Back

COMPATIBILITY OF LONG AND HEAVY CARGO VEHICLES WITH THE GEOMETRIC DESIGN STANDARDS OF BRAZILIAN RURAL ROADS AND HIGHWAYS

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Abstract

The paper presents results of an investigation of the compatibility of several long and heavy CCV – cargo combination vehicle - configurations which circulate on a road network that was built to a geometric design standard based on design vehicles with shorter length and smaller GCM – gross combination mass. Results are presented, identifying traffic restrictions on several road classes, and adjustments to adequate road geometry to the new operating conditions are indicated. Four main aspects are considered: low speed offtracking, performance on long grades, lateral rollover threshold and intersection sight distance. Design vehicle characterisitics have been usually limited to size parameters and serves as a reference for the horizontal geometric design of roads and vertical clearances. An argument that other characteristics of the design vehicle are important to assure higher safety levels on the South American road network is presented.

Keywords: Highways, Geometric Design, Long Vehicles, Compatibility.

Résumé

Ce article présente les résultats d'une recherche sur la compatibilité de plusieurs configurations de CVM (combinations de véhicules de marchandises) longs et lourds qui circulent sur une route conçue selon une norme de géométrie basée sur des véhicules types de longueur plus courte et de MBC - masse brute combinée – plus faible. Les résultats sont présentés, en identifiant les restrictions de trafic sur plusieurs classes de routes, et des adaptations sont proposées pour adapter la géométrie des routes aux nouvelles conditions d'exploitation. Quatre critères principaux sont considérés : perte de trajectoire à vitesse réduite, performances sur de longues pentes, seuil de renversement et distance de visibilité en intersection. Les paramètres de la conception des véhicules ont été traditionnellement limités aux dimensions et ont servi de référence pour la conception du profil géométrique horizontal des routes et les gabarits. Nous expliquons que d'autres paramètres de conception du véhicule sont importants pour assurer une sécurité plus élevée sur le réseau routier sud-américain.

Mots-clés: routes, conception géométrique, véhicules lourds, compatibilité.

1. Introduction

Significant change in cargo vehicle characteristics has occured on the Brazilian road network over the last two decades. The continuous search for more productive transport vehicles in the heavy goods and general cargo transport market, permitted the advent and continuous growth of a fleet of quite innovative configurations of CCVs-Cargo Combination Vehicles. These vehicles, with one or more towed units are longer and heavier than the design vehicles used to design the roads which they traverse. It is estimated that the total truck fleet grew from about 1,051 million trucks in 1992 to 1,436 million units in 2005.

This growth is largely due to an increase in heavy truck traffic with gross combined weights ranging from 23 and 45 t. While in 1992 these vehicles represented only 6.9% of the total fleet, in 2005 they represented 17%. Extra-heavy vehicles, with GCMs (gross combined masses) over 45t are growing gradually, and were estimated at about 4% of the fleet at the end of 2006.

These changes in traffic conditions demand adjustments of road infrastructure to meet the increasing vehicle requirements. To ignore this issue may result in damages to the infrastructure and increase accident risks in an environment that is already well below international safety standards.

Design vehicle characterisitics have been usually limited to size parameters and serve as a reference for the horizontal geometric design of roads and intersections and to guarantee vertical clearances on underpassses. An argument that other characteristics of the design vehicle like the traction/mass relation are important to assure higher safety levels on the South American road network is presented.

2. Geometric Design Guidelines

The Brazilian geometric design manual (DNER, 1999) is strongly influenced by the AASHTO Green Book of 1994 (AASHTO, 1994), following the majority of its guildelines. However, the design vehicles of the Brazilian manual are outdated when compared with newer road design manuals used in other countries (AASHTO, 2004 ; AUSTROADS, 2002 ; TAC, 1999). The manual proposes only four design vehicles: (i) passenger car 5,1 m length; (ii) single-unit truck, including also buses, normally with two axles, six wheels and 9,1m length; (iii) single-unit longer trucks and buses, with three axles and 12,2m length, and (iv) semi trailer, comprising a tractor unit and a semitrailer, with 16,8m length. The new intersections design manual (DNIT, 2005) has added one more vehicle, a double-trailer combination, 19,8m length. But all these design vehicles have dimensions and operating characteristics that are less restrictive than many CCVs that presently circulate on the road network. This fact results in some significant traffic conditions of incompability of longer and heavier CCVcs with the road infrastructure, especially on roads of lower functional classes, that are theoretically built to promote regional development through road transport of agricultural and mining products that demand large capacity CCVs to reduce unit transport cost of low value products.

3. Methodology and results

Four main aspects are considered in this study in terms of evaluating the compatibility of a given CCV configuration with the geometric characteristics of a road segment: low speed offtracking, performance on long grades, lateral rollover threshold and intersection sight distance. The main vehicle and road parameters to be evaluated for each road class are presented in Figure 1.

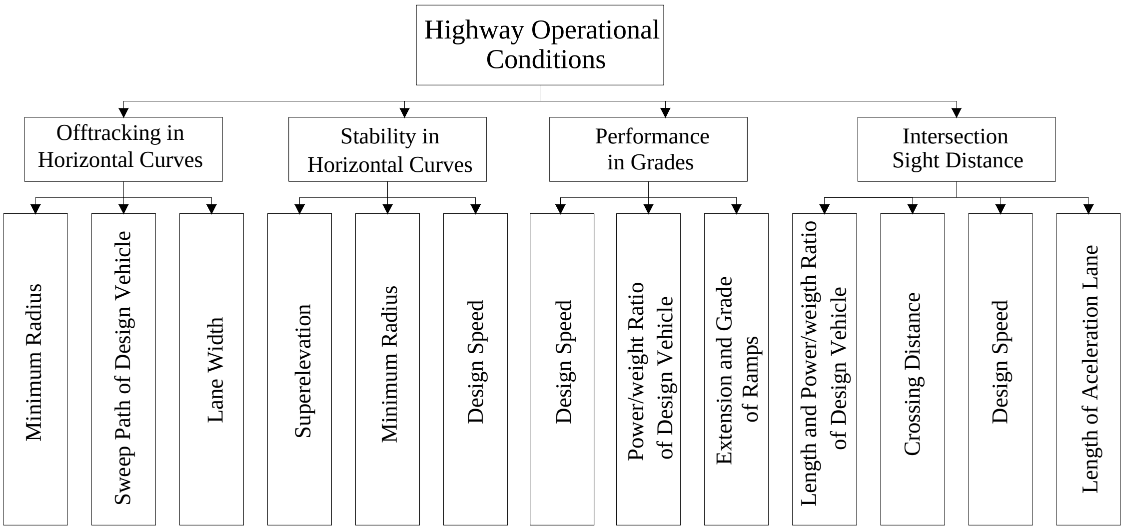


Figure 1 – Investigated vehicle and road parameters.

The parameters are influenced by two groups of variables. The first group is related to road geomety standards, that are defined according to the technical class of a road, like minimum radius, maximum grade, width of traffic lanes and with of shoulders. The other is related to vehicles variables, represented by the design vehicle, and defines aspects of swept path, length, height, center of gravity height, power/weight ratio, braking capacity, etc.

Interactions of these two groups of variables will determine the level of incompatibility. Thus, a total or partial compatibility between vehicles and roads depends on the technical class of the road and on the choice of a proper design vehicle. The vehicles that were investigated in the study are presented in Table 1.

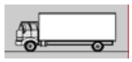
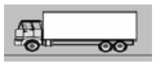
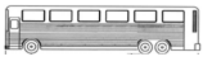
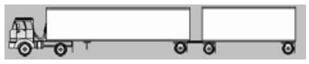
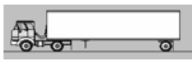
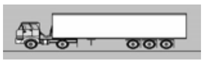
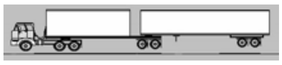
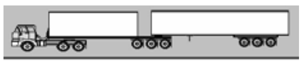
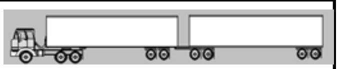
3.1 Offtracking

Maximum steady state offtracking in horizontal curves with the minimum radius allowed for each road class for the trucks and buses presented in Table 1 are calculated and shown in Table 2.

The results presented in Table 2 show that present road design standards, based on the DNER design vehicles (shown in bold letters), are not compatible with the swept path demands of some vehicles, considering the maximum allowed width of a heavy truck or CCV of 2.6m.

It shows also that this is true not only for vehicles operating according to special traffic authorizations, but also for some vehicles that are allowed to operate with unrestricted access to the road network (shown in bold italic letters).

Table 1 – Investigated vehicles.

Vehicle	Nomenclature	Length	Pictogram
Unit Truck (2 axles)	CO(DNER	9.1	
	U	14	
Unit Truck (3 axles)	O(DNE)	12.2	
	U	14	
Intercity Bus	O2(ROD	13.4	
	CO(DNER	9.1	
Intercity Bus (3	O(DNER	12.2	
	O3(ROD	13.95	
Articulated Bus (3	O2S	18	
Semitrailer (5 axles)	SR(DNER	16.8	
Truck and Trailer (5 axles)	RE(DNIT	19.8	
Semitrailer (3 axles)	2S1(18,2m)	18.2	
Semitrailer (4 axles)	2S2(20m)	20	
	2S2(22,4m)	22.4	
Semitrailer (5 axles)	2S3(18,2m)	18.2	
B-train (7 axles)	3S2S2(20m)	20	
	3S2S2(26m)	26	
B-train (9 axles)	3S3S3(26m)	26	
A-Train (9 axles)	3S2A2S2(30m	30	

However, the results in Table 2 also show that:
Longer vehicles do not necessarily imply greater offtracking requirements. In general, vehicles with more articulation points and smaller distances between axle groups have smaller offtracking needs. In particular the seven axles, 20 m long B-train, the 3S2S2, is less critical than most of the CCVs with one or two towed units;
A single-unit truck with 14 m length, U2, allowed to operate without restrictions on the highway network, has larger offtracking requirements than the CO and O design vehicles;
The most critical vehicle in terms of offtracking requirements is the 2S2 (22,4m), a automobile transport unit that has traffic rights on an annual special permit basis on the whole Brazilian intercity road network.

3.2 Lateral Stability in Horizontal Curves

To analyze stability in horizontal curves the criteria proposed by Harwood and Mason (1994) considering skidding and rollover of vehicles on dry and wet pavement was used. Geometric design parameters were based on the technical classes of roads. The results are presented in Table 3 and can be summarized as follows:

Table 2 – Maximum offtracking for vehicles and road classes on different terrain.

ROAD CLASS/ TERRAIN (**)	0 (L)	II (L)	0 (R) and I (L)	III (L)	0 (M) and I (R)	II (R)	I (M)	III (R)	IVa (L)	II (M)	III (M)	IVa (R)	IVa (M)
Design Speed (km/h)	120	100	100	80	80	70	60	60	60	50	40	40	30
Superelevation (%)	10	8	10	8	10	8	8	8	8	8	8	8	8
Radius (m)	540	375	345	230	210	170	125	125	125	80	50	50	25
Lane Width (m)	7,2	7,2	7,2	7	7,2	7	7,2	6,6	6	6,6	6,6	6	6
CO(DNER)	**0,4**	**0,44**	**0,47**	**0,72**	**0,57**	**0,8**	**0,7**	**1**	**1,3**	**1,23**	**1,57**	**1,87**	**2,83**
RE(DNIT)	**0,41**	**0,45**	**0,49**	**0,75**	**0,6**	**0,84**	**0,75**	**1,05**	**1,35**	**1,3**	**1,69**	**1,99**	**3,09**
2S3(18,2m)	0,44	0,5	0,54	0,83	0,68	0,94	0,89	1,19	1,49	1,52	2,04	2,34	3,81
O2S1	0,45	0,51	0,55	0,85	0,7	0,97	0,92	1,22	1,52	1,57	2,13	2,43	3,96
O3	0,46	0,52	0,56	0,86	0,71	0,98	2,76	1,24	1,54	1,61	2,19	2,49	4,07
O(DNER)	**0,46**	**0,52**	**0,56**	**0,86**	**0,71**	**0,98**	**0,94**	**1,24**	**1,54**	**1,61**	**2,19**	**2,49**	**4,08**
O2(13.4m)	***0,47***	***0,53***	***0,58***	***0,88***	***0,74***	***1,02***	**0,94**	***1,29***	***1,59***	***1,68***	***2,3***	***2,6***	***4,31***
U3(14m)	***0,48***	***0,55***	***0,59***	***0,9***	***0,77***	***1,05***	**0,99**	***1,33***	***1,63***	***1,75***	***2,41***	***2,71***	***4,57***
3S2B2(20m)*	0,5	0,57	0,62	0,95	0,81	1,11	1,03	1,41	1,71	1,87	2,62	2,92	5,01
U2(14m)	*0,51*	*0,6*	*0,64*	*0,99*	*0,85*	*1,16*	*1,18*	*1,48*	*1,78*	*1,98*	*2,79*	*3,09*	*5,36*
SR(DNER)	**0,53**	**0,62**	**0,67**	**1,02**	**0,89**	**1,2**	**1,24**	**1,54**	**1,84**	**2,07**	**2,94**	**3,24**	**5,68**
3S3B3(26m)*	0,61	0,73	0,79	1,21	1,1	1,46	1,3	1,89	2,19	2,63	3,84	4,14	7,67
2S1(18,2m)	***0,64***	***0,78***	***0,84***	***1,29***	***1,18***	***1,56***	**1,59**	***2,03***	***2,33***	***2,85***	***4,21***	***4,51***	***8,48***
3S2B2(26m)*	0,65	0,79	0,86	1,3	1,2	1,59	1,73	2,07	2,37	2,9	4,29	4,59	8,67
2S2(20m)*	0,66	0,81	0,87	1,33	1,23	1,62	1,77	2,11	2,41	2,97	4,4	4,7	8,93
3S2A2S2(30m)*	0,69	0,86	0,92	1,41	1,31	1,73	1,81	2,26	2,56	3,2	4,78	5,08	9,8
2S2(22,4m)*	0,72	0,89	0,97	1,47	1,38	1,81	1,96	2,37	2,67	3,39	5,09	5,39	10,52

* vehicles allowed to operate with special traffic authorization

** road classes : 0 to IV ; terrain: Level (L), Rolling hills(R) and Mountainous (M).

Table 3 – Speed limits for lateral skidding and rollover at different CG heights (in % of g).

Road Class (Terrain)	Design Speed (km/h)	Speed Limits (km/h)								
		Skidding				Rollover				
		Cars		Trucks		Cars	Trucks			
		Dry	Wet	Dry	Wet	ac_{max} 1,2	ac_{max} 0,25	ac_{max} 0,3	ac_{max} 0,35	ac_{max} 0,4
0(L)	120	267	184	227	158	299	155	166	176	185
II (L)	100	221	152	186	129	247	125	135	143	151
0 (R) ; I(L)	100	214	149	181	128	239	124	132	140	148
III (L)	80	173	123	146	104	193	98	105	112	118
0 (M) ; I (R)	80	167	119	141	102	186	97	103	110	115
II (R)	70	149	107	125	91	166	84	91	96	102
III (R) ; IV(L)	60	127	94	107	80	143	72	78	83	87
I (M)	60	123	92	104	78	138	71	76	81	85
II (M)	50	102	77	86	65	114	58	62	66	70
III (M) ; IV (R)	40	81	63	68	53	90	46	49	52	55
IV (M)	30	57	46	48	38	64	32	35	37	39

road classes: 0 to IV ; terrain: Level (L), Rolling hills (R) and Mountainous (M).

The following results are obtained from Table 3:

- Road design speed-limits limits offer higher safety margins for cars than for trucks;

- Passenger cars, in general, reach the skidding threshold at lower speeds than the rollover threshold, both on dry and wet pavement, for all highway classes;
- On dry pavements, trucks rollover at smaller speed then skidding for all rollover threshold limits considered (between 0,25 and 0,40g). In the case of trucks with a rollover threshold of 0.25g this trend is also observed on wet pavements. For trucks on dry pavement in good condition, skidding will occur before rollover for a rollover threshold greater than 0.65 g;
- Evaluating rollover on dry pavements, trucks with a rollover threshold of 0.25 g have safety margins below 20 km/h on most road classes. In Class II (mountainous terrain), III (mountainous terrain), IV (rolling terrain) and IV (mountainous terrain), all trucks have safety margins below 20 km/h, whereas, for Class IV (mountainous terrain), this value does not reach 10 km/h. Only trucks with a rollover threshold of 0.70 g or higher have a safety margin of 20 km/h on Class IV (mountainous terrain);
- Considering wet pavements, trucks with a rollover threshold of 0.35 g or greater will skid before rolling over for most of the simulated conditions. Considering the safety margin against skidding, results show speed limits of around 30% higher than the design speed. Critical cases are observed on Road Class III and IV (rolling and mountainous terrain), where the design speed is 40 km/h and the skidding threshold occurs at 53 km/h and on Road Class IV (mountainous terrain), where the design speed is 30 km/h and the skidding threshold occurs at 38 km/h.

Some countries, such as Australia and New Zealand, have established minimum performance standards for rollover threshold of cargo vehicles and buses, with limits based on accident statistics. The recommended values in these studies are situated between 0.35 g 0.40 g (Fancher et al., 1989; Winkler and Fancher, 1992). Through a project developed by AUSTROADS and the National Road Transport Commission (NRTC), called Performance Based Standards (PBS), minimum values for the rollover threshold were established: 0.40 g for tankers and buses and 0.35 g for other heavy vehicles (Prem et al., 2001).

3.3 Performance on Ascending Grades

To investigate the compatibility of vehicles operating on ascending grades, the critical length for a loss of 20 km/h with respect to the road design speed limit was used as the basic performance parameter. It is assumed that climbing lanes would have to be built on ascending grades with a length larger than the critical length value. Simulations of typical Brazilian trucks and CCVs were processed using a simulation model (Demarchi, 2004), with the power/weight ratios ranging from 3,16 cv/t to 13,15 cv/t. The results considered design speed and maximum slope conditions established in the Brazilian highway design manual (DNER,1999). Table 4 presents the results, which show that only vehicles with power/weight ratios in the range of 10 cv/t or more have critical lengths larger than 300 m, considering grades varying from 0 to 6%. For lower power/weight ratios critical lengths were lower than 100m for some inferior road classes, where trucks are assumed to enter the ascending grade at smaller speeds. The dashes in Table 4 indicate that the speed loss on the ascending grade is less than 20 km/h.

3.4 Intersection Sight Distance

Intersection sight distance was studied considering crossing time required by trucks on at-level intersections. By simulating different power/weight ratios and vehicle lengths, the impacts of long and heavy CCVs were obtained. A simulation model of truck performance (Demarchi, 2004) was used and the results in Table 5 show the time needed for a truck stopped at the decision point of the secondary road to cross a standard width intersection with a main road.

The same power/weight ratios were used and vehicles lengths of 25 and 30m, (the size of some common CCVs in Brazil) were investigated. Some assumptions were considered to define crossing distance as follows:
Traffic lanes and shoulder widths considered are the minimum values adopted in the Brazilian geometric design manual for each road class;
A 3% cross fall limit was used on the straight crossing track, the first half of the distance uphill and the second half downhill;
A fixed value of 2.5 seconds was added to crossing time, to represent perception and reaction time of drivers.

Table 4 - Critical Length of Grade by Maximum Grade Allowed in Brazilian Road Classes and Typical Trucks (meters).

Road Class	Terrain	Grade (%)	Design Speed (km/h)	Power/Weight Ratio (cv/t)					
				3,16	4,67	6,97	7,42	9,76	13,15
Class 0	Level	3	120	660	750	780	850	960	1040
	Rolling	4	100	460	520	580	680	780	1260
	Mountainous	5	80	320	360	450	540	710	–
Class I–A	Level	3	100	590	670	810	990	–	–
	Rolling	4,5	80	350	400	520	660	960	–
	Mountainous	6	60	200	240	–	–	–	–
Class I–B	Level	3	100	350	400	450	510	600	980
	Rolling	4,5	80	210	240	290	340	410	780
	Mountainous	6	60	130	150	190	240	320	–
Class II	Level	3	100	350	400	450	510	600	980
	Rolling	5	70	170	200	250	300	390	–
	Mountainous	7	50	90	110	150	200	–	–
Class III	Level	4	80	240	270	330	400	510	720
	Rolling	6	60	130	150	190	240	320	–
	Mountainous	8	40	60	80	–	–	–	–
Class IV–A	Level	4	60	190	240	380	–	–	–
	Rolling	6	40	90	120	–	–	–	–
	Mountainous	8	30	–	–	–	–	–	–
Class IV– B	Level	6	60	130	150	190	240	320	–
	Rolling	8	40	60	80	–	–	–	–
	Mountainous	10	30	–	–	–	–	–	–

Crossing times obtained in the simulation were consistent with field results found by Demarchi, Setti and Widmer (1994). Considering the 25 and 30 m vehicle lengths, their crossing times are significantly higher than those needed by the design vehicles used in the Brazilian geometric design manual. The results obtained show that, as a general rule, higher intersection sight distances are necessary in order to offer safe operation of longer CCVs on the road network if present power/ratios, in the range of 5 to 6 cv/t, are maintained as an acceptable vehicle standard. If a road was designed to a standard of the RE design vehicle, than a 25m CCV will be compatible with the intersection sight distance only if it has a power/weight ratio larger than 10 cv/t.

The 30 m CCVs requirements in this case are compatible only for vehicles with power/weight ratio of 13 cv/t or more, as indicated by the results in Table 6.

Table 5 - Intersection sight distance for the RE (DNIT) project vehicle and simulated 25m length CCVs.

Road Class		Intersection Sight Distance (m)						
		Vehicle Simulated						
	Terrain	RE (DNIT)	3,16 cv/t	4,67 cv/t	6,97 cv/t	7,42 cv/t	9,76 cv/t	13,15 cv/t
I	L	292	459	403	320	306	292	278
	R	234	356	322	256	245	234	222
	M	175	267	242	192	183	175	167
II	L	292	445	403	320	306	292	278
	R	204	311	282	224	214	204	195
	M	146	222	195	160	153	146	139
III	L	234	356	322	256	245	234	222
	R	175	267	234	192	183	175	167
	M	117	178	156	128	122	117	111
IV	P	175	259	234	183	175	167	158
	L	117	172	156	122	117	111	106
	R	88	129	113	92	88	83	79

Table 6 – Intersection sight distance for the RE (DNIT) project vehicle and simulated 30m length CCVs.

Road Class		Intersection Sight Distance (m)						
		Vehicle Simulated						
	Terrain	RE (DNIT)	3,16 cv/t	4,67 cv/t	6,97 cv/t	7,42 cv/t	9,76 cv/t	13,15 cv/t
I	P	292	487	431	348	320	306	292
	O	234	389	334	267	256	245	234
	M	175	292	250	200	192	183	175
II	P	292	487	417	334	320	306	292
	O	204	341	292	234	224	214	204
	M	146	236	209	167	160	153	146
III	P	234	389	334	267	256	245	234
	O	175	284	250	200	192	183	175
	M	117	189	167	133	128	122	117
IV	P	175	284	250	200	192	175	175
	O	117	189	167	133	128	117	117
	M	88	138	121	96	92	88	83

Thus, current geometric design limits of at-grade intersections are incompatible with most of the long and heavy CCV’s that are allowed to operate with special permits on the road network. Considering that Brazil has a relatively hilly countryside, where roads have many horizontal curves of relatively small radii and grades of 6% and more, providing safe sight distances that are compatible with the longer and heavier CCVs is not an easy task.

4. Concluding Remarks

Providing traffic compatibility of newer vehicles with the geometric design characteristics of roads designed in the past, complying to less restrictive design vehicle characteristics, demands an in depth review of some of the basic standards established for each road class. This is particularly true on lower class roads which, nonetheless, should provide access to large and heavy CCVs, in general engaged in low value agricultural, livestock and mining products.

The vehicle characteristics that are necessary to assess its impact on the traffic stream of a given road go beyond its size and weight characteristics. Legal minimum power/weight ratio is one of these characteristics. As is closely linked to the acceleration capacity it has a strong influence on loss of speed on grades, which adds risks in terms of rear end collisions, and affects crossing and merging times at intersections and junctions.

The consolidation of relatively new technologies, like self-steering axles, will contribute to reduce the negative impact in terms of offtracking characteristics of longer CCVs and will, in turn, permit that length limits are traded for lower CG vehicles that offer a safety gain in terms of the rollover risk.

The effort of Australia, New Zealand and South Africa in terms of developing a Performance Based Standards approach to the licensing of CCV operations may be applicable to road design standards, substituting the design vehicle approach and preparing the road network for the next generation of longer and heavier CCVs. This may be particularly true in the less developed parts of the world, where the vast majority of the road network is still unpaved or inexistent.

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