.96	0.93	0.91	0.87	0.84	Ratio
4	0.75	0.86	0.99	0.97	0.92	0.84	0.77	0.71	0.65	0.59	Ratio
5	0.99	1.02	1.03	0.95	0.80	0.67	0.57	0.49	0.42	0.37	Ratio
6	0.65	0.76	0.89	0.99	1.01	0.98	0.92	0.84	0.77	0.69	Ratio
7	0.65	0.76	0.89	0.99	1.01	0.98	0.95	0.92	0.89	0.85	Ratio
8	0.65	0.80	0.95	1.01	0.97	0.91	0.85	0.77	0.70	0.63	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Max . Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.04	1.07	1.05	1.00	0.88	0.75	0.64	0.54	0.51	0.48	Ratio
2	0.74	0.88	1.06	1.18	1.21	1.18	1.09	0.97	0.95	0.93	Ratio
3	0.75	0.89	1.07	1.19	1.22	1.20	1.16	1.09	1.13	1.17	Ratio
4	0.72	0.89	1.03	1.13	1.12	1.05	0.95	0.85	0.84	0.81	Ratio
5	0.94	0.99	1.00	0.96	0.84	0.73	0.62	0.53	0.50	0.47	Ratio
6	0.62	0.73	0.87	1.00	1.06	1.06	1.00	0.91	0.90	0.88	Ratio
7	0.62	0.73	0.87	1.00	1.06	1.07	1.04	0.99	1.04	1.08	Ratio
8	0.61	0.77	0.93	1.02	1.02	0.99	0.92	0.83	0.82	0.80	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Max . Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.51	0.56	0.56	0.53	0.51	0.47	0.44	0.41	0.38	0.35	Ratio
2	0.36	0.46	0.56	0.63	0.70	0.74	0.75	0.74	0.71	0.68	Ratio
3	0.37	0.46	0.56	0.63	0.70	0.75	0.79	0.83	0.85	0.86	Ratio
4	0.35	0.46	0.54	0.60	0.65	0.66	0.65	0.65	0.62	0.60	Ratio
5	0.52	0.53	0.54	0.52	0.49	0.46	0.43	0.40	0.38	0.35	Ratio
6	0.34	0.40	0.47	0.54	0.62	0.67	0.70	0.69	0.68	0.65	Ratio
7	0.34	0.40	0.47	0.54	0.62	0.68	0.72	0.75	0.78	0.80	Ratio
8	0.34	0.42	0.50	0.55	0.60	0.63	0.64	0.63	0.62	0.59	Ratio

The 4 axle vehicle, variation 2 causes a theoretical overload at spans up to 25m relative to CS 454 ALL Model 1, with a peak overload of 8%. This occurs when looking at the shear effects for a 5m span, for the single vehicle scenario, and similarly to the 4 axle variation 1 is driven by tandem axle loads.

Relative to CS 454 ALL Model 2, the vehicle causes theoretical overload at all span lengths, with a peak overload of 22%. This occurs when looking at the shear effects for a 25m span for the 8-vehicle scenario.

The vehicle does not cause overloads relative to the Eurocode Load Model 1 (LM1) as defined by the UK National Annex to Eurocode BS EN 1991-2.

3.3 5 AXLE VEHICLE – VARIATION 1

Table 5: Utilisations by 5 axle vehicle, variation 1

5 - Axle Vehicle - Variation 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	422	499	559	579	589	583	573	560	546	530	kN
2	306	419	557	670	786	874	937	980	1002	1010	kN
3	310	419	557	670	786	888	991	1072	1152	1223	kN
4	309	419	523	617	711	767	798	829	843	847	kN
5	487	1231	2080	2881	3626	4324	4961	5557	6094	6574	kN.m
6	338	930	1762	2817	4288	5986	7729	9350	10841	12199	kN.m
7	339	930	1763	2819	4291	5990	7821	9725	11901	14221	kN.m
8	334	931	1861	2887	4160	5501	6916	8223	9426	10521	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.17	1.08	1.08	0.93	0.78	0.67	0.57	0.50	0.43	0.38	Ratio
2	0.84	0.91	1.08	1.07	1.04	1.00	0.93	0.87	0.80	0.73	Ratio
3	0.86	0.91	1.08	1.07	1.04	1.01	0.99	0.95	0.92	0.89	Ratio
4	0.85	0.91	1.01	0.99	0.94	0.87	0.79	0.73	0.67	0.61	Ratio
5	1.08	1.14	1.15	1.06	0.90	0.75	0.64	0.55	0.48	0.42	Ratio
6	0.75	0.86	0.97	1.04	1.06	1.04	0.99	0.92	0.85	0.77	Ratio
7	0.75	0.86	0.97	1.04	1.06	1.04	1.01	0.96	0.93	0.90	Ratio
8	0.74	0.86	1.03	1.07	1.03	0.96	0.89	0.81	0.73	0.66	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.12	1.11	1.13	1.09	0.96	0.83	0.71	0.60	0.56	0.53	Ratio
2	0.81	0.94	1.13	1.26	1.28	1.24	1.15	1.04	1.03	1.01	Ratio
3	0.82	0.94	1.13	1.26	1.28	1.26	1.22	1.14	1.19	1.23	Ratio
4	0.82	0.94	1.06	1.16	1.16	1.09	0.98	0.88	0.87	0.85	Ratio
5	1.03	1.10	1.12	1.08	0.94	0.82	0.70	0.59	0.56	0.53	Ratio
6	0.71	0.83	0.95	1.06	1.12	1.13	1.09	1.00	0.99	0.98	Ratio
7	0.72	0.83	0.95	1.06	1.12	1.13	1.10	1.04	1.09	1.14	Ratio
8	0.71	0.83	1.00	1.08	1.08	1.04	0.97	0.88	0.86	0.84	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.60	0.57	0.55	0.52	0.48	0.45	0.42	0.39	Ratio
2	0.40	0.49	0.59	0.66	0.74	0.78	0.79	0.79	0.77	0.74	Ratio
3	0.40	0.49	0.59	0.66	0.74	0.79	0.84	0.87	0.89	0.90	Ratio
4	0.40	0.49	0.56	0.61	0.67	0.68	0.67	0.67	0.65	0.62	Ratio
5	0.57	0.60	0.61	0.59	0.55	0.52	0.48	0.45	0.42	0.39	Ratio
6	0.40	0.45	0.51	0.57	0.65	0.72	0.75	0.76	0.75	0.72	Ratio
7	0.40	0.45	0.51	0.57	0.65	0.72	0.76	0.79	0.82	0.85	Ratio
8	0.39	0.45	0.54	0.59	0.63	0.66	0.67	0.67	0.65	0.63	Ratio

The 5 axle vehicle, variation 1 causes a theoretical overload at spans up to 35m relative to CS 454 ALL Model 1, with a peak overload of 17%. This occurs when looking at the shear effects for a 5m span, for the single vehicle scenario.

Relative to CS 454 ALL Model 2, the vehicle causes theoretical overload at all span lengths, with a peak overload of 28%. This occurs when looking at the shear effects for a 25m span for the 8-scenario.

The vehicle does not cause overloads relative to the Eurocode Load Model 1 (LM1) as defined by the UK National Annex to Eurocode BS EN 1991-2.

3.4 5 AXLE VEHICLE – VARIATION 2

Table 5: Utilisations by 5 axle vehicle, variation 2

5 - Axle Vehicle - Variation 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	420	499	545	569	581	577	568	556	542	526	kN
2	297	417	553	668	784	869	922	968	992	1001	kN
3	301	417	553	668	784	886	988	1070	1150	1221	kN
4	297	406	508	608	704	761	802	833	847	850	kN
5	475	1196	1977	2844	3594	4288	4928	5518	6054	6548	kN.m
6	328	897	1747	2814	4281	5949	7697	9318	10806	12168	kN.m
7	328	897	1749	2815	4282	5959	7802	9719	11889	14189	kN.m
8	324	886	1795	2836	4098	5469	6883	8192	9395	10490	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.16	1.08	1.06	0.91	0.77	0.66	0.57	0.49	0.43	0.38	Ratio
2	0.82	0.90	1.07	1.07	1.04	0.99	0.92	0.86	0.79	0.73	Ratio
3	0.83	0.90	1.07	1.07	1.04	1.01	0.98	0.95	0.92	0.89	Ratio
4	0.82	0.88	0.98	0.97	0.93	0.87	0.80	0.74	0.67	0.62	Ratio
5	1.05	1.10	1.09	1.05	0.89	0.75	0.63	0.55	0.47	0.41	Ratio
6	0.73	0.83	0.97	1.04	1.06	1.03	0.99	0.92	0.84	0.77	Ratio
7	0.73	0.83	0.97	1.04	1.06	1.04	1.00	0.96	0.93	0.90	Ratio
8	0.72	0.82	0.99	1.05	1.01	0.95	0.89	0.81	0.73	0.66	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.11	1.12	1.10	1.07	0.94	0.82	0.70	0.59	0.56	0.53	Ratio
2	0.79	0.93	1.12	1.25	1.27	1.23	1.14	1.03	1.02	1.00	Ratio
3	0.80	0.93	1.12	1.25	1.27	1.26	1.22	1.14	1.19	1.22	Ratio
4	0.79	0.91	1.03	1.14	1.14	1.08	0.99	0.89	0.87	0.85	Ratio
5	1.00	1.07	1.07	1.07	0.94	0.81	0.69	0.59	0.56	0.53	Ratio
6	0.69	0.80	0.94	1.05	1.11	1.12	1.08	0.99	0.99	0.98	Ratio
7	0.69	0.80	0.94	1.05	1.11	1.13	1.10	1.04	1.09	1.14	Ratio
8	0.68	0.79	0.97	1.06	1.07	1.03	0.97	0.87	0.86	0.84	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.58	0.56	0.55	0.51	0.48	0.45	0.42	0.39	Ratio
2	0.39	0.49	0.59	0.66	0.74	0.77	0.78	0.78	0.76	0.74	Ratio
3	0.39	0.49	0.59	0.66	0.74	0.79	0.83	0.86	0.89	0.90	Ratio
4	0.39	0.47	0.54	0.60	0.66	0.68	0.68	0.67	0.65	0.63	Ratio
5	0.56	0.58	0.58	0.58	0.55	0.51	0.48	0.45	0.42	0.39	Ratio
6	0.39	0.43	0.51	0.57	0.65	0.71	0.75	0.76	0.75	0.72	Ratio
7	0.39	0.43	0.51	0.57	0.65	0.71	0.76	0.79	0.82	0.84	Ratio
8	0.38	0.43	0.52	0.58	0.62	0.66	0.67	0.67	0.65	0.62	Ratio

The 5 axle vehicle, variation 2 causes a theoretical overload at spans up to 35m relative to CS 454 ALL Model 1, with a peak overload of 16%. This occurs when looking at the shear effects for a 5m span, for the single vehicle scenario.

Relative to CS 454 ALL Model 2, the vehicle causes theoretical overload at all span lengths, with a peak overload of 27%. This occurs when looking at the shear effects for a 25m span for the 8-vehicle scenario.

The vehicle does not cause overloads relative to the Eurocode Load Model 1 (LM1) as defined by the UK National Annex to Eurocode BS EN 1991-2.

3.5 COMPARISON WITH PREVIOUS STUDY

For spans up to 20m the results compare favourably with the previous study, with the reduced axles loads and lower overall vehicle weights resulting in lower utilisations. At spans over 20m the 3-vehicle and 8-vehicle scenarios are resulting in higher utilisations that the previous study. This is unexpected for the 4-axle vehicle.

CS 454 gives the following useful note, when comparing load effects from ALL Model 1 and ALL Model 2:

NOTE 1 *ALL model 1 is based on real vehicles with maximum authorised vehicle weights. It is particularly suitable for loaded lengths up to about 20m. For loaded lengths longer than about 20m the application of ALL model 1 can produce overly conservative estimates of the effects of traffic, since it is based on the worst possible arrangement of heavy vehicles, rather than a statistically representative distribution of traffic.*

This study has attempted to apply the loading in the same way as the previous study, however it is unclear whether the previous study has applied any reduction to the load effects for the 3-vehicle and 8-vehicle scenarios to consider the statistically representative distribution of traffic. The impact factor, width factor, overload factor and partial factors have been applied in a similar way in this study. The methodology used in the previous study refers to a paper *"Revision of short span loading: Appendix A: BES Division, Department of Transport"* which was not officially published, and for which we were unable to obtain a copy. Further studies would be needed in order to justify the application of statistical reductions to the VCM load models.

3.6 MASONRY ARCHES

Whilst not requested in the sub-task requirement it is noted that all of the vehicles investigated have tandem axle loads that exceed the limits in CS 454 Table 7.3.1a.

3.7 INCREASED SPACING

Scenarios 2,3,6 and 7 have been re-run for each of the vehicle variations considering an increased spacing between adjacent vehicles, as described in section 2.11. The results of this analysis are presented below, to aid comparison of the results all scenarios are included.

Table 6: Utilisations by 4 axle vehicle, variation 1 – Increased spacing for Scenarios 2, 3, 6 and 7 shown in ***bold italics***; no changes for Scenarios 1, 4, 5 and 8 results

4 - Axle Vehicle - Variation 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	421.40	497.308	536.4656	546.5988	551.8464	543.244	531.696	518.3112	503.6864	488.2032	kN
2	298.06	399.28	483.7384	580.94	653.2992	738.7548	806.628	846.2212	866.9696	874.5192	kN
3	298.102	399.28	483.7384	580.9452	653.2992	738.7548	806.616	874.0832	934.9424	986.0724	kN
4	289.464	410.088	517.5072	609.7476	696.1152	743.6032	769.464	796.8388	809.1776	811.0044	kN
5	476.98	1159.62	1928.48	2651.312	3322.726	3952.525	4534.728	5071.3	5555.435	5993.773	kN.m
6	311.78	830.186	1470.704	2235.552	3313.498	4659.498	6140.172	7572.793	8894.267	10100.61	kN.m
7	312.76	830.382	1471.248	2235.948	3313.638	4660.304	6141.864	7627.29	9196.118	10912.64	kN.m
8	312.76	912.786	1778.2	2780.897	3979.533	5262.411	6600.696	7835.80	8971.446	10012.83	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.16	1.07	1.04	0.88	0.73	0.62	0.53	0.46	0.40	0.35	Ratio
2	*0.82*	*0.86*	*0.94*	*0.93*	*0.87*	*0.84*	*0.80*	*0.75*	*0.69*	*0.63*	Ratio
3	*0.82*	*0.86*	*0.94*	*0.93*	*0.87*	*0.84*	*0.80*	*0.77*	*0.75*	*0.71*	Ratio
4	0.80	0.89	1.00	0.98	0.92	0.85	0.77	0.71	0.64	0.59	Ratio
5	1.06	1.07	1.07	0.98	0.82	0.69	0.58	0.50	0.43	0.38	Ratio
6	*0.69*	*0.77*	*0.81*	*0.83*	*0.82*	*0.81*	*0.79*	*0.75*	*0.69*	*0.64*	Ratio
7	*0.69*	*0.77*	*0.81*	*0.83*	*0.82*	*0.81*	*0.79*	*0.75*	*0.72*	*0.69*	Ratio
8	0.69	0.84	0.98	1.03	0.98	0.91	0.85	0.77	0.70	0.63	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.12	1.11	1.08	1.02	0.90	0.77	0.66	0.55	0.52	0.49	Ratio
2	*0.79*	*0.89*	*0.98*	*1.09*	*1.06*	*1.05*	*0.99*	*0.90*	*0.89*	*0.88*	Ratio
3	*0.79*	*0.89*	*0.98*	*1.09*	*1.06*	*1.05*	*0.99*	*0.93*	*0.97*	*0.99*	Ratio
4	0.77	0.92	1.05	1.14	1.13	1.05	0.95	0.85	0.84	0.81	Ratio
5	1.01	1.04	1.04	0.99	0.86	0.75	0.64	0.54	0.51	0.48	Ratio
6	*0.66*	*0.74*	*0.79*	*0.84*	*0.86*	*0.88*	*0.86*	*0.81*	*0.82*	*0.81*	Ratio
7	*0.66*	*0.74*	*0.79*	*0.84*	*0.86*	*0.88*	*0.86*	*0.81*	*0.84*	*0.87*	Ratio
8	0.66	0.82	0.96	1.04	1.04	0.99	0.93	0.83	0.82	0.80	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.57	0.54	0.52	0.48	0.45	0.42	0.39	0.36	Ratio
2	*0.39*	*0.47*	*0.52*	*0.58*	*0.62*	*0.66*	*0.68*	*0.68*	*0.67*	*0.64*	Ratio
3	*0.39*	*0.47*	*0.52*	*0.58*	*0.62*	*0.66*	*0.68*	*0.71*	*0.72*	*0.73*	Ratio
4	0.38	0.48	0.55	0.60	0.66	0.66	0.65	0.64	0.62	0.60	Ratio
5	0.56	0.56	0.56	0.54	0.51	0.47	0.44	0.41	0.38	0.36	Ratio
6	*0.37*	*0.40*	*0.43*	*0.45*	*0.51*	*0.56*	*0.60*	*0.62*	*0.61*	*0.60*	Ratio
7	*0.37*	*0.40*	*0.43*	*0.45*	*0.51*	*0.56*	*0.60*	*0.62*	*0.63*	*0.65*	Ratio
8	0.37	0.44	0.52	0.57	0.61	0.63	0.64	0.64	0.62	0.59	Ratio

There is no change in the peak overload relative to CS 454 ALL Model 1 with the increased axle spacing for the 3 vehicle and 8 vehicle scenarios. The peak overload factor is caused by the single vehicle scenario in shear for the 5m span. This is common for all vehicle variations.

Relative to CS 454 ALL Model 2, the peak overload across all scenarios has reduced from 24% to 14%. The 3 vehicle and 8 vehicle scenarios are no longer critical with the increased spacing.

Table 7: Utilisations by 4 axle vehicle, variation 2 – Increased spacing for Scenarios 2, 3, 6 and 7 shown in ***bold italics***; no changes for Scenarios 1, 4, 5 and 8 results

4 - Axle Vehicle - Variation 2											
Load Effects											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	392	478	521	533	539	532	521	508	494	479	kN
2	279	388	473	570	644	729	798	839	861	869	kN
3	279	388	473	570	644	729	798	865	927	978	kN
4	271	396	510	604	692	740	772	799	811	813	kN
5	444	1104	1860	2571	3236	3857	4433	4962	5441	5873	kN.m
6	291	797	1436	2225	3297	4632	6108	7539	8861	10069	kN.m
7	291	797	1437	2225	3299	4632	6110	7599	9177	10900	kN.m
8	291	866	1727	2728	3930	5230	6568	7804	8939	9982	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Max . Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.08	1.03	1.01	0.85	0.71	0.61	0.52	0.45	0.39	0.35	Ratio
2	*0.77*	*0.84*	*0.92*	*0.91*	*0.85*	*0.83*	*0.79*	*0.74*	*0.69*	*0.63*	Ratio
3	*0.77*	*0.84*	*0.92*	*0.91*	*0.85*	*0.83*	*0.79*	*0.77*	*0.74*	*0.71*	Ratio
4	0.75	0.86	0.99	0.97	0.92	0.84	0.77	0.71	0.65	0.59	Ratio
5	0.99	1.02	1.03	0.95	0.80	0.67	0.57	0.49	0.42	0.37	Ratio
6	*0.65*	*0.74*	*0.79*	*0.82*	*0.81*	*0.80*	*0.79*	*0.74*	*0.69*	*0.64*	Ratio
7	*0.65*	*0.74*	*0.79*	*0.82*	*0.81*	*0.80*	*0.79*	*0.75*	*0.72*	*0.69*	Ratio
8	0.65	0.80	0.95	1.01	0.97	0.91	0.85	0.77	0.70	0.63	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Max . Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.04	1.07	1.05	1.00	0.88	0.75	0.64	0.54	0.51	0.48	Ratio
2	*0.74*	*0.87*	*0.96*	*1.07*	*1.05*	*1.03*	*0.98*	*0.89*	*0.89*	*0.87*	Ratio
3	*0.74*	*0.87*	*0.96*	*1.07*	*1.05*	*1.03*	*0.98*	*0.92*	*0.96*	*0.98*	Ratio
4	0.72	0.89	1.03	1.13	1.12	1.05	0.95	0.85	0.84	0.81	Ratio
5	0.94	0.99	1.00	0.96	0.84	0.73	0.62	0.53	0.50	0.47	Ratio
6	*0.62*	*0.71*	*0.77*	*0.83*	*0.86*	*0.88*	*0.86*	*0.80*	*0.81*	*0.81*	Ratio
7	*0.62*	*0.71*	*0.77*	*0.83*	*0.86*	*0.88*	*0.86*	*0.81*	*0.84*	*0.87*	Ratio
8	0.61	0.77	0.93	1.02	1.02	0.99	0.92	0.83	0.82	0.80	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Max. Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Max . Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.51	0.56	0.56	0.53	0.51	0.47	0.44	0.41	0.38	0.35	Ratio
2	*0.36*	*0.45*	*0.50*	*0.57*	*0.61*	*0.65*	*0.67*	*0.68*	*0.66*	*0.64*	Ratio
3	*0.36*	*0.45*	*0.50*	*0.57*	*0.61*	*0.65*	*0.67*	*0.70*	*0.71*	*0.72*	Ratio
4	0.35	0.46	0.54	0.60	0.65	0.66	0.65	0.65	0.62	0.60	Ratio
5	0.52	0.53	0.54	0.52	0.49	0.46	0.43	0.40	0.38	0.35	Ratio
6	*0.34*	*0.39*	*0.42*	*0.45*	*0.50*	*0.56*	*0.60*	*0.61*	*0.61*	*0.60*	Ratio
7	*0.34*	*0.39*	*0.42*	*0.45*	*0.50*	*0.56*	*0.60*	*0.62*	*0.63*	*0.65*	Ratio
8	0.34	0.42	0.50	0.55	0.60	0.63	0.64	0.63	0.62	0.59	Ratio

Relative to CS 454 ALL Model 2, the peak overload across all scenarios has reduced from 22% to 13%. The 3 vehicle and 8 vehicle scenarios are no longer critical with the increased spacing.

Table 8: Utilisations by 5 axle vehicle, variation 1 – Increased spacing for Scenarios 2, 3, 6 and 7 shown in ***bold italics***; no changes for Scenarios 1, 4, 5 and 8 results

5 - Axle Vehicle - Variation 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	422	499	559	579	589	583	573	560	546	530	kN
2	306	408	485	598	685	771	855	911	968	958	kN
3	306	409	486	600	686	772	856	920	989	1045	kN
4	309	419	523	617	711	767	798	829	843	847	kN
5	487	1231	2080	2881	3626	4324	4961	5557	6094	6574	kN.m
6	338	922	1629	2456	3561	4981	6615	8272	9800	11199	kN.m
7	339	922	1629	2456	3561	4982	6616	8273	9938	11743	kN.m
8	334	931	1861	2887	4160	5501	6916	8223	9426	10521	kN.m
ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.17	1.08	1.08	0.93	0.78	0.67	0.57	0.50	0.43	0.38	Ratio
2	*0.84*	*0.88*	*0.94*	*0.96*	*0.91*	*0.88*	*0.85*	*0.81*	*0.77*	*0.69*	Ratio
3	*0.84*	*0.88*	*0.94*	*0.96*	*0.91*	*0.88*	*0.85*	*0.81*	*0.79*	*0.76*	Ratio
4	0.85	0.91	1.01	0.99	0.94	0.87	0.79	0.73	0.67	0.61	Ratio
5	1.08	1.14	1.15	1.06	0.90	0.75	0.64	0.55	0.48	0.42	Ratio
6	*0.75*	*0.85*	*0.90*	*0.91*	*0.88*	*0.87*	*0.85*	*0.82*	*0.76*	*0.71*	Ratio
7	*0.75*	*0.85*	*0.90*	*0.91*	*0.88*	*0.87*	*0.85*	*0.82*	*0.77*	*0.74*	Ratio
8	0.74	0.86	1.03	1.07	1.03	0.96	0.89	0.81	0.73	0.66	Ratio
ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.12	1.11	1.13	1.09	0.96	0.83	0.71	0.60	0.56	0.53	Ratio
2	*0.81*	*0.91*	*0.98*	*1.12*	*1.11*	*1.09*	*1.05*	*0.97*	*1.00*	*0.96*	Ratio
3	*0.81*	*0.91*	*0.98*	*1.12*	*1.12*	*1.09*	*1.05*	*0.98*	*1.02*	*1.05*	Ratio
4	0.82	0.94	1.06	1.16	1.16	1.09	0.98	0.88	0.87	0.85	Ratio
5	1.03	1.10	1.12	1.08	0.94	0.82	0.70	0.59	0.56	0.53	Ratio
6	*0.71*	*0.82*	*0.88*	*0.92*	*0.93*	*0.94*	*0.93*	*0.88*	*0.90*	*0.90*	Ratio
7	*0.71*	*0.82*	*0.88*	*0.92*	*0.93*	*0.94*	*0.93*	*0.88*	*0.91*	*0.94*	Ratio
8	0.71	0.83	1.00	1.08	1.08	1.04	0.97	0.88	0.86	0.84	Ratio
ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.60	0.57	0.55	0.52	0.48	0.45	0.42	0.39	Ratio
2	*0.40*	*0.48*	*0.52*	*0.59*	*0.65*	*0.69*	*0.72*	*0.74*	*0.75*	*0.71*	Ratio
3	*0.40*	*0.48*	*0.52*	*0.59*	*0.65*	*0.69*	*0.72*	*0.74*	*0.76*	*0.77*	Ratio
4	0.40	0.49	0.56	0.61	0.67	0.68	0.67	0.67	0.65	0.62	Ratio
5	0.57	0.60	0.61	0.59	0.55	0.52	0.48	0.45	0.42	0.39	Ratio
6	*0.40*	*0.45*	*0.48*	*0.50*	*0.54*	*0.60*	*0.65*	*0.67*	*0.68*	*0.67*	Ratio
7	*0.40*	*0.45*	*0.48*	*0.50*	*0.54*	*0.60*	*0.65*	*0.67*	*0.69*	*0.70*	Ratio
8	0.39	0.45	0.54	0.59	0.63	0.66	0.67	0.67	0.65	0.63	Ratio

Relative to CS 454 ALL Model 2, the peak overload across all scenarios has reduced from 28% to 16%. The 3 vehicle and 8 vehicle scenarios are no longer critical with the increased spacing.

Table 9: Utilisations by 5 axle vehicle, variation 2 – Increased spacing for Scenarios 2, 3, 6 and 7 shown in ***bold italics***; no changes for Scenarios 1, 4, 5 and 8 results

5 - Axle Vehicle - Variation 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
1	420	499	545	569	581	577	568	556	542	526	kN
2	297	392	480	588	671	759	840	899	932	949	kN
3	297	393	481	589	672	759	842	907	976	1033	kN
4	297	406	508	608	704	761	802	833	847	850	kN
5	475	1196	1977	2844	3594	4288	4928	5518	6054	6548	kN.m
6	327	885	1592	2444	3549	4969	6581	8237	9766	11166	kN.m
7	327	886	1593	2444	3549	4970	6582	8239	9925	11730	kN.m
8	324	886	1795	2836	4098	5469	6883	8192	9395	10490	kN.m

ULS CS 454 - ALL MODEL 1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	450	1083	1810	2710	4050	5755	7772	10124	12828	15829	kN.m
Shear	362	463	516	625	754	877	1005	1128	1255	1380	kN
Comparison											
1	1.16	1.08	1.06	0.91	0.77	0.66	0.57	0.49	0.43	0.38	Ratio
2	*0.82*	*0.85*	*0.93*	*0.94*	*0.89*	*0.87*	*0.84*	*0.80*	*0.74*	*0.69*	Ratio
3	*0.82*	*0.85*	*0.93*	*0.94*	*0.89*	*0.87*	*0.84*	*0.80*	*0.78*	*0.75*	Ratio
4	0.82	0.88	0.98	0.97	0.93	0.87	0.80	0.74	0.67	0.62	Ratio
5	1.05	1.10	1.09	1.05	0.89	0.75	0.63	0.55	0.47	0.41	Ratio
6	*0.73*	*0.82*	*0.88*	*0.90*	*0.88*	*0.86*	*0.85*	*0.81*	*0.76*	*0.71*	Ratio
7	*0.73*	*0.82*	*0.88*	*0.90*	*0.88*	*0.86*	*0.85*	*0.81*	*0.77*	*0.74*	Ratio
8	0.72	0.82	0.99	1.05	1.01	0.95	0.89	0.81	0.73	0.66	Ratio

ULS CS 454 - ALL MODEL 2											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	474	1118	1857	2669	3842	5290	7102	9385	10901	12473	kN.m
Shear	377	448	495	533	615	705	811	939	969	998	kN
Comparison											
1	1.11	1.12	1.10	1.07	0.94	0.82	0.70	0.59	0.56	0.53	Ratio
2	*0.79*	*0.88*	*0.97*	*1.10*	*1.09*	*1.08*	*1.04*	*0.96*	*0.96*	*0.95*	Ratio
3	*0.79*	*0.88*	*0.97*	*1.10*	*1.09*	*1.08*	*1.04*	*0.97*	*1.01*	*1.04*	Ratio
4	0.79	0.91	1.03	1.14	1.14	1.08	0.99	0.89	0.87	0.85	Ratio
5	1.00	1.07	1.07	1.07	0.94	0.81	0.69	0.59	0.56	0.53	Ratio
6	*0.69*	*0.79*	*0.86*	*0.92*	*0.92*	*0.94*	*0.93*	*0.88*	*0.90*	*0.90*	Ratio
7	*0.69*	*0.79*	*0.86*	*0.92*	*0.92*	*0.94*	*0.93*	*0.88*	*0.91*	*0.94*	Ratio
8	0.68	0.79	0.97	1.06	1.07	1.03	0.97	0.87	0.86	0.84	Ratio

ULS EN 1991-2 LM1											
Scenario	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	Unit
Bending	852	2066	3424	4922	6558	8335	10250	12305	14493	16828	kN.m
Shear	768	856	939	1008	1062	1125	1185	1238	1298	1356	kN
Comparison											
1	0.55	0.58	0.58	0.56	0.55	0.51	0.48	0.45	0.42	0.39	Ratio
2	*0.39*	*0.46*	*0.51*	*0.58*	*0.63*	*0.67*	*0.71*	*0.73*	*0.72*	*0.70*	Ratio
3	*0.39*	*0.46*	*0.51*	*0.58*	*0.63*	*0.68*	*0.71*	*0.73*	*0.75*	*0.76*	Ratio
4	0.39	0.47	0.54	0.60	0.66	0.68	0.68	0.67	0.65	0.63	Ratio
5	0.56	0.58	0.58	0.58	0.55	0.51	0.48	0.45	0.42	0.39	Ratio
6	*0.38*	*0.43*	*0.46*	*0.50*	*0.54*	*0.60*	*0.64*	*0.67*	*0.67*	*0.66*	Ratio
7	*0.38*	*0.43*	*0.47*	*0.50*	*0.54*	*0.60*	*0.64*	*0.67*	*0.68*	*0.70*	Ratio
8	0.38	0.43	0.52	0.58	0.62	0.66	0.67	0.67	0.65	0.62	Ratio

Relative to CS 454 ALL Model 2, the peak overload across all scenarios has reduced from 27% to 14%. The 3 vehicle and 8 vehicle scenarios are no longer critical with the increased spacing.

3.7.1 RESULTS SUMMARY

With increased spacing between vehicles, the 3-vehicle and 8-vehicle scenarios are resulting in lower utilisations than the previous study for the 4 axle vehicles with a reduction in overload from 16% to 9%. The 5 axle vehicle scenarios utilisations have increased marginally from the previous study from 8% to 12%.

The changes above results in different scenarios or load effects giving the most critical utilisation compared to the initial analysis undertaken for this study. Based on this, the following theoretical ULS overload % for the VCM vehicles have been determined:

- 17% when compared to CS 454 ALL Model 1
- 16% when compared to CS 454 ALL Model 2

3.8 CONSEQUENCES OF OVERLOAD

3.8.1 ULS CONSEQUENCES

For structural assessments in accordance with CS 454, bridges with an assessed capacity showing a similar order of magnitude of overload to that in Section 3.7.1 would be classified as sub-standard in accordance with CS 470. Such bridges would be subject to CS 470 sub-standard structure management, including interim measures. Note that any loading outside the existing CS 454 load models will have to be investigate on a case-by-case basis, in a similar manner to abnormal loading

The analysis in this study shows that shear is the critical overload load effect. As shear failures do not show visual signs of increasing distress over a period of time, monitoring interim measures are likely to be unsuitable for overloading resulting from VCMs.

At present, it is unknown how many structures would be overloaded by the VCMs in real life. Overloaded structures would need to be managed with interim measures in accordance with CS 470, significant resources and funding will need to be diverted to manage structures overloaded by the VCMs.

3.8.2 SLS CONSEQUENCES

Although not investigated as part of this study, similar serviceability limit state (SLS) overload factors are likely. Overload at SLS is likely to result in increased wear and tear to bridge elements and components, e.g. cracking to concrete bridges, accelerated deterioration of expansion joints and increased wearing of surfacing. This will have an impact on the whole life durability of bridges.

Additionally, while the occasional passage of overloaded vehicles on a bridge may not significantly increase the risk of fatigue damage to bridge components, bridge components will become vulnerable to fatigue damage if overloaded vehicles are frequent. This could be a particular issue on bridges near to concrete batching depots.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 INITIAL ANALYSIS

Theoretical load effects have been calculated for four vehicle types, looking at two scenarios for each of the 4 axle and 5 axle vehicles.

The load effects were calculated using the same methods as the previous study and using the same procedure as that employed in the development of the of the short span bridge live load model published in BD37/01 and as implemented in CS 454. No statistical reductions have been applied to the axle loads in the 3-vehicle and 8-vehicle scenarios.

The ULS load effects from the four vehicles have been compared to the ULS load effects from CS 454 ALL Model and Model 2 and BS EN 1991-2 LM1.

When applying an overload factor of 1.4, all vehicles have been found to cause theoretical overload when compared with CS 454 ALL Model 1, with a peak overload of 17%. All vehicles have also been found to cause theoretical overload when compared with CS 454 ALL Model 2, with a peak overload of 28%. All vehicles fall within the load effects for BS EN 1991-2 LM1, this would generally only apply to structures designed after 2010.

4.2 FURTHER ANALYSIS WITH INCREASE SPACING BETWEEN VEHICLES

A further comparison has been undertaken using more accurate front and rear overhang distances to increase the spacing between vehicles to approximately 5.2m for the 3-vehicle and 8-vehicle scenarios. No change is observed to the theoretical overload when compare with CS 454 ALL Model 1, as the single vehicle scenario is critical. When compared to CS 454 ALL Model 2, the peak theoretical overload reduces from 28% to 16%. The 3-vehicle and 8-vehicle scenarios are no longer critical.

4.3 RECOMMENDATIONS

This study shows that VCM will likely result in the overloading of existing bridges by 16-17% when compared to CS 454 assessment load models.

The findings in this study could be reviewed in the future if sufficient statistical data for VCM load distribution becomes available such that the adoption of reduced overload factors similar to CS 458 can be justified.