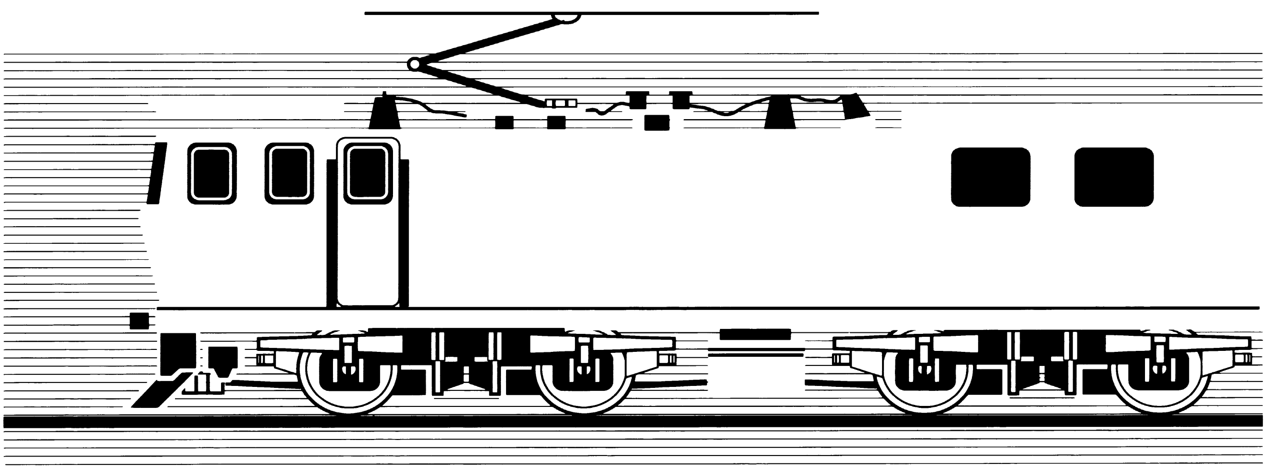
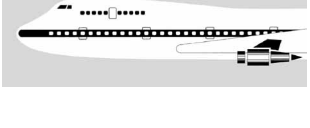
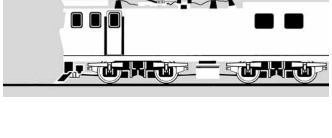
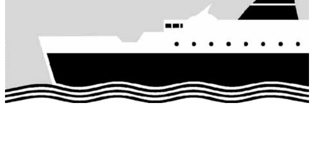


RAILWAY OCCURRENCE REPORT

04-123 **Electric multiple unit traction motor fires, Wellington Suburban Network** **7 May 2004 – 30 September 2004**







TRANSPORT ACCIDENT INVESTIGATION COMMISSION NEW ZEALAND

Report 04-123

electric multiple unit traction motor fires

Wellington Suburban Network

7 May 2004 - 30 September 2004

Abstract

Between Friday 7 May 2004 and Thursday 30 September 2004, four incidents involving traction motor fires on Tranz Metro[1] electric multiple unit passenger services occurred on the Wellington suburban passenger network. These incidents occurred on 4 different driving sets, and all resulted in smoke entering the passenger compartments.

There were no injuries to passengers or crew in any of the incidents.

Safety issues identified included:

- the use of incorrect crimp lugs in cable connections
- inadequate crimping of connections
- the ability to inspect connections
- poor maintenance procedures
- lack of awareness of critical points associated with quality crimp joints
- potential for connector bolts to work lose because of vibration

Because of the similarities arising from each incident, all 4 incidents have been combined into one report.

In view of the safety actions taken by Toll NZ Consolidated Ltd no safety recommendations have been made.

[1] Tranz Metro was the group within Toll Rail with responsibility for the operation of suburban train services in Wellington

Contents

Figures

Abbreviations

AC	alternating current
A	Amperes
DC	direct current
EMU	electric multiple unit
GANZ	GANZ-Mavag (manufacturer)
LEMU	locomotive engineer multiple unit
mm	Millimetres
Toll Rail	Toll NZ Consolidated Limited
UTC	coordinated universal time
V	volts

Data Summary

Rail Occurrence Number	Train Number	Electric Multiple Unit Number	Date	Time	Location
04-114	Train 5612	EM1154	7 May 2004	0707[2]	Petone
04-122	Train 6278	EM1119	22 September 2004	1905[2]	Kaiwharawhara
04-123	Train 6260	EM1315	27 September 2004	1640[2]	Paremata
04-124	Train 2601	EM1321	30 September 2004	0515[2]	Ngauranga

Type of occurrences: electric multiple unit traction motor fires

Injuries: nil

Damage: extensive scorching to cable insulation and surrounding localised areas

Operator: Toll NZ Consolidated Limited (Toll Rail)

Investigator-in-charge: D L Bevin

[2] Times are New Zealand Standard Time (UTC + 12 hours) and are expressed in the 24-hour mode.

1 Introduction

1.1 From 7 May 2004 to 30 September 2004, there were 4 separate incidents involving traction motor fires on Tranz Metro electric multiple unit (EMU) passenger services on the Wellington suburban network, all resulting in smoke entering the passenger compartments.

1.2 All incidents involved GANZ-Mavag (GANZ) EMU driving sets.

1.3 Because of the commonality of the incidents they have been combined into one report. The factual information applicable to each incident is dealt with separately, followed by common sections covering description of traction motors, analysis, findings and safety actions.

1.4 A summary of the individual incidents follows.

2 Factual Information

2.1 Occurrence 04-123, Train 6260, Porirua and Paremata, 27 September 2004

2.1.1 On Monday 27 September 2004, Train 6260 was the scheduled 1600 Tranz Metro EMU passenger service from Wellington to Paraparaumu. It consisted of 2 EM powered passenger cars and 2 ET non-powered passenger cars and was crewed by a locomotive engineer multiple unit (LEMU), a train manager and a passenger operator.

2.1.2 At about 1615, as Train 6260 approached Porirua, the traction motor overload circuit breaker tripped[4], bringing up a light on the console in the driver's cab. The LEMU brought the train to a stop at the platform before resetting the circuit breaker.

2.1.3 When the LEMU looked back from his cab window, he saw smoke rising from beneath EM1315, the powered car immediately behind the non-powered car from which he was driving. He went back and climbed under the train to investigate. He observed a fire amongst the wires beneath EM1315, so he called to the train manager for a fire extinguisher and extinguished the fire.

2.1.4 After he had satisfied himself that there were no further hotspots the LEMU returned to the drivers cab, reset the overload circuit breaker, cut out the affected traction motors and departed from Porirua

2.1.5 The train manager said that when the train stopped at Porirua he arranged for his assistant to advise the passengers of the situation, while he accompanied the LEMU to locate the source of the fire.

2.1.6 At about 1640, as Train 6260 approached Paremata, the overload circuit breaker tripped again and the LEMU allowed the train to coast to the platform, where he stopped. The guard's assistant came from the rear of the train and told him that smoke was again coming from under EM1315. The LEMU called the Wellington platform fitter, who told him to return the service to Wellington.

2.1.7 The train manager said that when the LEMU went to the rear driver's cab, he got the fire extinguisher and climbed down on to the track. He couldn't see any flames, just smoke, but directed the fire extinguisher at the source and gave another burst. He said the local Volunteer Fire Service arrived at the station about this time but he did not know who had rung them.

2.1.8 The passengers were disembarked at Paremata to await a following service. After the Fire Service was satisfied that the flames were extinguished, Train 6260 was coupled to a Wellington-bound EMU service and towed back to the EMU depot for inspection.

[4] The overload protection breaks the power to the traction motors

2.1.9 Inspection of EM1315 at the EMU depot revealed that the nuts and bolts securing the wooden cable clamps had vibrated free and allowed the traction motor cables to hang loose. The wires of the cable were frayed adjacent to the crimp connection.

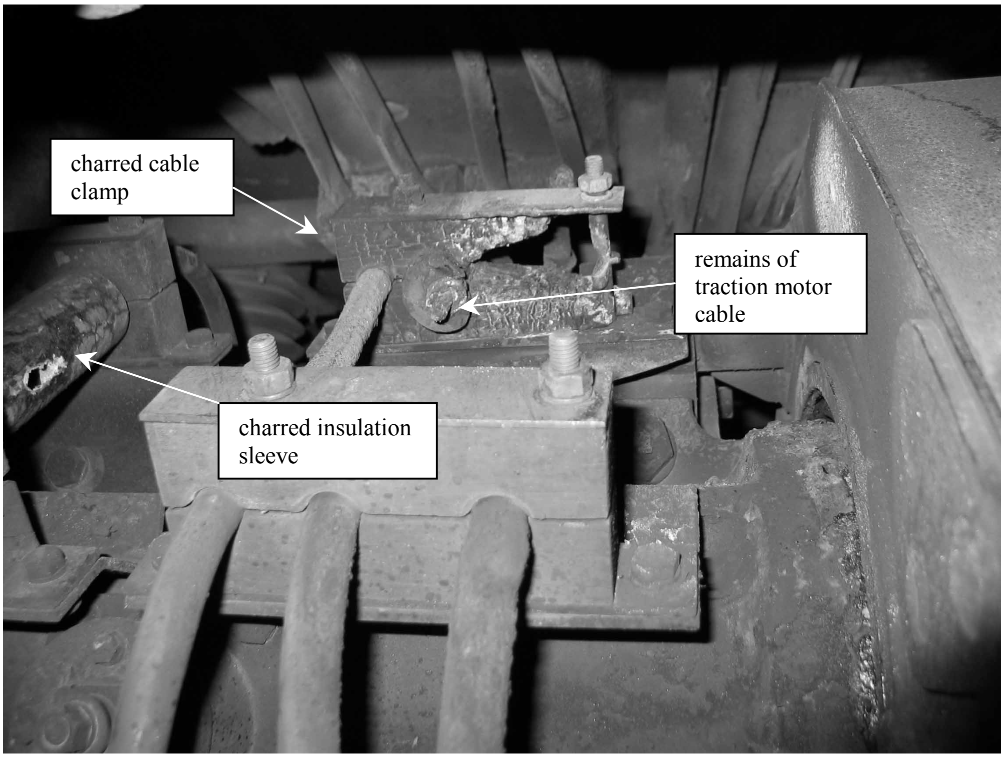


Figure 1
The fire-damaged cable joint area, including the cable clamp, on EM1315 (Train 6260)

2.1.10 There was evidence of a small, localised fire in the vicinity of the wooden cable clamping block, which had burnt.

2.2 Occurrence 04-114, Train 5612, Petone, 7 May 2004

2.2.1 On Friday 7 May 2004, Train 5612 was the scheduled 0622 Tranz Metro EMU passenger service from Wellington to Melling and return. It consisted of 2 EM powered passenger cars and 2 ET non-powered passenger cars and was crewed by an LEMU, a train manager and a passenger operator.

2.2.2 At about 0637 Train 5612 had just departed from Petone after completing passenger work when the LEMU felt the consist surge and the LEMU on a passing train advised him that flames were visible under Train 5612. At the same time the LEMU received a traction motor overload light in his cab.

2.2.3 He stopped the train and reset the traction overload button then got out and went to find the fault. The third and forth traction motor group on the powered car, EM1154, were found to be defective so the LEMU returned to his cab and isolated them. The fire had extinguished itself so it was not necessary for the LEMU to use the fire extinguisher.

2.2.4 After the LEMU had advised train control of the incident, he continued on to Melling and returned as scheduled to Wellington, where the set was removed from service and taken to the EMU depot for investigation.

2.2.5 The investigation at the EMU depot revealed that the connection between the traction motor leads and the bogie leads and the surrounding area, including the wooden cable clamps designed to secure the connection, were charred and burnt.

2.2.6 EM1154 was found to have loose wooden cable clamps. The nut and bolts securing the wooden cable clamps to the bogie had vibrated free, allowing the wooden cable clamps and the traction motor cables to hang free. The free movement resulted in the wires of the cable fraying. As each wire frayed the remaining ones took more current and gradually heated up, contributing to a deterioration of the lug connection.

2.3 Occurrence 04-122, Train 6278, Kaiwharawhara, 22 September 2004

2.3.1 On Wednesday 22 September 2004, Train 6278 was the scheduled 1900 Tranz Metro EMU passenger service from Wellington to Paraparaumu. It consisted of an EM powered passenger cars and 2 ET non-powered passenger cars and was crewed by a LEMU, a train manager and a passenger operator.

2.3.2 At about 1905 Train 6278 had just departed from Kaiwharawhara after completing passenger work when the LEMU felt a surge and the traction motor overload circuit breaker tripped, bringing up a light on the console in the drivers cab. He reset the circuit breakers from the driving cab then started the train again. It had only moved a short distance when it stopped again, this time because the emergency brake had been automatically applied.

2.3.3 The LEMU left the driving cab and walked back through the carriages. From the third carriage he could see into the fourth carriage and noticed that it was starting to fill with smoke and that the passengers were evacuating towards him into the third carriage.

2.3.4 When he got to the fourth carriage he realised the smoke was coming from a traction motor so he jumped down on to the ballast and carried out a quick inspection of the traction motors and the traction motor cables. Although there was no sign of fire there was evidence of arcing and flashing around the traction motors and cables under EM1119.

2.3.5 He returned to the driving cab and cut out the affected traction motors, then continued on to Paraparaumu before returning to Wellington, where the set was taken to the EMU depot for inspection.

2.3 Occurrence 04-122, Train 2601, Ngauranga, 30 September 2004

2.4.1 On Thursday 30 September 2004, Train 2601 was the scheduled 0430 Tranz Metro EMU passenger service from Upper Hutt to Wellington. It consisted of one EM powered passenger car and one ET non-powered passenger car and was crewed by a LEMU and a train manager.

2.4.2 At about 0515 Train 6278 had just departed from Ngauranga after completing passenger work when the LEMU heard a crackling sound from underneath his driving cab in EM1321. He stopped the train, got out, and looked under the cab where he saw flames so he grabbed a fire extinguisher and put out the fire.

2.4.3 After satisfying himself that the fire was out the LEMU inspected the rest of the train but saw no further evidence of fire.

2.4.4 The LEMU said that the traction motor overload circuit breaker had not tripped because he had smelled the fire and stopped the train first.

2.4.5 He cut out the affected traction motors and continued on to Wellington where the set was taken to the EMU depot for inspection.

2.4.6 EM1321 was found to have loose wooden cable clamps. The nuts and bolts securing the wooden cable clamps to the bogie had vibrated free, allowing the clamps and the traction motor cables to hang free. The free movement resulted in the wires of the cable fraying. As each wire frayed the remaining ones took more current and gradually heated up, contributing to a deterioration of the lugs connection.

3 Traction Motors

3.1 General

3.1.1 The traction motors on each powered unit were arranged in 2 sets of 2 with one set on the front bogie and the other on the rear bogie. Each motor came with short cable tails fitted with crimp lugs for connection to the fixed wiring of the unit.

3.1.2 The traction motors were connected to the fixed wiring by bolting the respective cable end crimp lugs together. The cables were clamped between wooden blocks, placed either side of the uninsulated crimp connectors, and the joints insulated using fibreglass sleeves which fitted snugly between the wooden cable clamps (see Figure 2).

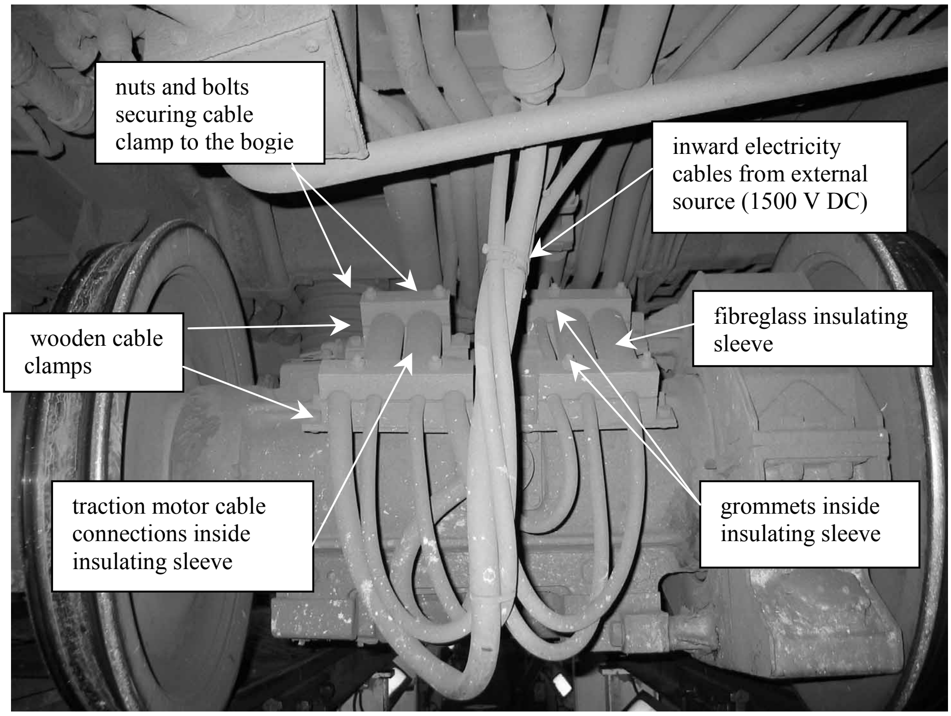


Figure 2
Typical traction motor connections, insulated and clamped

3.1.3 The wooden cable clamps through which the cables passed before entering the insulation sleeve were fastened to the bogie by nuts and bolts. The clamps secured the cable connection by preventing movement while the vehicle was in motion. However, that part of the bogie did not have suspension, so the clamps and cable connection within the insulation sleeve were subjected to continuous shock loads[3] and vibration as the train moved.

[3] The transient load generated when the wheel strikes a rail joint.

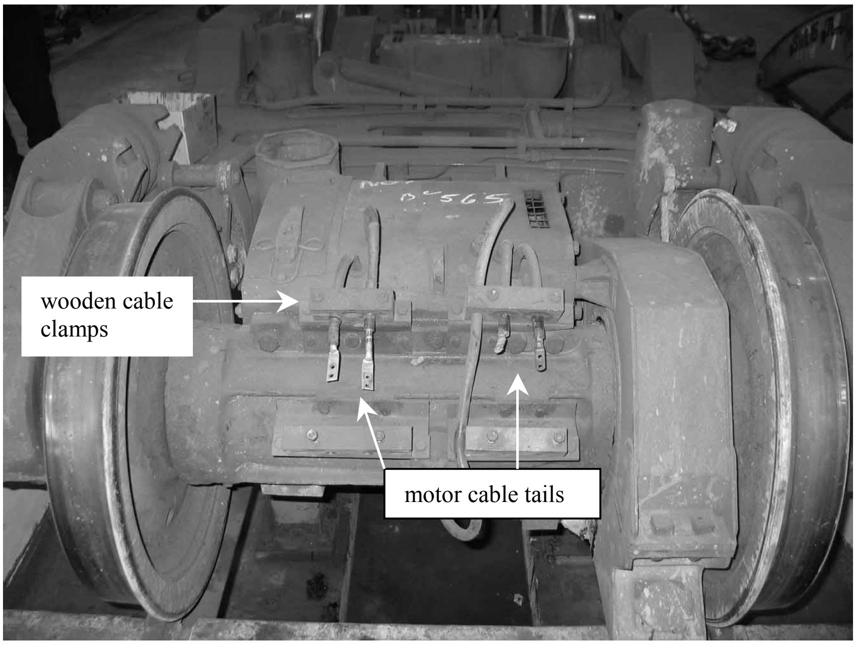


Figure 3
A traction motor bogie showing motor cable tails and cable clamps

3.1.4 The lugs were constructed of cadmium-plated copper (see Figure 4) and were crimped to the exposed ends of the 35 mm^2 cables with a mechanical crimping tool.

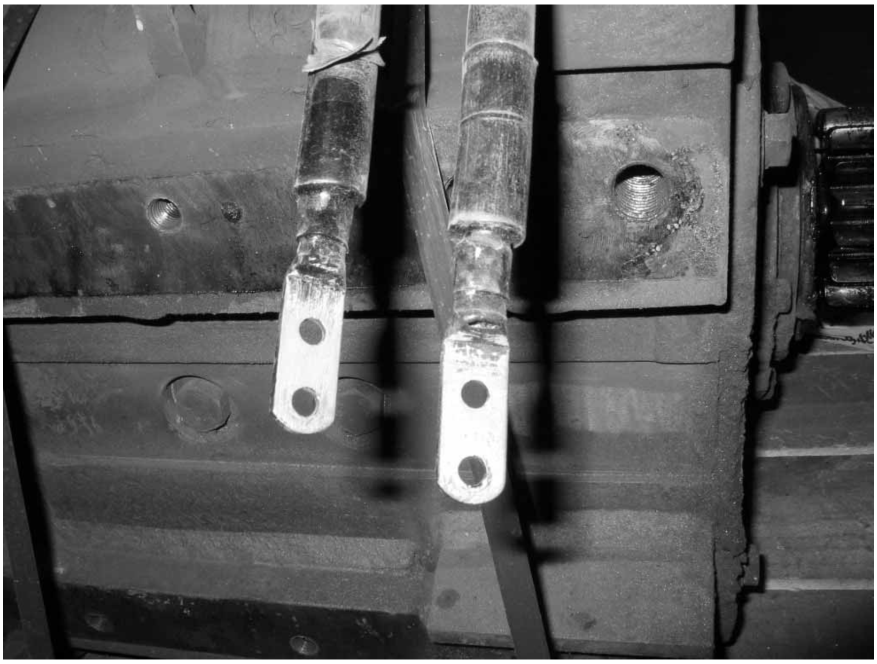


Figure 4
A 35 mm^2 lug crimped to the 35 mm^2 cable ends

3.1.5 The cables carrying the voltage from the overhead pantograph were 35 mm^2 and were joined inside the insulation sleeve to the traction motor cables by bolting together the crimped lugs at each end of the joining cables (see Figure 5). Design specifications required that 35 mm^2 lugs be used.

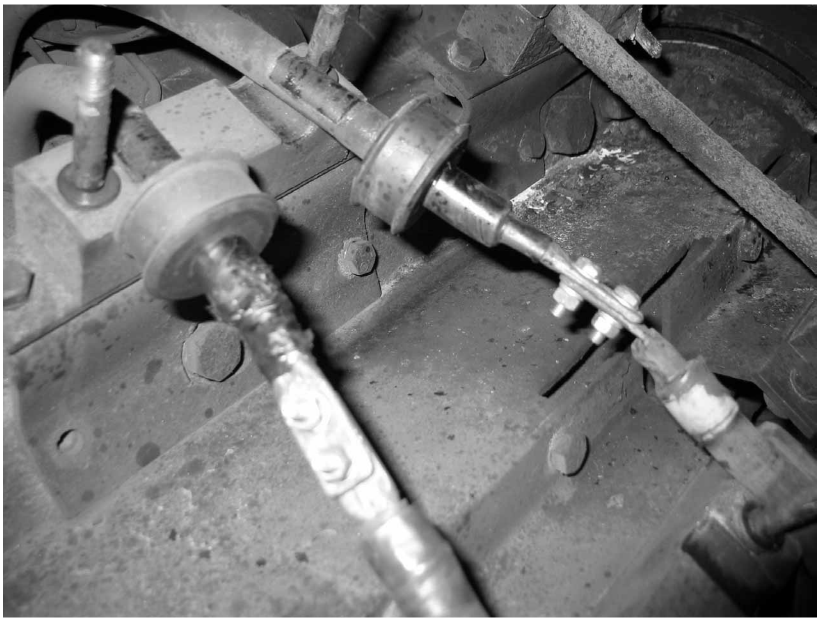


Figure 5
The exposed cable connection

3.1.6 Two nuts, bolts and spring washers were used to join the lugs, and a rubber grommet, through which the cables passed, was fitted into each end of the insulation sleeve.

3.2 Motor arrangement

3.2.1 The GANZ traction motors were fitted to each of 4 axles on the EM unit's 2 bogies. The motors were 750 V connected in series at each bogie set to the supply voltage of 1500 V DC. The front and rear bogie sets could be operated in series or parallel with each other or separately as a single bogie set.

3.3 Maintenance

3.3.1 A shortage in the supply of 35 mm^2 lugs meant that mechanical depot and workshop staff had resorted to the use of 50 mm^2 lugs. However, when 50 mm^2 lugs were crimped to the 35 mm^2 cable ends, a weak point was created between the lug and the cable insulation (see Figure 6). If the cable connection within the insulation sleeve could move for any reason the resulting stress caused the exposed cable strands to fray and the remaining strands overheated, as they took more current.

3.3.2 Alternatively, if the interface between the lugs at the cable connection was not right, either through incorrect size, surface area or pressure on the connection, the vibrations could loosen the connection and again create heat.

3.3.3 Staff in the workshop and the mechanical depot were not aware of any specifications for the amount of pressure required when joining the lugs at the cable connection, so a ratchet tool was used for the purpose.

Figure 6
A 50 mm^2 lug crimped to the 35 mm^2 cable end

3.4 Motor controls

3.4.1 The traction motor speed control system utilised the series coupled DC motor's characteristic curve of the motor current versus speed. When such a motor was started, the load current was very high, but as the motor sped up the motor current dropped. A current sensor monitored the motor current and initiated a gear change when the current dropped to the set point.

3.4.2 The automatic controls switched the front and rear bogie set into series or parallel with each other and altered a resistor in series with the motor winding and another in parallel with the field winding in steps to accelerate the train. Each step was initiated from the motor current dropping to a preset level as the train speed increased.

3.4.3 The LEMU operated a lever like an automatic shift in a car, but there was no throttle. When a gear was selected, the train accelerated as fast as it could to the maximum possible speed for that gear. The driver selected the Coast position if the train reached the desired speed or the driver wanted to slow down. When more power was required the driver moved the selector to an appropriate gear and held it there until the desired speed was again reached.

3.5 Motor protection

3.5.1 The power supply from the overhead pantograph to each EMU was fed through a high-speed circuit breaker. The tripping controls for the circuit breaker sensed the front and rear bogie motor-set currents and tripped the breaker if either bogie motor-set current exceeded a preset limit. When the high-speed breaker tripped, it stopped all drive power for the EMU, but control voltages were still available.

3.5.2 The driver could manually open and close the high-speed breaker from the push buttons in his cab. A light above the push buttons was labelled High Speed Breaker Open and indicated that the breaker was open. This light also illuminated if the breaker tripped.

3.5.3 When the high-speed breaker tripped, the trip circuit had to be manually reset before the breaker would operate again. A local Traction Overload light, together with the High Speed Breaker Open light, illuminated in the driver's cab of the affected EMU and illuminated in all cabs on the Traction Overload light.

3.5.4 A selector switch allowed the driver to manually isolate any EMU's motor bogies, either individually or both. This switch then allowed the high-speed breaker to be reset to isolate a faulty motor set and the train could be restarted. Train acceleration and speed were reduced but the EMU could continue on to the maintenance depot.

3.6 The traction motor

3.6.1 The traction motors were 750 V DC series coupled with a maximum current of approximately 375 A. There was no evidence to suggest that the motors were faulty or drawing excessive motor current. The failures were confined to the crimp lug connection and the motor was still useable once the connection had been replaced at the EMU depot.

3.6.2 Although there were several possibilities for motor failures, due to the power levels involved, such failures would generally result in sudden and severe damage to the motor. The high-speed breaker tripping units were set at approximately 400 A for each bogie motor set. In the incidents covered by this report the traction motors were still serviceable after the crimp connections had been replaced.

3.7 The traction motor cable

3.7.1 The traction motors were provided with very flexible cable tails of approximately 35 mm^2 cross sectional area. One traction motor refurbished by Siemens in Australia had new cable tails with the size marked on them as 35 mm^2. Wiring on other motors refurbished in New Zealand and existing fixed wiring on the EM units was not marked but believed to be 35 mm^2 and 50 mm^2 in some cases. All motor cables observed were the very flexible type with large numbers of very fine copper strands and an outer rubber sheath.

3.7.2 The typical alternating current (AC) rating for a 50 mm^2 flexible cable is about 215 A continuous and 180 A continuous for a 35 mm^2 cable (AC current ratings from AS/NZS 3008.1.2:1998 which would be similar for direct current (DC) current as in this application). For both cable sizes, the maximum continuous current rating of the flexible motor cables on the GANZ electric units is substantially less than the maximum motor current of about 375 A.

3.7.3 There was no evidence to suggest failure of the cables themselves.

3.8 Traction motor damage

General

3.8.1 Initial investigation revealed burnt-out motor leads and evidence of localised fires. In some cases the fire damage allowed the motor cables to short circuit to the adjacent metal chassis of the EMU and tripped the High Speed Breaker. In all cases the smoke came from a fire in the wooden cable clamping blocks mounted on top of the traction motors.

3.8.2 Each incident was very similar, the main difference being in the severity and extent of the burnt area. The source of the smoke was a localised fire, centred on the traction motor's electrical connections to the carriage fixed wiring.

3.8.3 Typical observations of the fire damage were:

- damage was confined to the area around the 2 wooden cable clamping blocks on top of a traction motor
- the heat source was between the 2 wooden clamping blocks and spread radially along the copper conductors to ignite the wooden clamping blocks
- no pattern emerged as to which traction motor connections failed, on which bogie, or on any particular motor units
- charring damage to fibreglass insulation sleeves was from the inside out and centred on the bolted crimp lug connection

- where an electrical connection failed mechanically, there was additional damage from electrical arcing
- motor cables showed no signs of insulation stress or damage beyond the localised fire or electrical arc damage
- the absence of adjacent combustible materials prevented the fire from spreading
- the fire damage usually destroyed the faulty connections.

Heat source

3.8.4 The damage observed confirmed that the heat source was always centred on the bolted crimp lug connections inside the fibreglass insulating sleeve. This in turn confirmed that the electrical current passing through the bolted crimp lug connections generated the heat source.

3.8.5 The connections could overheat for 2 reasons:

- the current was too high, that is, the current passing through the connections was well above their rated capacity

  or

- the resistance was too high, that is, the connections were substandard and were not able to carry the required current.

In this context a substandard connection is one that has a relatively high contact resistance due to the installation or construction method. The extra resistance causes a voltage drop as current passes through it, thus generating heat.

3.8.6 Also, if a crimp lug broke from metal fatigue initiated by vibration, the separated ends could arc together and cause a fire.

4 Driver technique

4.1 In order to evaluate the effect of driving techniques on traction motor performance a test run from Wellington to Porirua was made with a driver trainer at the controls. It became apparent during the test run that the driver's operation of the gear shift had no bearing on the motor overload as each gear was just an end point, while the acceleration to that speed was controlled automatically.

5 Crimp lugs

5.1 General

5.1.1 Crimp lugs were typically made from a tube with one end pressed into a flat palm. Less common methods were to mould or form the lug from a solid ingot then drill the cable barrel.

5.1.2 The function of the crimp lug was to enable a cable termination to be made that electrically connected all strands of the cable to the lug. A cable was stripped back so the conductor was bare then the exposed conductor was inserted into the barrel which was compressed with a crimping tool and the termination was ready to use.

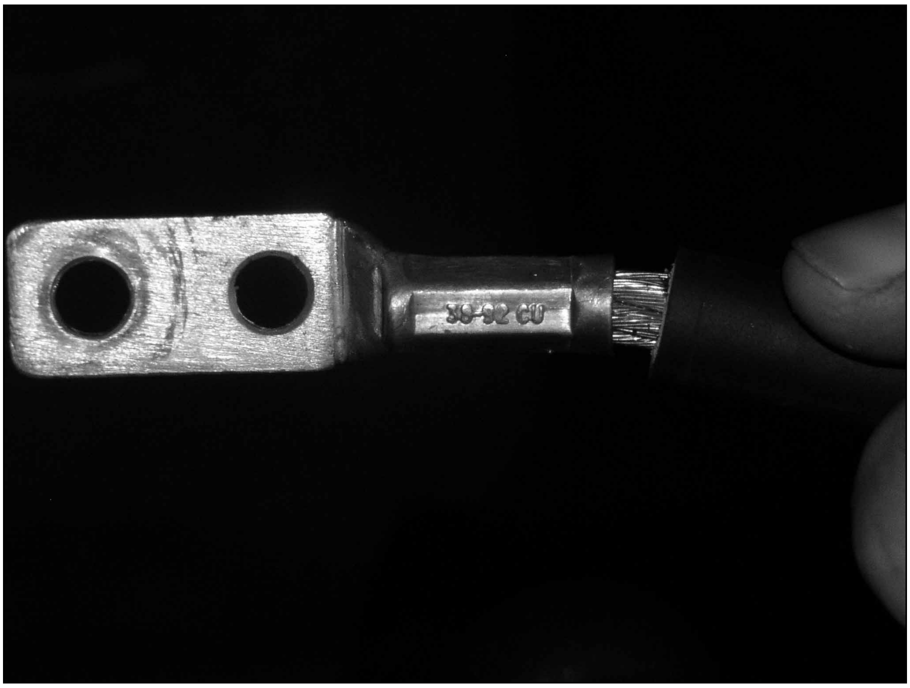


Figure 7
Typical hexagonal crimp lug showing die impression on the crimp

5.2 Crimp barrel

5.2.1 The barrel was required to match the cable size so that when the crimp connection was completed, all strands of the conductor were firmly held in contact with each other and the crimp lug barrel. The cross-sectional area of the cable should not be significantly reduced at any point through the joint. Excessive crimping pressure could distort the crimp barrel and reduce the wall thickness thereby weakening the connection.

5.2.2 Any reduction from the ideal crimp connection introduced electrical contact resistance, which generated heat under load.

5.3 Crimp palms

5.3.1 The crimp lug palm contact surface with the mating terminal was required to be large enough to provide at least the same contact area as the cross-sectional area of the cable. If the materials of the cable and lug were different (e.g. brass and copper) the palm contact surface may need to be even larger.

5.3.2 The crimp lug bolt hole should not be so large that the surface contact area became less than the cable cross-sectional area or the lug was physically weakened by the narrow wall thickness around the bolt hole. Flat washers should be used to increase the pressure contact surface area of the bolts against the palm and prevent the bolt tension from distorting the crimp lug palm. The bolts should also be tightened to an appropriate torque for the bolt size.

5.3.3 In the GANZ EMUs, 2 soft copper crimp lug palms were bolted together with 2 bolts rather than to a solid terminal, so the contact surface area was therefore more critical to the reliability of the joint. Failure to follow the guidelines above could result in the bolt over-compressing the lug palm and splaying it radially. This could curve the mating surfaces away from each other and reduce the palm-to-palm contact surface area. Alternatively, if the bolts were not tightened sufficiently the palm-to-palm contact surface area would also be reduced. Either situation would increase resistance-induced overheating.

5.3.4 Any reduction in the contact surface area below the cable size or poor contact pressure between the crimp lug palms would introduce an electrical contact resistance that generated heat under load conditions.

5.4 Crimp tools

5.4.1 Crimp tools came in a large variety of types. The smaller sizes were usually hand operated but for larger cable sizes the tool was usually hydraulically operated. For high quality joints and crimp reliability, specialised crimping systems were created. These used crimps and tools that were matched to each other and dedicated for a particular cable type and size to produce a reliable and consistent crimp joint. High quality crimping tools automatically controlled the maximum pressure that could be applied to the crimp joint.

5.4.2 Crimping methods and types of crimp systems varied considerably. Several common examples were:

- full hexagonal compression die
- half hexagonal compression die
- oval compression with indent on one side
- ‘v’ compression with indent on one side
- double tag fold and centre staple
- full round compression die.

5.4.3 Utilux, a manufacturer of crimping tools to a world-wide market, controlled the quality of their products and guaranteed the reliability of the completed joint by matching the crimp lugs to the cable, the crimp tool and the crimp die. They also stamped their name on their products. When the crimp connection was completed the die impressed a reference number on the crimped section. A completed joint using Utilux products and made according to their guidelines could be quickly identified and verified as being correct or not for the cable.

5.5 Flexible cable crimps

5.5.1 Crimp joints were very common throughout the electrical industry and a good crimp joint was regarded as important as the original cable. A good crimp joint held every cable strand together and ensured that the cable was in maximum contact with the inside of the crimp barrel. This permitted low resistance contact points within the joint and minimised the generation of heat under high current loads.

5.5.2 Cables were made with solid conductors or stranded conductors. Highly flexible cables had a large number of very fine strands, thinner than the strands used in a standard cable of the same cross-sectional area. It was essential that all strands were solidly connected in a crimp joint or the cross-sectional area (hence current rating) would be reduced. Highly flexible cables appeared to be larger than stranded cables of the same cross-sectional area because of the additional air gaps between the many round conductors.

5.5.3 Due to the extra physical size of highly flexible cables, matched crimp lugs may not fit. One supplier had solved this problem by recommending a crimp lug one cable size larger and using a half hexagonal die to compress the crimp back to the actual cable size. This was referred to as indent type crimping.

5.5.4 Utilux warned that indent type crimping methods were unsuitable for highly flexible cables because of the potential damage to the fine conductors. These types of crimps did not apply even pressure against all strands and the crimping barrel, so contact resistance varied between strands.

They could also sever some of the fine cable strands thus reducing the effective cable cross sectional area.

5.6 Observed standards of crimping

5.6.1 Several faulty motor units were examined during visits to the EMU Depot in Wellington and to the Alstom Hutt facility. During these visits the following observations were made:

- a Seimens Australia refurbished motor had 35 mm^2 flexible cable with full hex 35 mm^2 Utilux crimp die and a non-Utilux 35 mm^2 crimp lug (incorrect lug and die.)
- an EMU depot-installed cable lug used a 50 mm^2 lug on a 35 mm^2 flexible cable with an indent type, manually operated, simple crimp tool. The 35 mm^2 crimp lug was a snug fit on the cable. (Wrong lug and crimp tool. During the investigation the EMU Depot changed to a hydraulic tool with full hex dies.)
- there was a range of different crimp tools in use for traction motors but no official guidelines were available to the tradesmen
- when one crimped connection caused smoke, the adjacent connections were not usually checked. When motor connections on one EMU were checked for this investigation, some were found to be near failure and others were acceptable. The general maintenance practise was to replace only the faulty (burnt-out) connections and ignore all other connections
- crimp connections at Alstom Hutt were made with a simple hand tool (see Figure 8) using 35 mm^2 cable and 50 mm^2 lugs. The crimp method was a V shape barrel distortion and indent. The tool was adjustable for a range of several cable sizes but the operator technique determined the quality of the joint and depth of the indent. The operator noticed that the crimp connections were usually loose so often made 2 crimp indents on each lug
- recently crimped connections at Alstom Hutt were found to have loose strands inside the crimp lug barrel

Figure 8
The manually operated, adjustable crimping tool in use at Alstom Hutt

5.6.2 All crimp connections observed during the investigation all had some element that reduced the quality of the joint. The crimp tools, cable size and type, and crimp lugs were not matched for the application on any of the observed joints. Some products were from Utilux but new stock lugs were sourced from a different supplier and in the 50 mm^2 size only. Utilux would not guarantee the completed connections if alternative products were used.

Figure 9
The hydraulic crimping tool in use at the EMU depot

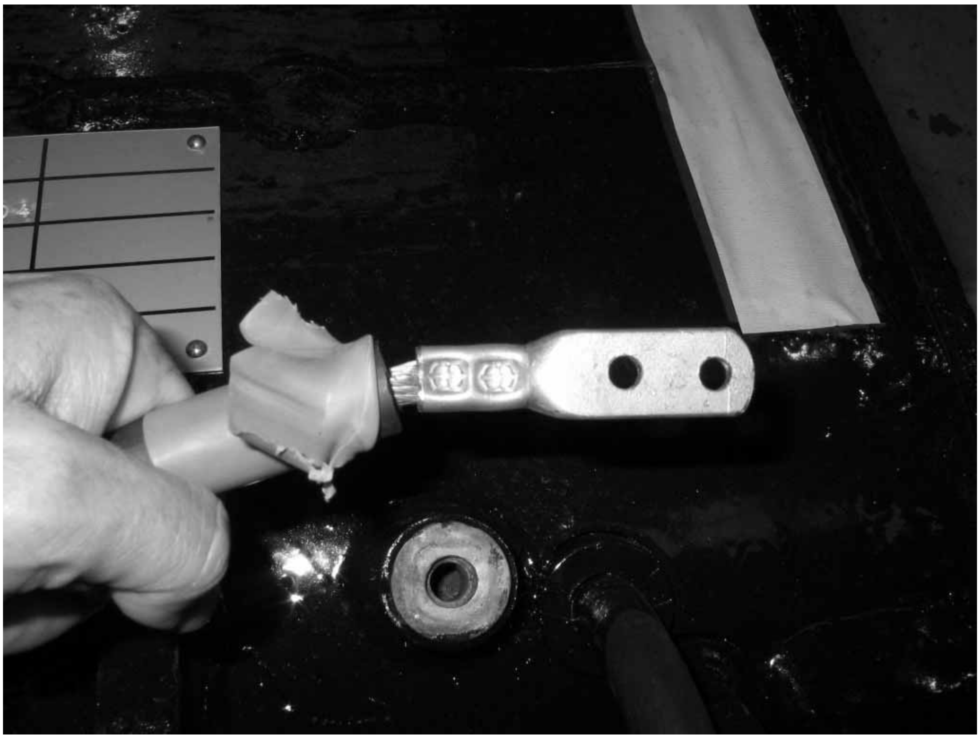


Figure 10
Standard 50 mm^2 crimp on 35 mm^2 highly flexible cable showing excessive clearance (Alstom Hutt)

Figure 11
Recently crimped joint showing loose cable strands (Alstom Hutt)

5.6.3 These reduced quality crimp joints created high contact resistance between individual cable strands and the crimp connector barrel due to low contact pressure. This extra electrical resistance generated heat under load. The effect of this poor quality connection was to reduce maximum current capacity to a point where normal operating load currents generated excessive heating at the joint.

5.6.4 Several examples of ready-for-service crimp connections to the motor cables were examined by the Commission's electrical engineering consultant at the EMU depot and at Alstom Hutt. Common faults identified included:

- crimp method not suitable for cable type
- loose strands in the crimp barrel
- uneven pressure applied to strands that were retained
- wide variations in crimping methods and crimp pressures
- all crimping (with the exception of reconditioned motors from Siemens Australia) done with manually operated tools
- no guidelines in place to achieve consistent quality of the crimp connections
- quality dependent upon the individual tradesman
- crimp joint electrical resistance could vary with every crimp joint
- none of the crimp joints observed met the external supplier's recommendations for matching the lug and die with cable size and type.

5.6.5 The bolted connections of the crimp lugs were not examined, although staff advised that the bolts were not torqued to a set value.

6 Vibration

6.1 The GANZ traction motor unit was in direct contact with the steel bed rails without any suspension or vibration dampening. The carriage body was supported by the bogies and provided with a sophisticated vibration damper and isolation suspension system. The joints between the motor cable tails and the carriage fixed wiring were made on the motor housing so were subject to extreme vibration. In an attempt to reduce the vibration effect upon the bolted crimp lugs, 2 wooden cable clamps had been fitted either side of the joint. These supported the cables against the motor housing. The carriage's fixed (flexible cable) motor wiring spanned the gap between the undamped bogie and the damped carriage and absorbed the vibrations created at the bogie end.

6.2 Wooden cable clamps and fibreglass sleeves around the crimp lug connection were fitted by the manufacturer to reduce the vibration effect upon the cable joint. . This had proved reasonably effective but could still fail. A traction motor fire inspected on 1 October 2004 was a result of such a failure when one bolt holding the wooden cable-clamping block came adrift and allowed the block to pivot on the remaining bolt. The mechanical stress was absorbed by the cable crimp lug until it eventually failed. The palm broke across the bolt hole and separated. The broken joint arced as it parted, which caused a motor failure with smoke in the carriage.

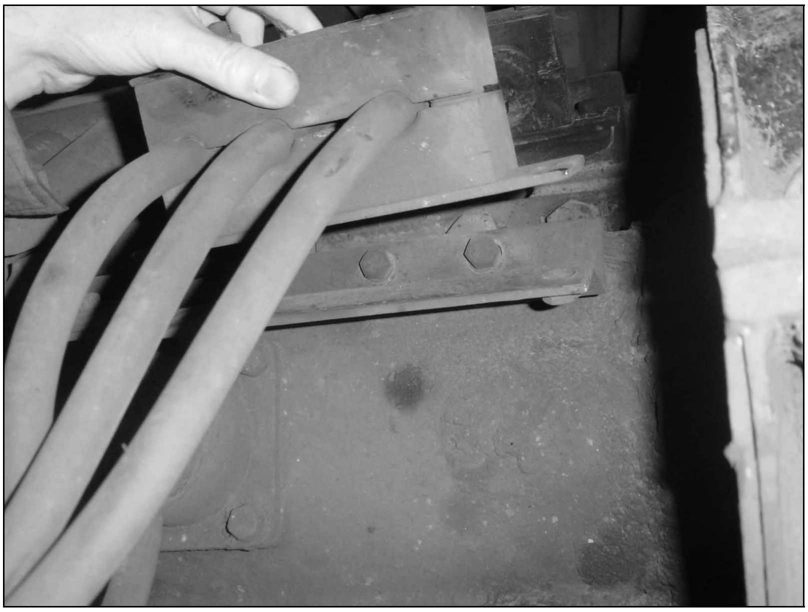


Figure 12
The wooden cable clamp with the mounting bolt missing

6.3 The flexible cable was now suspended between 2 fixed points (the wooden cable clamps), approximately 300 mm apart, with both points firmly connected to the bogie and fully exposed to the train vibration. In the centre of this short cable span was a solid mass formed by the crimp lugs and bolts. The mass of this connection, suspended by a flexible cable, was free to oscillate with the vibrations of the bogie. This continually stressed the cable lugs and the cable at the point where it entered the fiberglass barrel.

Figure 13
The cable clamp free to pivot and the failed crimp lug in the rear

6.4 The older English Electric EMUs in service with Tranz Metro had a superior motor connection. The motor tails were much longer and the bolted crimp lugs were joined on the carriage body, which was isolated from vibration with the rails. This allowed the long flexible motor cable tails to flex as they were designed to do, and safely absorb the different vibration frequencies of the two suspension points on the bogie and carriage.

7 Analysis

7.1 The fires were not caused by traction motor overload, traction motor fault or LEMU driving technique. Motor currents appear to have remained within the sustained operating capacity of the connecting motor cables and the automatic nature of the traction motor control would not have allowed LEMUs to overload the traction motors under normal operating conditions. The automatic trips would also have prevented an electrical motor overload or fault from causing widespread damage.

7.2 Although the heat energy that caused the smoke was converted from electricity, the electrical current flows involved were not excessive for the design conditions. The heat source was due to the normal motor currents passing through an excessive contact resistance in the traction motor cable joints. The heat conducted along the copper cable which eventually became so hot, about 150 mm either side of the joint, that the cable insulation’s maximum operating temperature (approximately 90^{o} C) was exceeded and the wooden cable clamping blocks started to smoulder. The snug fitting fiberglass sleeve restricted convection cooling of the cable joint area, while the cable outside the clamping blocks had maximum convection cooling.

7.3 The bolted connections of the crimp lugs had not been examined, but it was likely they were a contributing factor. Because the bolts were not torqued to a set value it was possible that the bolted connection could be overtightened and cause the crimp lug palm to distort or work loose from the severe vibrations of the bogie. A loose bolted connection or distorted palm contact surface on the other hand would increase the contact resistance and produce local heating under load. As the cable strands heated, the heat was transferred along the exterior cable insulation to the wooden cable clamps, which initially started to smoulder before bursting into flames.

7.4 The bolted connections were suspended between the wooden cable clamps but physically linked to the extreme vibrations on the bogie set and, as a result, were likely to be under constant vibration stress while the train was in motion. Metal fatigue from vibration stresses appeared to be the cause of at least one motor connection failure but was likely to have been a contributing factor in all failures. However, in view of the safety actions taken by Toll Rail regarding the bolted connections of the crimp lugs no safety recommendation has been made.

7.5 While the wooden cable clamps probably reduced the vibration stresses that the crimp lug joints were subjected to while the train was in motion, they would not have totally eliminated that stress.

7.6 The motor cables showed no evidence of excessive heat or insulation failure beyond the immediate vicinity of the crimp lug joints, indicating that the 35 mm^2 cables to the motors were probably adequate and a matching crimp lug should also have been suitable for the operating current. The fact that the heat source for the smoke was consistently seen to be the motor cable connections suggested that they were not appropriate for the application. The problems were probably due to 3 factors at the motor cable joints:

- poor crimp joint
- poor bolted connection between the 2 crimp lugs.

Vibration would have exacerbated either problem but would not have caused a failure of their own accord.

7.7 The use of 50 mm^2 and 35 mm^2 cables initially suggested a poor design feature because the cables were under-rated to cope with the maximum current. However this appeared to be a standard factory feature and as the cables had not failed in these instances, or historically, it was assumed that the average motor current was less than the maximum sustained current rating of the 35 mm^2 flexible cable, i.e. less than 180 A. The cable size was therefore not considered a contributing factor to the fires.

7.8 The fires had in most cases destroyed the faulty connections so it had not been possible to observe any operational in-service connections before they failed. Because of this the crimp connections observed were those on spare parts ready to be placed into service. However the connections observed confirmed that the crimp connections were poorly made and that the poor crimping standard was widespread among Toll Rail's maintenance providers. These observations indicated a potential industry-wide lack of knowledge of quality factors in crimp joints and that the recommendations from a world-renowned supplier of crimp systems had not been implemented. However, in view of the safety actions taken by Toll Rail regarding crimping no safety recommendation has been made.

7.9 The crimp joints observed on the EMU traction motor assemblies were substandard and probably failed under load. The concern arising from this situation was that the traction motor maintenance providers did not realize the importance of a crimp joint and what elements constituted a good connection, or chose to accept lesser standards. Impressions gained during the investigation however suggested there was a lack of understanding about crimping connections rather than a deliberate action to lower the standard.

7.10 Train driving technique was reviewed as a potential contributing factor to the high speed breaker tripping or the electrical overloading of the traction motors, leading to the smoke situations. A likely situation would be that the LEMU was able to hold the motor in a high current condition where the motor current was greater than the cable rating but less than the high-speed breaker trip setting. Such a long duration overload may create a condition where the motor cables and crimp connections would overheat.

7.11 One such possible scenario could be when one motor bogie set was isolated at the driver's cab while the train was fully loaded. This could create a situation where the remaining motor bogie set could not accelerate the train sufficiently to initiate an automatic gear change. The solution would be to remain in a lower gear selection and accept a slower maximum train speed.

However, this likelihood was discounted because it would take a deliberate, although not impossible, action to isolate one bogie set; the reduced acceleration rate would be immediately obvious to an experienced LEMU and would be discernable in the performance of the EMU.

8 Findings

8.1 The traction motor fires were caused by the in-service failure of the crimped and bolted lug connections to the traction motor cables. Traction motor overload, traction motor faults or driver technique did not contribute to the fires.

8.2 The fires were limited to a smouldering state and to the immediate proximity of the motor cable connections because of the general lack of adjacent combustible materials.

8.3 The motor cable connections failed because they were poorly made using unsuitable equipment and materials.

8.4 The rail maintenance organisations contracted to Toll Rail were generally unaware of the mechanics of a good crimp joint.

8.5 In some cases, mechanical vibration contributed to the failure of a traction motor connection.

8.6 The actions of the LEMU and train crew in each incident were appropriate and ensured the safety of the passengers at all times.

9 Safety Actions

9.1 On 1 October 2004, Toll Rail advised that the following steps were being taken in the Tranz Metro EMU depot in an attempt to rectify the problems:

- Toll Rail was employing an electrical engineer to review the problems and become involved in the fixes
- Tranz Metro were intending to start replacing the lugs on all traction motor cables with new 35 mm lugs which were due to arrive from the manufacturer on 4 October 2004
- A staff member was being put on late shift to undertake the replacement work, it was anticipated this would start on Monday 11 October 2004. The plan was that one car would be done per day, 5 cars per week, which would see the 44 EM cars finished by Christmas 2004.

9.2 On 18 October 2004, Toll Rail advised:

> Toll has openly acknowledged concern about the recent EMU fires and has proactively sought to address this issue by immediately implementing a number of targeted initiatives as follows:
>
> - Immediate engagement of an electrical engineer to assist in the investigation and follow-up of issues contributing to the fire
> - Completion of a timely investigation report identifying key mechanical issues
> - Regular updates during this process with both the TAIC and LTSA to ensure they were aware of the issues being identified and the steps being taken. This has included a number of on-site visits by these agencies. The TAIC has involved their own engineer in these visits and reviews

- Involvement of key personnel from both the Metro depot and Alstom Depot to assist with the investigation and to be actively involved in the follow-up

Our investigation has established that there has been a number of related facts which have contributed to connector failures and the resulting fires. The key issues identified include:

- Incorrect crimp lugs being used – crimp lugs were substituted for a larger (50mm) size when stocks of the correct lug were unavailable
- Inadequate crimping due to inability to mechanically crimp the larger 50mm lugs
- Potential for the connector bolts to work loose from track vibration, and
- Difficulty inspecting the connection due to design of the electrical insulation.

Although the specification for the crimp lugs was exceeded, increasing the conductive area, this is ineffective as the manual crimping process did not ensure a good contact between the lug and cable. These factors created the potential for a high resistance join that would result in overheating. Although the EM sets have operated for a number of years without previous connector failure this cannot be eliminated as a contributing cause as the connector, encased in an insulating sleeve, is not readily visible.

Mechanical Safety Actions

Toll Rail have initiated the following safety actions:

- All EM's will be fitted with new, correctly sized lugs. This involves inspecting each EM set, each set having 16 connections. This work is proceeding at the rate of one car per day
- The quality assurance process has been reviewed and tightened to ensure that material supply is controlled to prevent future use of inappropriate material
- All crimping will be done hydraulically and no mechanical crimping will be accepted, both at the EMU Depot and Alstom Hutt. Additional hydraulic crimping machinery has been provided to the EMU Depot for this to occur.
- All connections will be tightened to specific torque.
- A design change is being investigated to enable easy inspection of the connection. This will allow Toll Rail to include this inspection in the maintenance schedule to assess the condition of connections on a regular basis.

All key personnel including relevant Alstom staff have been fully involved in the investigation and follow-up and are assisting in remedial action.

9.3 On 1 November 2004, Toll Rail provided the following update on the progress of the safety actions that had been initiated:

All lugs are now being inspected (as opposed to replaced) for any sign of failure at the rate of eight traction motors per day. Connections showing any sign of deterioration are being replaced. This has sped up the rate at which we are able to complete inspections to two sets per day, and we estimate that the entire fleet will have been inspected by 26 November 2004.

The reason for the change of philosophy from what was previously advised is to speed up the process and mitigate the risk of traction motor fires as quickly as possible.
We currently have three staff working full time on the inspection process – two tradesmen (including one hired from Alstom) and a helper.
Once the inspections have been completed we will begin a replacement process to ensure all connections on traction motors are of an acceptable standard. We estimate this process will take a further four months.
We will be closely monitoring and recording the results of the inspection process and will review findings and progress on a weekly basis. The findings from the inspection process will help determine the prioritisation for the replacement process.

It was discovered through further analysis that there were other factors impacting on the badly crimped lugs, and therefore the prioritisation method used initially was no longer relevant. Units are now inspected as they are available, rather than on a set roster.

Should time be available after an inspection, non-standard lugs will be replaced on a prioritised basis:

1. Long Barrel Terminals
2. Hand Crimped Terminals
3. Hydraulically crimped 50mm^2 Terminals
4. Original 20 year old 35mm^2 Terminals

Mounting Brackets will be secured to the new standard after the inspection.
All type of lugs installed on each motor of each unit will be logged.

9.4 On 27 November 2004, Toll Rail completed the inspection of the entire GANZ fleet and lugs showing signs of risk had been replaced at that time.

9.5 On 27 April 2005, Toll Rail advised that all lugs had been replaced.

Approved for Publication 26 May Report

Hon W P Jeffries

Chief Commissioner

Recent railway occurrence reports published by
the Transport Accident Investigation Commission
(most recent at top of list)

04-123	Electric multiple unit traction motor fires, Wellington Suburban Network, 7 May 2004 – 30 September 2004
04-120	Express freight Train 726, collision with runaway locomotive, Pines, 18 August 2004
04-112	Diesel multiple unit passenger Train 2146, fire in auxiliary engine, Boston road, 16 April 2004
04-111	Express freight Train 736, track occupation irregularity involving a near collision, Christchurch, 14 April 2004
04-110	Shunt L9, run away wagon, Owen’s Siding Onehunga, 5 April 2004
03-114	Express freight Train 220, derailment, Shannon, 21 November 2003
04-113	express freight Train 220, and empty truck and trailer, collision, farm access level crossing, 162.56 km between Maewa and Rangitawa, 27 April 2004
03-113	diesel multiple unit, passenger Train 3366, passed conditional stop board without authority, Glen Innes, 30 October 2003
04-109	passenger express Train 804, Tranz Alpine, stalled and slid back, Otira Tunnel, 28 March 2004
04-107	express freight Train 237, derailment, near Kopaki, 24 March 2004
04-102	motor trolley, derailment, Lepperton, 25 January 2004
03-112	diesel multiple unit Train 2153, collision with truck, St Georges Road level crossing, Avondale, 28 October 2003
03-110	express freight Train 337, derailment, Kaimai Tunnel west portal, 9 August 2003
03-109	diesel multiple unit passenger Train 3347, driveshaft failure, Meadowbank, 27 June 2003

Transport Accident Investigation Commission
P O Box 10-323, Wellington, New Zealand
Phone +64 4 473 3112 Fax +64 4 499 1510
E-mail: reports@taic.org.nz Website: www.taic.org.nz

Price $26.00 ISSN 0112-6962