Interface analysis and design: Improving heavy vehicle road safety barrier design

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Abstract

The Safe System Approach recognises the holistic paradigm of safer vehicles, safer roads, safer road users and safer speeds. However, failures in our road safety system continue to occur regularly because of breakdowns in system safety at various interfaces. The authors will present a series of papers, based on their experience with hundreds of crash investigations, road safety research, system design and applied interventions, examples of how formalised Interface Analysis and Design methods can be applied to improve road safety in all domains: road infrastructure, vehicles and road user behaviour. The particular case of heavy vehicle impacts into roadside, median and bridge barriers and design performance requirements is investigated as the first paper of this series. Described is the recent crash event on Melbourne's Bolte Bridge on 17 May 2013 where an unloaded truck swerving in the far lane to avoid hitting a smaller vehicle, struck the bridge barrier at a high impact angle. Fortunately, while the barrier design withstood this impact, the collision also highlighted the need for a critical review of current bridge barrier design criteria, bridge speed and lane management for heavy vehicles. The conclusions are: barrier systems can now be designed and crash tests carried out to validate that they perform in a crashworthy manner at an affordable cost; the movement of trucks over bridges needs to be controlled in terms of speed and their location (kept to the left lane) relative to the bridge barrier depending on the barrier capacity; and truck drivers, heavy vehicle operators and regulators can play a major role in ensuring the barrier system is effective. That is, the *interface* of these elements need to be considered in concert.

Introduction

Many hundreds of thousands of collisions occur in Australia each year. Based on data from the Bureau of Infrastructure, Transport and Regional Economics, the result of the approximately 700,000 road crashes in Australia each year was around 1,300 fatalities and 35,000 serious injuries in 2011 (BITRE, 2012). The types and distribution of fatal traffic crashes including vulnerable road user collisions by road user category indicate vehicle occupants (including heavy and light vehicles) make up 69% of the total, pedestrians 14%, motorcyclist 15% and bicyclists 2%. There have been 228 deaths from 195 crashes involving heavy trucks year ending September, 2012. The distribution of serious injury in 2008-2009 by road user type was vehicle occupants 35%, pedestrians 7%, motorcyclists 27%, bicyclists 18% (AIHW, 2012). It is interesting to note the significantly higher percentage of motorcyclist serious injuries compared to other road users.

In terms of the public risk associated with road use, it has declined significantly in Australia between 1975 and 2010. In 1975, Australia-wide, there were 26.8 road deaths per 100,000 population; this rate had fallen to 6.1 deaths in 2010–a drop of around 77%. Over this same period, the median rate for OECD nations also declined. In 1975, the OECD median rate was 18.5 deaths, and in 2010 it had reduced to 6.2 deaths–a drop of around 67%. Nevertheless, despite this seemingly good progress, Australia's rate was double that of world's best practice nations such as Sweden, the Netherlands and UK. Its ranking slipped in 2010 to 16th out of 32 OECD nations, i.e. only one ranking short of Australia finding itself in the higher risk half of these nations to drive on a road. Australia's current ranking is 5.1 per 100,000 population (14th) with the UK in first place at 3.1 (BITRE, 2013 & 2012b, International Transport Forum, 2013). This begs the question of can Australia be a global leader in road safety? Mooren et al (2013) proposes that Australia has the

potential to be a global leader in road safety but is held back by some important and persistent shortcomings in its commitment to the endeavour. The authors, Grzebieta and Rechnitzer, suggest that a more formalised approach than currently exists to Interface Analysis and Design (IAD) methods can be applied to improve significantly road safety in all domains: road infrastructure, vehicle crashworthiness and behavioural (Rechnitzer et al 2007).

The authors intend to present a series of papers demonstrating how this more formalised approach should be taken to Interface Analysis and Design of the components of the road transport system if Australia is to reach road safety targets in 2020.

This paper is the first of that series and in this instance focuses on heavy vehicle impacts into bridge, median and roadside barriers. The recent crash event on Melbourne's Bolte Bridge in May 2013 will be used to exemplify IAD methods. A truck was travelling in the far right lane and was forced to swerve left to avoid a passenger vehicle in its path, resulting in it travelling across four lanes and impacting the bridge edge barrier at a high impact angle. Fortunately, the barrier design was sufficient to withstand the impact as a result of sound engineering decisions rather than as a result of any research outcomes from Australian crash tests, computer simulations, or investigations of in service performance of heavy vehicles barrier impacts. The driver, presumed not wearing a seat belt, was ejected from the truck to the roadway underpass below receiving serious injuries. The collision caused chaos on Melbourne's roads for almost 12 hours¹. Damage repair cost are not yet known but are expected to be significant.

From an Interface Analysis and Design perspective, the issues are how effective was the barrier– road-traffic system design, what were the heavy vehicle-barrier interface parameters (speed, mass, vehicle frontal impact characteristics, angle of impact, vehicle re direction, driver injury, traffic delay; bridge outage and repair costs), and what redesign/improvements are required?

Some reporters and media spoke of the event as an 'Accident': 'Truck Accident on Bolte Bridge' (ABC Friday May 17, 2013, 8.03 am), 'Accident of Bolte Bridge' (ABC Friday May 17, 2013, 6.19pm), 'Lane change led to truck accident' (bigpondnews, Friday, May 17, 2013 » 11:58pm; Sky News Updated: 23:58, Friday May 17, 2013), and 'He suffered serious head and pelvic injuries in the accident' (metro.co.uk, Friday 17 May 2013 8:44 am). Before outlining in detail the IAD methodology, it should be noted that the term 'accident' is often used by some professionals, laypersons, the general public and media. Two definitions of the term 'accident' provided in the Oxford Dictionary are: 'an unfortunate incident that happens unexpectedly and unintentionally, typically resulting in damage or injury; an event that happens by chance or that is without apparent or deliberate cause'. Webster's Dictionary denotes 'acts of God' as those 'accidents' which arise from physical causes, and which cannot be prevented. Continued use of the word 'accident' promotes the concept that these events are outside of human influence or control. However, we can identify the causes of 'accidents'; that is, they are not 'acts of God' but predictable results of the laws of physics and human decisions. In fact, they are predictable results of specific actions. Moreover, within the United States (US) Department of Transportation's National Highway Traffic Safety Administration (US DOT/NHTSA), the word 'accident' is no longer used in materials published and distributed by that agency. In addition, NHTSA is no longer using "accidents' in speeches or other public remarks, in communications with the news media, individuals or groups in the public or private sector (Anikeeff, 1997). The authors of this paper suggest we should eliminate this word from our vocabulary in Australia when discussing road crashes and collisions as a first step to any safe system Interface Analysis and Design.

Similar to the US, the Australian Transport Council made up of all Federal and State Ministers

¹ <u>http://www.theweeklyreviewmelbournetimes.com.au/story/1513490/bolte-bridge-truck-driver-off-critical-list-but-remains-in-very-serious-condition/</u>

responsible for roads and transport, released the National Road Safety Strategy for 2011 to 2020 (ATC, 2011), where the word 'crash' or 'crashes' was intentionally used in place of the word 'accident'. The strategy is firmly based on Safe System paradigm and is framed by the guiding vision that no person should be killed or seriously injured on Australia's roads. The initiatives and options are set out in four key areas - Safe Roads, Safe Speeds, Safe Vehicles and Safe People. However, little is detailed concerning the interfaces between these options in the Australian context. Safe System principles require a holistic view of the road transport system and the interactions among road users both inside and outside of vehicles, how they interact with each other and on roads and with roadsides, and how travel speeds govern that interaction. The strategy also acknowledges that a large proportion of casualty crashes result from drivers - or other road users making mistakes. It aspires to create a road transport system in which human mistakes do not result in death or serious injury. When we talk about human mistakes we need to include not only the road user but also the designers and operators of the system. For example, a politician/Minister responsible for roads may decide to increase speed limits in response to voter pressure. However, the laws of physics and evidence base related to crash casualties need to dictate such decisions as higher speeds will always result increased casualties unless the roads and vehicles have been redesigned and retro fitted to be more forgiving of human error at the higher speeds.

Safe System approach also recognises that there are known physical limits to the amount of force the human body can tolerate before it is injured. It further recognises that system designers and operators need to take into account the limits of the human body in designing and maintaining roads, vehicles and speeds (Corben et al, 2004). Hence, it is critical that the IAD methodology also takes into account the human limits at the interfaces. It also considers the management of the system and how the kinetic energy of the system can be managed through regulatory/administrative controls, i.e. speed limits and speed limiters, driver pay rates that reduce urgency and aggressive driving, control of driving lanes, and segregation of various road users. An overview of how Safe System approach was developed, and how it now underpins not only Australia's road safety strategy but also the World Health Organisation (WHO) and United Nations (UN) Decade of Action for Road Safety, is provided by Mooren et al (2011) and Grzebieta et al (2012).

Example IAD Case – Western Link (Bolte Bridge) Barrier Crash

In the early morning of Friday 17th May, an empty dump truck with a trailer unit attached struck a bridge safety barrier on the approach overpass to the Bolte Bridge in Melbourne, Victoria. The truck was travelling in the far right lane, swerved across four lanes of traffic to avoid another vehicle, and collided into the bridges' concrete road side safety barrier at a large angle. The barrier ruptured as shown in Figure 1, causing the truck's front end to pocket into the concrete barrier. The truck then jack-knifed and yawed around in an anticlockwise direction after which it continued along the barrier until the rear unit and tow unit climbed the barrier, coming to rest and hung over the barrier. The speed limit on this portion of freeway is 100km/h. The combined truck and trailer mass is estimated at less than 16 tonnes.



Photo: 7 News cameramen Chris MartinPhoto courtesy David Hurley from Herald Sun
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 from Herald Sun
 Figure 1. Bridge Barrier Crash on Approach to Bolte Bridge, Melbourne, Victoria

The Bolte Bridge forms a key segment of the freeway system in Melbourne and was built in 1996-1999. It is part of the CityLink system of toll roads that connects the Tullamarine Freeway from the northern suburbs with the West Gate Freeway and the Domain and Burnley tunnels to the Monash Freeway and the south eastern suburbs².

At the time when the Bolte Bridge was being designed in 1996-1997 and constructed the code of practice available was the 1992 Austroads Bridge Design Code SAA HB 77-1996 (Austroads, 1992). The design code had three Levels of protection (Level 1 to Level 3) where Level 1 edge

barriers were recommended for situations at the highest risk and severity level. A barrier height of 820 mm, made from concrete with a safety shape shown in Figure 2, could be used. Further recommendations were that the barriers be used for bridges over major highways, railways, houses, factories, and deep water and for high bridges. The design assessment was to take into account types of vehicles to be contained, e.g. cars, buses, vehicles with high centre of mass, heavy trucks, the total traffic volume, the bridge width and the consequences of a vehicle penetrating or vaulting the barrier. Further, Level 1 barriers were required to safely contain the identified vehicles under severe impact conditions, i.e. at speeds up to the design speed of the



Figure 2. Concrete Safety Shape

roadway and impact angles up to 15 degrees. No loads or vehicle types (other than generic terms) were provided or specified. The only impact loads that were specified were for a lower risk Level 2 barrier being 90 kN to 125 kN (9 to 12.5 tonne). These are low loads for a vehicle impact scenario, and a low impact angle.

Discussions with the 1996/97 design team engineers revealed that the barrier design on the approach overpasses to the Bolte Bridge was based on the then available American Association of State Highway and Transportation Officials (AASHTO) bridge railing design guide which recommended an ultimate transverse outward load of 500 kN (50 tonne). The effective barrier height of 1100 mm was chosen by the team, likely based on US tests at that time that showed this height was conservative (AASHTO, 1989, O'Connor and Shaw, 2000). At the time, this was the first design of its kind in Australia where considerable thought, mainly supported by US barrier

² <u>http://en.wikipedia.org/wiki/Bolte_Bridge</u>

crash test experience, went into what the bridge barrier design loads and what the height should be. It was decided that a high-level barrier be constructed.

At that time (1996/97), AASHTO (1989) designated the high-level barrier as PL-3, capable of containing a 22-tonne semi-trailer at 80 km/h at an impact angle of 15°. PL-3 barriers were designed for a transverse force of 516 kN, a longitudinal load of 173 kN and a vertical load of 222 kN downward. The transverse (impact) force and longitudinal (frictional) loads were assumed to act over a distance of 2.44 m; the length of vehicle resting on top of the barrier was assumed to be 12.2 m. For concrete barriers plastic mechanism yield line failure analysis as indicated in Figure 3 was recommended as it replicated impact damage profiles from experimental crashes as highlighted by Bligh et al. (2010) in their historical context of how barrier loads were established. A number of tests have subsequently been carried out for different shaped concrete barriers.

It is some 13 years later that the first major barrier crash has occurred after many millions of vehicles and many hundreds of millions of kilometres travelled that a real world crash tested this design decision to its limit and appears it has worked successfully- to a point. Comparing Figures 1 and 3, similarities appear between how the barrier failed in the Bolte Bridge overpass approach and the mechanism used to design such barriers. The main difference between the crash test (22-tonne semi-trailer at 80 km/h at an impact angle of 15°) and the actual crash (Figure 1) was the magnitude of the load in the case of the Bolte Bridge was likely higher because of the larger impact angle. The kinetic energy of the vehicle at impact will increase with vehicle speed and impact angle according to the following equation:

Kinetic Energy = $\frac{1}{2}m(Vsin\theta)^2$

where *m* is the mass of the vehicle, V the velocity of the vehicle at impact and θ is the impact angle. The energy dissipated by the barrier can be related to the force and vehicle deceleration and the work done by the barrier and vehicle during impact in a lateral direction as a result of barrier deformation. Thus the work done during deformation of the barrier in the lateral direction is equated to the kinetic energy of the impacting vehicle also in the lateral direction. It then becomes obvious that the narrower the impact angle the smaller the kinetic energy imparted onto the barrier and the converse; the larger the angle the greater the kinetic energy imparted onto the barrier and thus the higher the forces becomes that are imposed on the barrier. Hence, to reduce the risk of a heavy truck breaching a barrier it would be appropriate to keep the trucks adjacent to the barriers, i.e. minimise the likely impact angle by restricting vehicles to the left lane similar to UK motorways where trucks can only travel in the left lane and overtake in the second lane. If the truck is not overtaking it is required to move to the left lane. This would reduce the impact angle as well as allow smaller vehicles in the third and wider lanes to readily pass the heavier vehicles. It also segregates the heavier vehicles from the smaller, more vulnerable vehicles.





Figure 3. Plastic failure yield line analysis commonl

Computer simulation of a truck impact into high performance level bridge barrier.

It should be noted that the truck in Figure 1 was empty when the crash occurred. The truck's mass (estimated at less than 16t) was significantly less than a 44 tonne semi-trailer or B-double that regularly travels on freeways around Australia. To assess what loads can be expected when a 44 tonne semi-trailer impacts a barrier, Zou and Grzebieta (2004) carried out a computer simulation of a 45,000kg truck impacting a "High Performance" Safety Bridge Barrier (HPSBB). A three dimensional model computer model of the HPSBB System was generated using the multi-body program MADYMO (2003). The truck's dimensions are shown in Figure 4. The truck was simulated to impact the bridge barrier at an impact speed of 100km/h and 15° impact angle. The truck model consisted of 14 elastic-plastic bodies representing the prime mover, the trailer and 12 wheels. The fifth wheel connected to the prime mover and trailer was modelled as a revolution joint. The wheels connected to the prime mover and to the trailer where all defined as passenger car, while the stiffness of the engine compartment was assumed to be double that of a passenger car. The stiffness profile used to model the truck is shown in Figure 5.

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Figure 4. Truck Dimensions (in millimetres)



Figure 5. Truck stiffness assumed in the computer model

The length of the bridge barrier modelled was 60 meters. The barrier was divided into separate rigid bodies in the longitudinal direction exactly 1 metre in length. This was to ensure that local deformations could be modelled with reasonable detail. A 3-m long section of the model is sketched in Figure 6. A spherical joint connected the barrier sections, i.e. three rotational degrees of freedom (Rx, Ry, Rz). The connection between each barrier section and the deck was modelled

using point restraints, i.e. translation in the x, y, z directions. Two point restraints were applied for each deck section as shown in the diagram



Figure 6. Joints and point restraints defined for the bridge barrier system

The barrier dimensions are shown in Figure 6. Young's modulus for reinforced concrete section was assumed 40,000 MPa, the density of concrete was 2600 kg/m^3 , and the ultimate tensile strength of concrete was adopted as 3 MPa.

In terms of the results, the peak deceleration for the prime mover reaches around 19g in the outward transverse direction at around 70ms into the impact event. The trailer's peak deceleration reaches a similar magnitude though it was delayed until around 200ms into the crash event as expected (trailer slap). The crash pulses for the prime mover and the trailer are shown in Figure 7.

The bridge deck/barrier impact loads along the barrier length were calculated at 70ms. Figure 8 shows the load distribution at 70ms in the lateral outward direction. Each bar represents the load at a 1-meter barrier section. It should be noted that the first impact point was on the 7th section of the barrier where the barrier sections were numbered in the direction of the travelling truck. The impact load was distributed mainly to a short 6-meter section of the barrier with a peak load of around 400kN at the 7th section. Hence the load is localised and confirms the localised deformation we can expect as visible in Figure 1 and 3.



Figure 7. Crash pulse of prime mover for the base truck impact



Figure 8. Bridge deck loads resulting from the base truck impact

Figure 9 shows how the the truck interacts with the barrier. The truck rolls onto its side with the rear trailer yawing horizontally, slapping and then climbing the barrier and then sliding along the top. The maximum loads the barrier underwent during the simulated crash are provided in Table 1. These impact loads are compared to the loads recommended in Table A2 in Appendix A of the Australian Standard AS 5100.2-2004: Bridge Design Part 2: Design loads.

O'Connor and Shaw (2000) highlight that: "Colosimo (1996) suggests that a high-level barrier should be capable of containing a van-type tractor-trailer vehicle with a mass of 44 tonnes at speeds of 90 kph, at impact angles up to 15°. An ultimate design containment force of 900 to 1200 kN, and a minimum barrier height of 1300 to 1500 mm are nominated. Since the high-level barrier is designed for heavy vehicles, Colosimo suggests such a barrier may be required when commercial vehicle volumes on busy, major roadways exceed 500 per day in rural areas and 2000 per day in urban areas. If these volumes are exceeded, high-level barriers should be specified in thefollowing situations:

- (a) bridges over major roadways with an AADT of 8000 or more vehicles per day;
- (b) bridges over electrified railways or goods lines carrying large quantities of either noxious or flammable substances;
- (c) bridges over water more than 2 m deep;



Figure 9. Kinematics of the base truck during impact

Barrier Performance Level	Ultimate Transverse Outward Load (kN)	Ultimate Longitudinal or Transverse Inward Load (whichever larger) (kN)	Vehicle Contact Length for Transverse and Longitudinal Loads (m)	Ultimate Vertical Downward Load (kN)	Vehicle Contact Length for Vertical Loads (m)
Greater than Test Level 6 [*] (44 t articulated van)	1000	330	2.5	380	15
Test Level 6 (36 t articulated tanker)	750	250	2.4	350	12
Computer Simulation Results (44 t articulated truck)	830	200	2.5	650	15

Table 1. Computer simulated ultimate contact loads compared to recommended design loads specified in AS 5100.2-2004, Appendix A, Table A2 for Special Performance Barriers

* Test Level 6 is the highest crash test severity level adopted in AS/NZS 3845:1999 which in turn is based on the US NCHRP 350 crash test procedures. The US has a set of six crash test levels, TL1 to TL6 developed as part of the National Cooperative Highway Research Program, published in Report 350 (NCHRP, 350, 1993). The crash test procedures required by AS/NZS 3845:1999 are based on the Federal Highway Administration (FHWA) NCHRP 350 (1993) report and Australian jurisdictions generally require compliance with NCHRP 350, or other equivalent procedures.

- (d) bridges over houses, factories, etc;
- (e) bridges more than 10 m high;
- (f) bridges on horizontal curves with a radius of 600 m or less."

On the basis of the computer simulation and the actual crash shown in Figure 1, it would appear that Colisimo (1996), and indeed the recommendation in Appendix A in AS 5100.2-2004, appears accurate in terms of load resistance necessary to redirect the heavier vehicles. It should be noted that this is an informative Appendix and not normative. This is a concern in that the normative section recommends 'Regular' and 'Low' bridge barrier loads shown in Table 2 and appear completely inadequate for the speeds and vehicles considered in this paper and commonly encoutered on freeways and major arterial roads. The Medium barrier loads recommended in Appendix A in Table A1 are also shown in Table 2 below. They reflect the recommended loads in AASHTO (1989) high-level PL-3 barrier recommendations.

Table 2. Recommended design loads specified in AS 5100.2-2004, Table 11.2.2 and Appendix A,Table A1.

Barrier Performance Level	Ultimate Transverse Outward Load (kN)	Ultimate Longitudinal or Transverse Inward Load (whichever larger) (kN)	Vehicle Contact Length for Transverse and Longitudinal Loads (m)	Ultimate Vertical Downward Load (kN)	Vehicle Contact Length for Vertical Loads (m)
Medium (informative)	500	170	2.4	350	12
Regular (normative)	250	80	1.1	20	5.5
Low (normative)	125	40	1.1	20	5.5

Appendix A also suggests that the minimum effective height of the Medium barrier should be 1.1 m and for the Special Performance barriers a height of 1.4 metres.

Given this situation and the cost of installing a Test Level 6 barrier being much higher than the cost of installing the AASHTO (1989) high-level PL-3 barrier (equivalent to a Medium barrier in Table 2), or indeed installing a Low or Regular performance barrier (Table 2) as is the case in many areas around Australia, an alternative to control the risk of the truck penetrating through the barrier is to reduce the speeds and impact angles of the vehicles and thus impact severity. For example, trucks should be limited to a top speed of 60 km/h and kept to the left lane with no overtaking in the case of bridge barriers where only Low or Regular barriers have been installed. Where Medium performance barriers have been installed, a higher speed could be recommended to 80 km/h albeit again vehicles would be kept to the left lane, with restricted overtaking options within for example a 10 km or 20 km radius of the CBD that are populated higher risk areas.

It is important to note that advanced finite element (FE) computer simulation models of semi-trailer infrastructure crashes that have been validated via crash testing are now freely available on the internet (Miele et al., 2010) (<u>http://tractor-trailer.model.ntrci.org/index.cgi?model=1&navv=0</u>). The program used is LSDYNA which is now the industry accepted standard (Ray et al., 2010). Such analyses, combined with a traffic mangement strategy concerning how to limit barrier impact loads, should be used to assess existing and new Australian bridge barriers. This should be required analysis from bridge designers and consultants by regulatory authorities approving designs, to ensure the interface design beteen heavy vehicles and bridge edge barriers are compatible when it comes to vehicle mass, speed, angle of impact and design requirements.

Conclusions

From an Interface Analysis and Design perspective, the example of the Bolte Bridge crash has highlighted a number of apparent incompatibilities in the interface analysis and design of the bridge barrier–road-traffic system design. Specifically that the heavy vehicle-barrier interface parameters involved (vehicle speed, vehicle mass, angle of impact, vehicle re direction, barrier structural load capacity) require reconsideration.

The following conclusions can be made concerning crashes and simulating crashes into roadside bridge barriers:

- 1) The Bolte Bridge approach ramp bridge barrier truck crash shown in Figure 1 appears to have exceeded impact conditions used to certify Medium (PL-3) barriers (36 tonne truck impacting at 80 km/h and 15° impact angle);
- 2) The Bolte Bridge approach ramp bridge barrier truck crash shown in Figure 1 indicates the design methodology and loads assumed and used for the first time in Australia in 1996/97, was capable of containing and preventing an unloaded truck from breaching the barrier, but may be vulberable for heavier vehicles at greater than 15° impact anagle;
- 3) The deformation of the barrier indicated in Figure 1 is consistent with yield line failure mechanism design methodology established in the early ninteen nineties;
- 4) Impact loads on bridge barriers resulting from 44 tonne semi-trailers, B-double and B-triple trucks are of the order of Special Reuiremnts as set out in Appendix A Table A2 of the Australian Standard AS 5100.2-2004: Bridge Design Part2: Design loads;
- 5) In order to reduce impacts loads that do not result in acomplete breach of Low, Regular and Medium bridge barriers, trucks need to be managed using the Safe System approch, i.e. the

speed need to be reduced significantly and the trucks kept close to the barrier to reduce the impact angle to less than 15 degrees if possible. What speeds and what angles should be determined from further research simulating typical crashes, using current validated Finite Element programs that are now freely avalable via the internet.

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