OTSI Office of Transport Safety Investigations

BUS SAFETY INVESTIGATION REPORT

BUS WHEEL SEPARATION

MACQUARIE PARK

22 OCTOBER 2014

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THE OFFICE OF TRANSPORT SAFETY INVESTIGATIONS

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EXECUTIVE SUMMARY

On the morning of 22 October 2014 a State Transit Authority (Sydney Buses) Mercedes-Benz bus lost a left rear wheel on a passenger service between Chatswood Station and Parramatta Station. There was only one passenger on the bus at the time, and no injuries resulted.

The investigation determined that the loss of the wheel was the result of fatigue failure of the wheel retaining bolts, due to the wheel nuts having been inadequately tensioned and checked as part of a scheduled service three weeks earlier.

Contributing to the wheel loss was the inability of a daily visual check of the bus to detect loosening wheel nuts. Furthermore, a visual check of the bus when rough riding was noticed did not detect a wheel bolt that had broken earlier.

Sydney Buses immediately investigated the servicing of the bus, and found strong indications that recent servicing involving the wheels had not been properly performed. Sydney Buses took appropriate action to prevent recurrence.

It is recommended that Sydney Buses take the further step of investigating the feasibility of introducing a daily inspection methodology with an increased ability to detect wheel nut loss of tension.

Full details of the findings and recommendation of this bus safety investigation are contained in Parts 3 and 4 respectively.

PART 1 FACTUAL INFORMATION

Incident narrative

1.1 At 0616 on 22 October 2014 a Sydney Buses Mercedes-Benz bus left Chatswood Station on a Route 545 service to Parramatta Station, following completion of a scheduled service from Ryde to Chatswood. When nearing Macquarie Park the driver noticed some jerkiness and rough riding in the behaviour of the bus. However, he had experienced roughness in the operation of this bus previously, and considered it to be not unusual for this model of bus.

1.2 When the jerkiness recurred the driver stopped and secured the bus at the Macquarie University Station stop to check the possibility of a deflated tyre. Although the tyres appeared normal, the driver noticed that the bus appeared to be leaning to the left. He considered that this may have been due to a loss of air from the suspension, a problem that had been experienced with this bus two months earlier.

1.3 After one passenger boarded the bus at Macquarie Centre the driver decided to continue, but the bus continued to ride roughly and the driver heard an increasing noise which he described to be like a tyre hitting the bodywork of the bus.

1.4 The driver brought the bus to a stop on Balaclava Road just before Epping Road, and was immediately informed by a passer-by that a wheel had come off. On alighting the driver found that the bus had lost its left rear outer wheel, with the inner wheel supporting the bus but no longer secured to the hub. The broken ends of wheel studs could be seen through stud holes of the inner wheel, and the outer wheel could be seen lying on the footpath about five metres behind the bus.

1.5 Neither the driver nor the passenger was injured in the incident.

1.6 During a search of the route followed by the bus, two broken ends of bolts, with nuts in place, were found approximately 500 metres and five kilometres before the point at which the bus finally stopped. These broken pieces of bolt

were later matched with the remains of bolts removed from the left rear hub of the bus.

Incident location

1.7 The path taken by the bus took it through Macquarie Park, a major business park in Sydney's north west. Macquarie Park borders with Macquarie University, a locality taking its name from the major educational institution within its boundaries, but also home to a number of smaller tertiary education establishments.

1.8 The stopping position of the bus, as shown in *Figure 1*, was on the south western boundary of Macquarie University.

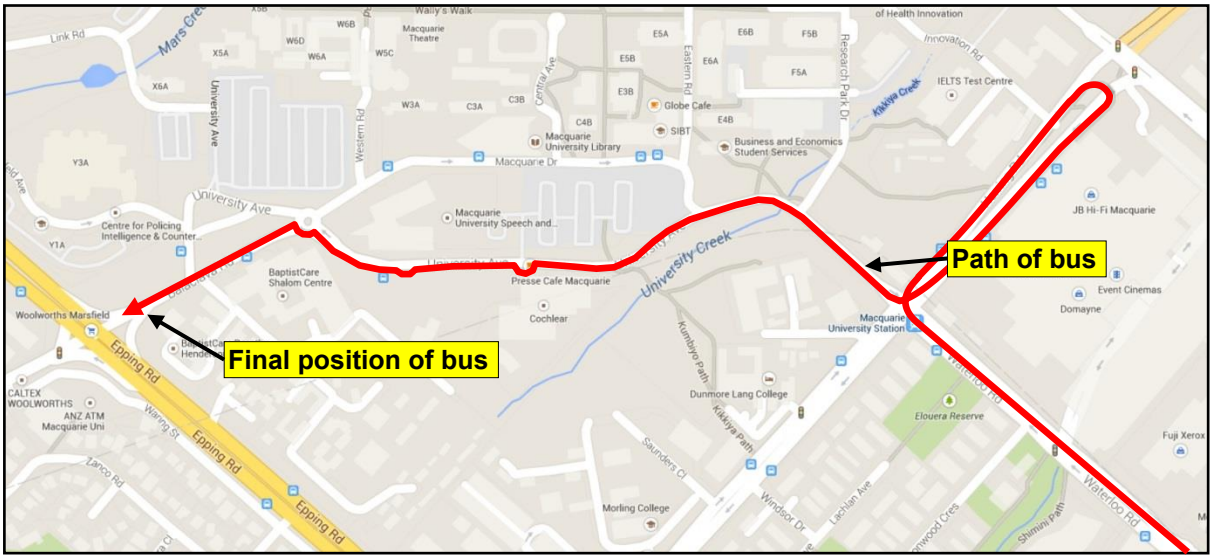


Figure 1: Location of incident

Environmental information

1.9 The minimum overnight temperature was recorded as 13°C at the nearest Bureau of Meteorology station, and had reached 16°C by 0900. It was a clear, calm day, with a maximum temperature of around 22°C. The weather is not considered to have been a factor in the incident.

The bus

1.10 The bus was a Mercedes-Benz O405NH with a Custom Coaches body, completed in July 2000. It was identified by Vehicle Identification Number

WEB35748821095503, registered as MO1196, and constructed to seat 45 passengers and to carry a further 17 standing. Of the 300 of these CNG-fuelled buses originally built, 299 remained in Sydney Buses service at the time of the incident.

1.11 When viewed after the incident the bus had travelled an indicated 802743 km.

1.12 The bus was fitted with six identical steel wheels, single on the steer axle and dual on the drive axle. The wheels, of Mercedes-Benz manufacture, were marked as being 22.5 x 8.25, these figures indicating the diameter and width of the rim in inches.

1.13 STA's maintenance records show that MO1196 was fitted with wheel nut retaining clips on 31 July 2013. Although not stated in the maintenance records, indications are that these were then re-fitted each time servicing required their removal, as they were present at the time of the incident.

1.14 On 28 September 2014, MO1196 underwent a comprehensive service which included lubricating and re-tensioning all wheel fixings to the method set out in Maintenance Instruction WI 26.04.40. This was signed off as having been performed. At this stage the odometer showed a distance of 799387 km.

1.15 MO1196 passed a Roads and Maritime Services Heavy Vehicle Inspection Scheme check on 8 October 2014, with an odometer reading of 799762 km.

The driver

1.16 The driver of MO1196 was a 63 year old male whose 20 years of bus driving experience had all been with Sydney Buses. He had frequently driven Mercedes-Benz O405NH buses, and had worked the early morning shift for 11 years. He had finished his shift the previous day at 1345, and had slept from 1630 to 1900 and again from 2130 to 0330. This was a normal rest pattern for him when working the early shift.

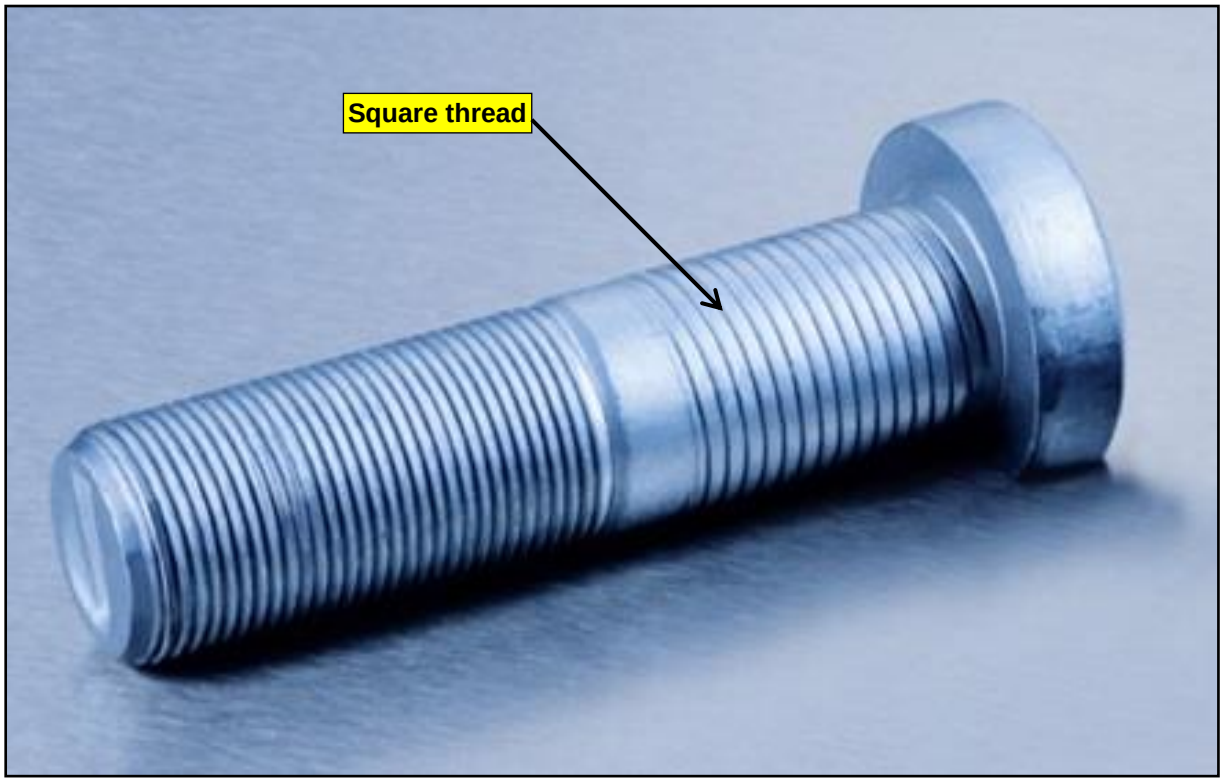
1.17 On the day of the incident the driver had risen at his usual time of 0330 and after a drive of less than 30 minutes, arrived at the Sydney Buses Ryde depot at 0445. He signed on, and after a visual pre-departure check of the bus, left the depot at 0522 and drove MO1196 to Ryde Shopping Centre where he commenced his first run at 0533. This run finished at Chatswood Station at

0603. The following run, during which the incident occurred, commenced at Chatswood Station at 0616.

PART 2 ANALYSIS

Wheel installation and security

2.1 The dual rear wheels were fixed to the corresponding hub by means of ten bolts and nuts, with the bolt holes in the wheels sized so as to provide clearance around the bolts. The bolts were pressed into the hub with an interference fit between a square-threaded section on the bolt, and a marginally smaller hole in the hub. The type of bolt used is shown in *Photograph 1*.



Photograph 1: Wheel fixing bolt

2.2 Centring of the wheels relative to the axis of the hubs was achieved by the use of a tapered centring ring between the inner wheel and the hub, and a spherical lock washer between the outer wheel and the hub. This arrangement is illustrated in *Figure 2*.

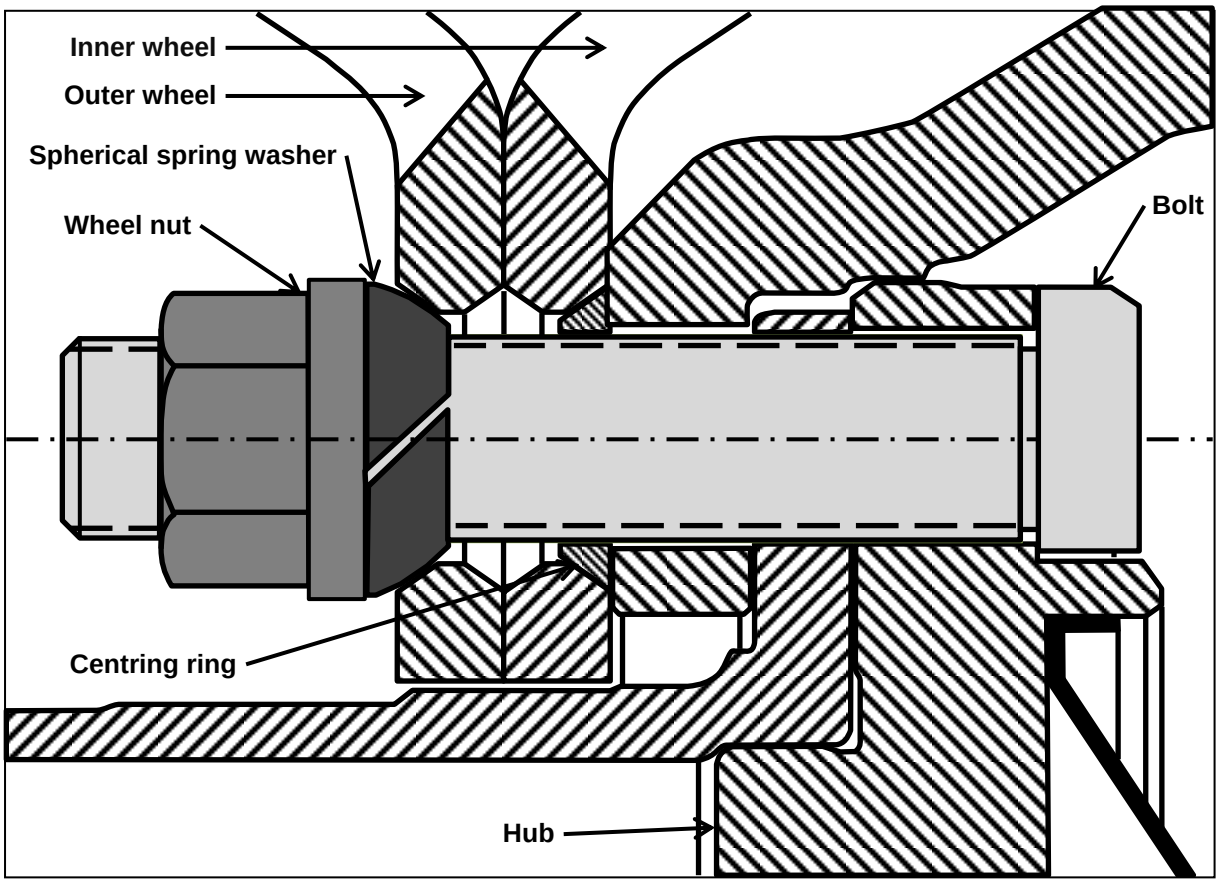


Figure 2: Wheel retention assembly (partial section)

2.3 As accurate centring of the wheel relative to the axis of rotation of the hub is achieved by means of the centring ring and spring washer rather than by positive radial contact between the wheel and the hub, control of the tension in the wheel bolts is critical. There must be sufficient tension developed in the bolts to prevent any movement between the wheel and the hub under operating conditions, so that the bolts are not subject to bending or shear stresses.

Wheel nut retention

2.4 The wheel nuts were also fitted with Checklock® nut retaining clips, as shown in *Photograph 2*. As stated by the manufacturer[1], their primary function "Provides a retaining function, reducing the likelihood of nuts loosening."

[1] Checklock® is a product of Business Lines Ltd of Carnforth, Lancashire, trading as Checkpoint Safety.

Photograph 2: *Checklock*® nut retaining clip

2.5 As discussed in OTSI's report on wheel loss from a bus earlier in 2014[2], there is a tendency for wheel retention failures to occur more commonly on the left side of vehicles than on the right. This is discussed in an analysis by Baily and Bertoch[3], based on passenger cars, light trucks and RVs where the wheels were secured using tapered nuts which can be considered to be functionally similar to the centring rings and spherical spring washers used in this incident. When the nuts loosen, the wheel centre can move relative to the hub centre in a manner that Bailey and Bertoch suggest will cause right hand threaded nuts on the left side of the vehicle to further loosen, while right hand threaded nuts on the right side will tend to be prevented from further loosening.

2.6 Nut retaining clips such as were used in this case, are likely to reduce the tendency for wheel nuts that are not fully tightened to continue to loosen until they fall off with consequent complete detachment of the wheel. However, the wheel bolts will then be subjected to high shear and bending stresses, with the probability of ultimate failure due to fatigue if the loosening is not

2 Technical Inspection Findings: Wheel detached from Busabout bus MO5184, Catherine Field, 14 January 2014, NSW Office of Transport Safety Investigations, Sydney 2014.

3 *Mechanisms of Wheel Separations*, SAE Technical Paper 2009-01-0111.

detected. A bolt end recovered from this incident, with nut and conical spring washer in place (*Photograph 3*), shows evidence of movement between the wheels and the bolt over time, resulting in fatigue failure of the bolt.

Photograph 3: Recovered wheel bolt end with nut and washer

Effectiveness of wheel loss preventive measures

2.7 In addition to wheel nut retaining clips, there are a number of other products marketed to aid in the prevention of wheel loss. As detailed in OTSI's report on the wheel loss incident on 14 January 2014, these products fall into three basic groups:

1. Products which give a visual indication of nut movement.
2. Products that arrest slackening of wheel nuts.
3. Products that lock the wheel nuts so that they cannot move.

2.8 There is little objective information available on the effectiveness of these devices. However, a study conducted by TRL Limited for the Department for

Transport in the United Kingdom[4] reported on a survey conducted with the Vehicle Operator and Services Agency (VOSA) in which 2% of recorded wheel defects involved wheels equipped with nut retention devices and 15% involved visual nut movement indicators. However, no information was available on the presence of these devices across the vehicle population, so their level of effectiveness could not be ascertained. The VOSA survey also reported from face-to-face consultations with operators, that

> ".. concern was expressed about the possibility of operators becoming complacent and relying on the devices, to the detriment of basic maintenance. Most of the small group of operators spoken to and most manufacturers of the add-on devices themselves agreed that such solutions could form a valuable supplement to rigorous maintenance procedures but could not replace them."

2.9 The effectiveness of these devices relies on the wheels being properly fitted, and on periodic checks of the appropriate type and at appropriate intervals being conducted.

Bolt failure mechanism

2.10 The broken bolts can be seen in *Photograph 3*, and typical damage around the bolt holes of the outer wheel in *Photograph 4*.

Photograph 4: The broken wheel bolts

4 *Heavy Vehicle wheel detachment: frequency of occurrence, current best practice, and potential solutions*, Project Report PPR086, TRL Limited, August 2006.

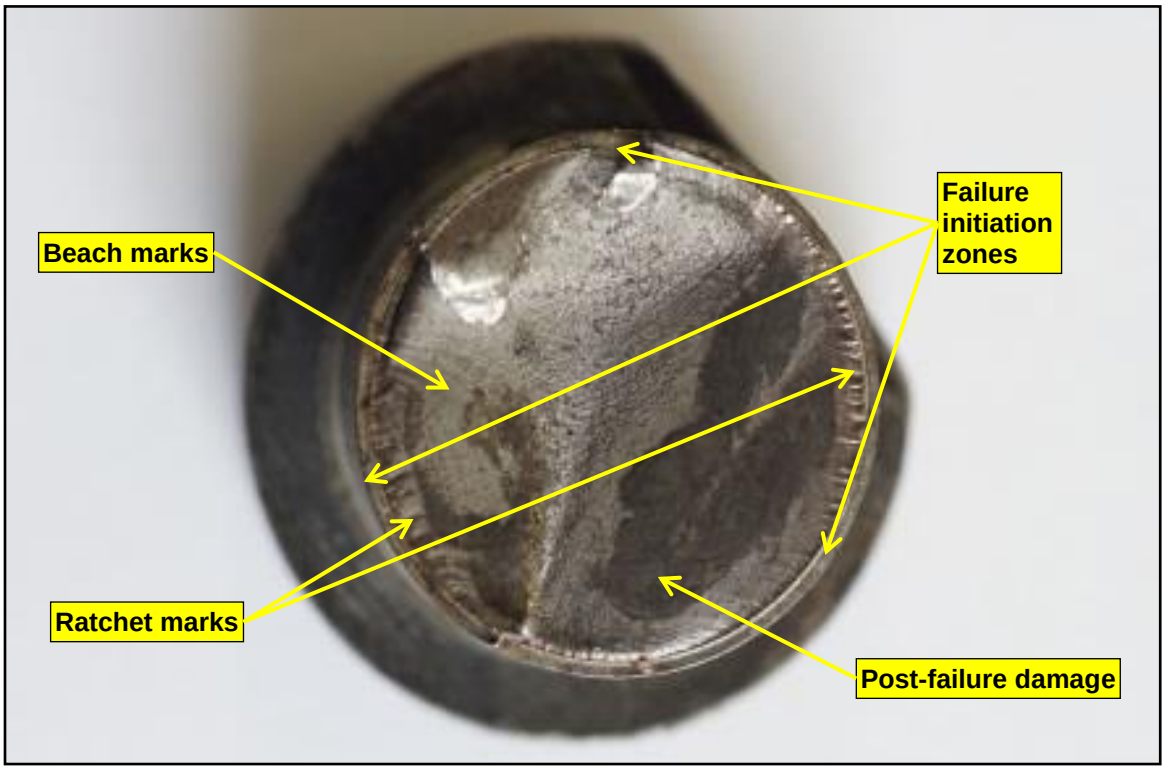
Photograph 5: Outer wheel stud hole damage

2.11 The degree of damage visible at the periphery of the wheel stud hole in *Photograph 5* indicates that movement had taken place between the wheel, the stud and the spherical spring washer for some time. Likewise the bolt failure pattern seen in *Photograph 6* exhibiting readily visible "beach marks"[5] with multiple initiation points is typical of a fatigue failure due to rotational bending over time. Two of the initiation zones also exhibits "ratchet marks"[6] due to the presence of multiple initiation points on slightly different planes.

2.12 The dark area on the fracture surface is most likely due to damage caused post-fracture by the method used to remove the broken bolt from the hub.

5 Beach marks are parallel lines on the fracture surface due to variations in the rate of fatigue crack growth as the load condition changes.

6 Ratchet marks commence in different planes, and as they progress, generally combine onto a single plane on which beach marks may be visible.



Photograph 6: Bolt failure pattern

2.13 STA commissioned a Consulting Metallurgist to examine the wheel bolts, nuts and washers recovered after the wheel loss. His conclusion was that the wheel bolts "…all failed as a result of the initiation and propagation of fatigue cracking." He further stated that "Unless there are design issues associated with the clamping system, this type of failure is invariably associated with poor tightening procedures."[7]

2.14 It is clear from the fact that all wheel bolts fractured, and the nuts remained present on the only recovered wheel bolt ends, that the nuts remained in place and the bolts failed progressively until the wheel was free to fall off.

Mercedes-Benz fitting procedure

2.15 These are the salient points in the wheel installation procedure supplied by Mercedes-Benz Australia:

- Do not damage the threads on the bolts when removing or installing the disk wheels.

7 Metallurgical Investigation Report JLG04-697, *Investigation into the Failure of Wheel Studs*, John L. Gray, 20 November 2014.

- Before disk wheels are positioned, remove rust and dirt from contact surfaces of brake drums, rims and wheel nuts.
- Apply some graphite paste to bolts in order to avoid “jamming” of the wheel nuts.
- Prior to positioning the inner wheel (twin wheels), check whether all the spherical spring washers are properly seated.
- After having positioned the outer wheel, screw in and tighten two to three wheel nuts together with spherical spring washers.
- Make sure wheel is correctly centered (wheel bolts exactly in the center of the wheel disk holes).
- Position and tighten remaining spherical spring washers and wheel nuts.

Sydney Buses fitting procedure

2.16 The procedure in use by STA at the time of the incident was set out in a Maintenance Instruction titled *Securing of Road Wheels*, and dated 14 May 2012. Its salient points follow.

- Before mounting a wheel, you should make sure that the wheel stud threads are clean and lightly oiled.
- The contact surfaces on the hub and the brake drum should be completely free from impurities, rust and paint to ensure the correct contact.
- Only primer and original top coat paint are allowed on the wheel contact surfaces.
- When mounting the wheel, the wheel brake must not be applied. Ensure wheel chocks are used.
- Replace spherical lock washers… …at every tyre change, i.e. replacing worn tyres.
- Lower the bus until the wheel contacts the ground and the majority of the weight of the bus is still carried by the jacks.
- Tighten the wheel nuts in a crosswise pattern to the prescribed tightening torque.

2.17 A tightening torque of 450 Nm is specified.

2.18 This specific instruction for a range of Mercedes-Benz buses including the O405NH, is preceded by a general instruction that includes the following additional requirements:

- Re-tensioning of wheel nuts must be carried out following the first completed road shift following any wheel removal.
- To ensure correct tensioning of the wheel nuts, wheel nuts and studs are to be free of corrosion and lightly lubricated with 10W/40 engine oil (unless otherwise specified).
- Care should be taken not to drag the wheel rim over the studs when taking the wheel on or off. This could damage the bolt threads; making it difficult to screw

on the wheel nuts and, in the worse case, the wheel nuts could seize on the damaged bolts.

- The wheel nuts should be check-tightened every 6 to 8 weeks, whether or not the wheels have been slackened.

2.19 Further instructions are given specifically for the fitting of dual wheels but they add nothing relevant to the type of wheel fixing used on Mercedes-Benz O405NH buses, other than a requirement to position the wheels so that the tyre valves are diametrically opposed.

Thread friction and clamping force considerations

2.20 In order for wheel security to be reliably achieved, the tightening torque applied to the wheel nuts must provide a predictable and consistent clamping force. For this to be achieved, friction forces resisting translation of tightening torque into clamping force must be consistent.

2.21 The tension in the bolts, and therefore the clamping force, can for practical purposes be considered to be directly proportional to the torque applied to the wheel nuts when they are tightened. The following three factors determine the efficiency with which this torque is converted into clamping force: [8]

1. A geometric factor based on the shape of the threads.
2. A thread friction related factor.
3. An underhead friction factor related to the nut rotating on the surface it contacts. This is the friction between the face of the nut and the spherical spring washer, as the spring washer is not intended to rotate relative to the wheel.

2.22 The first factor is fixed by the thread form and pitch. The other two factors will vary depending on the condition of the bolt and nut, and any lubrication used.

2.23 In this case, the wheel fitting procedure specified by STA involved lightly oiling the bolt thread, while that specified by Mercedes-Benz specified the use of graphite paste as a lubricant.

2.24 Although the clamping force achievable varies greatly between lubricated and dry threads, the use of a lubricant results in a higher level of consistency and

8 *Bolted Joint Design*, Federal Engineering & Design Support, 2009.

the variation in friction between the two lubrication methods is small[9]. The choice of thread lubricant is not considered to have been a factor.

Checking and re-tensioning

2.25 The STA maintenance instruction required that the wheel nuts be re-tensioned following the first completed road shift following wheel removal. After a wheel was fitted, a work order for the re-tensioning was to be created. Further checks were required every six to eight weeks.

2.26 Before the first run each day, the driver was required to inspect the bus for obvious faults. This included a visual check of the wheels, and would have been expected to detect any missing wheel nuts or nut retaining clips. It would not be expected to detect incipient loosening of wheel nuts, which could only be detected by physically checking whether the nuts had been adequately torqued.

2.27 When interviewed the driver stated that he had carried out this check.

2.28 The fact that the wheel did not become detached until all wheel securing bolts had fractured is a clear indication that all nuts were present when the bus commenced its first run of the day.

Other incidents

2.29 Wheel loss incidents on buses in NSW are rare, particularly on buses operated by STA. Since OTSI commenced recording incidents in September 2004 there have been 14 wheel loss incidents recorded, while a further three recorded incidents involved loosening or loss of wheel nuts.

2.30 One incident involved a Mercedes-Benz O405NH bus in March 2010, prior to the use by STA of nut retaining clips. In that incident wheel loosening was detected by the driver and the bus was brought to a stop before the left rear wheels were completely separated from the bus. Six of the 10 wheel securing bolts were found to have sheared off, and only one nut remained in place. The left rear wheels of this bus had been re-fitted after tyre

9 *Handbook of Bolts and Bolted Joints,* Marcel Dekker Inc., New York, 1998

replacement a week earlier, and it was concluded that the specified wheel nut tightening and checking had not been properly performed.

2.31 In all the incidents investigated by OTSI, indications are that poor wheel fitting and checking practices were the predominant causal factors.

Safety actions taken

2.32 In its investigation of this incident STA found evidence that in some instances wheel nut tensioning and checking was not being properly performed. STA has taken action to rectify this problem.

PART 3 FINDINGS

Causation

3.1 The left outer rear wheel became detached from the bus after the wheel fixing bolts fractured.

Contributory Factors

3.2 It is highly probable that a service including lubrication and re-tensioning of the wheel nuts 24 days before the incident was not properly conducted, and that a follow-up check of nut tension was also not properly conducted.

3.3 The visual inspection conducted by drivers on a daily basis is not capable of detecting loss of wheel nut tension.

3.4 The wheel nut retaining clips used on the bus prevent loss of the wheel nuts if they loosen, but rely on detection of a loose wheel by the driver before the studs fail and the wheel becomes detached.

3.5 Rough riding of the bus was initially interpreted by the driver as having a cause other than wheel looseness.

3.6 When the driver stopped the bus to check on the cause of rough running about 1.4 km before the wheel loss, he did not notice that at least one stud was broken and its end, with the nut in place, was not present.

PART 4 RECOMMENDATION

To prevent a recurrence of this type of incident, it is recommended that the following remedial safety actions be undertaken by the specified responsible entity.

State Transit Authority

4.1 Investigate the feasibility of introducing a practicable daily inspection methodology capable of detecting wheel nut loss of tension.

APPENDIX 1 SOURCES AND SUBMISSIONS

Sources of Information

- State Transit Authority
- Mercedes-Benz Australia/Pacific Pty Ltd

Submissions

The Chief Investigator forwarded a copy of the Draft Report to the Directly Involved Parties (DIPs) to provide them with the opportunity to contribute to the compilation of the Final Report by verifying the factual information, scrutinising the analysis, findings and recommendations, and to submit recommendations for amendments to the Draft Report that they believed would enhance the accuracy, logic, integrity and resilience of the Investigation Report. The following DIPs were invited to make submissions on the Draft Report:

- Mercedes-Benz Australia/Pacific Pty Ltd
- Roads and Maritime Services
- State Transit Authority
- Transport for New South Wales

Responses were received from all the DIPs. The Chief Investigator considered all representations made by DIPs and responded to the author of each of the submissions advising which of their recommended amendments would be incorporated in the Final Report, and those that would not. Where any recommended amendment was excluded, the reasons for doing so were explained.