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HEAVY VEHICLE WHEEL SEPARATIONS: EXPLORING THE CAUSES

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ABSTRACT

Large truck wheel separations have resulted in 6 fatalities in the Province of Ontario, Canada since 1995. As a result of public concern, and by concluding that the wheel separations were the result of sub-standard maintenance practices, the Province of Ontario enacted severe penalties in an effort to reduce the problem. Despite the new measures and a significant effort from industry to improve wheel maintenance practices, wheel separations continue to occur in Ontario at a rate of 7 reported incidents per month. This paper examines the heavy truck wheel separation problem and discusses some unique technical factors that may be influencing the integrity of wheel systems.

INTRODUCTION

Wheel separation on a large truck is defined as the loss or detachment of a wheel while the vehicle is in motion. The cause of wheel separation includes:

- failure of the wheel unit, usually from metal fatigue resulting in the tire and rim detachment from the vehicle
- failure of the fastener system that secures the wheel to the brake drum, resulting in loss of the wheel and rim and in the case of dual wheel assembly, loss of both wheels
- failure of wheel bearings resulting in loss of the wheels, hub and brake drums

The mass of large truck wheels is significant. A set of dual wheels and brake drum is approximately 350kg. This represents a substantial body mass, which has the potential to cause severe damage to other vehicles and objects particularly when traveling at highway speed.

WHEEL TYPES

Until the 1980's, the most common heavy truck wheel design was known as the spoke system. The tires were mounted on simple rims supported by steel spoke wheels and secured by lugs, studs and bolts. These wheel systems were susceptible to wobble due to run out error that occurred during mounting or induced by shock loads that occurred as a result of rough roads and potholes. Disc wheels were developed to overcome these problems and to provide less massive wheel systems. The early disc wheel systems were known as stud-piloted wheels. These wheels used complex two-piece threaded fastener systems that independently secured the inner and outer wheels of a dual wheel set. The studs locate and supported the wheel about the rotational axis resulting in high stresses at the studs and wheel stud holes. The high stresses manifested in fatigue failures of the studs and wheel discs.

The most common wheel system used today is the hub-piloted wheel. An exploded view of the hub-piloted wheel is illustrated in Figure 1. The hub-piloted wheel is a disc wheel with 8 or 10 stud holes in a concentric bolt circle that allow the wheel to be fastened to the hub. The wheel has a precision cut hole at the axle centre, which engages on curved extension or seating pads extending from the hub. The engagement of these parts precisely locates the wheel about the centre of the axle, and the clamping force generated by the fasteners immobilizes the wheel. This has the affect of reducing the vertical load support sheer stresses at the studs, which was one of the weaknesses in the fastener system used for the older generation stud-piloted wheels.

From Accuride, January 2001

Figure 1. Exploded view of a hub-piloted wheel system.

ONTARIO DATA

In the province of Ontario, the Ministry of Transportation compiles wheel separation data. (1). The database tracks the location of the wheel separation within the province, the vehicle type, the cause of the wheel separation and the type of wheel. The database reveals that approximately 60% of all reported wheel separations in the Province of Ontario are related to fastener failures. This paper therefore will concentrate on the issue of fastener failures.

A review of the data to determine the frequency of wheel separations is found in Table 1. The data indicate that there are approximately 7 reported wheel separations in Ontario per month. (The number of unreported wheel separations is unknown.)

Table 1. Wheel Separations in the Province of Ontario

Year	Total Number of Separations	% Fastener Failure	Fastener Failures		
			% Hub Piloted	% Stud Piloted	% Spoke
2000	83	57%	64%	23%	17%
1999	79	62%	46%	31%	15%

Note: The values expressed in percentage do not add up to 100 as some of the wheel separations involving fasteners were not identified to a particular wheel type.

The data also indicate that the most common failure mechanism is associated with the fastener system and the most common wheel system failure is the hub-piloted wheel. It is important to note that the hub-piloted wheel is by far the most common wheel system used today and the comparatively high failure rate is a reflection, at least in part, of this fact.

One serious limitation in the Ontario Ministry of Transportation wheel separation database is the lack of specific information pertaining to fastener failures. It does not provide any detail or description of the failure mode. For example, it does not distinguish between fasteners that failed catastrophically or fasteners that simply backed off the studs.

ANALYSIS OF PREVIOUS RESEARCH

There are very few independent studies on wheel separation described in the literature. Three Canadian publications were found. One is published by the Professional Engineers Ontario entitled "Wheel Separation on Tractor-Trailers" (2) the other is entitled "Heavy Truck Wheel Separations: An In-Depth Study of Real-World Incidents" published by Transport Canada (3). The third is a paper (4) that was presented to The Fourth International Conference on Accident Investigation, Reconstruction, Interpretation and the Law; August 13-16, 2001; Vancouver. It discusses the legal details and framework used in Ontario as a counter measure to the wheel separation problem and reviews the technical issues associated with wheel separation. In addition to these papers, several industry publications exist in the form of safety and service manuals.

Woodrooffe & Associates studied the details from 13 cases reported in the Transport Canada paper. Of the 13 cases, 6 of the wheel separation incidents were the result of non-wheel related component failure such as failure of the wheel bearing, structural failure of the hub or axle spindle failure. One incident involving a stud piloted wheel was the result of failure of the wheel structure, most likely the result of metal fatigue. The remaining 6 wheel separation cases were the result of wheel fastener detachment. They all involved hub-piloted wheels where fasteners detached or loosened from the studs.

WHEEL FASTENER DETACHMENT

Wheel fastener detachment is defined as the wheel nuts unwinding fully from the studs and allowing the wheel to separate from the vehicle. In this failure mode, the stud remains intact and the wheel nuts are missing. This appears to be a common failure mechanism among cases recorded by Transport Canada. It appears that once the wheel clamping force diminishes to the point where relative motion between the hub and the wheel can occur, the rotational action of the wheel relative to the fasteners, results in the unwinding of the wheel nuts from the studs. Transport Canada case HFVS-96-01 most closely resembles a specific case, which was first reported by Woodrooffe & Associates. In the case HFVS-96-01, the truck was traveling in the westbound driving lane of a four-lane highway when the wheels of the left side of the last axle of the trailer separated. The fastening system on the steel hub piloted wheels was the common 10-stud system used on most large vehicles. The report states that the nuts backed off the studs completely while the vehicle was traveling and eventually the wheel separated.

Brake maintenance had been carried out on the failed wheel assembly just three days prior to the separation. The repair invoice indicated that the brake linings had been replaced on the left side of the axle. The driver's logbook showed that the vehicle had traveled 571 km since the last service. The report states "The driver indicated that he did not feel anything unusual with his vehicle, and was unaware of the wheel separation. He also stated that on the day of the incident, he had checked the fasteners prior to starting his trip, having borrowed a torque wrench from another transport driver." The case investigated by Woodrooffe & Associates was almost identical to this Transport Canada case. A brake job was done on the wheel in question two days prior to the incident. The vehicle traveled approximately 580 km from the point of service to the location where the wheel separation occurred.

Another important observation found when reviewing the Transport Canada cases is that of the 6 cases resulting from wheel fastener detachment, 4 of the wheels had been removed for service within one week prior to the incident. Of the 4 wheels that had been removed for service, 3 had been removed to allow for brake replacement. It is unknown whether the wheels from the other two incidents had been removed for service. This detailed analysis reveals that in the sample of wheel separation incidents reported by Transport Canada, all of the incidents involving wheel fastener detachment were of the hub-piloted design and most of these were of wheels that had been recently removed for service. Based on this limited sample it appears that hub-piloted wheels are more susceptible to wheel fastener detachment than any other wheel type. In addition, because at least 50% of these cases involved wheels that had been removed to allow for brake replacement, there may be factors related to brake replacement procedures that influence hub-piloted wheel fastener security.

Transport Canada case HFVS-96-01 most closely resembles a separate case (5) examined in detail by Woodrooffe & Associates. The truck was traveling in the westbound driving lane of a four-lane highway when the wheels of the left side of the last axle on the trailer separated. The fastening system on the steel hub-piloted wheels was the common 10-stud system used on most large vehicles. The nuts backed off the studs while the vehicle was traveling and eventually the wheel separated. The Ottawa urban bus transit authority (OC Transpo) experienced an incident (6) where a wheel separated from an urban bus as a result of fasteners backing off the studs.

TWO PIECE FLANGE NUTS

Hub-piloted wheel systems in North America use two-piece flange nuts comprised of a hexagon nut mated to a hardened washer. SAE J1965 specifies a minimum - maximum torque/tension relationship for two-piece flange nuts. To meet the minimum requirements there must be at least 133 kN (30,000 lb) of tension in the stud when 500 N-m (370 ft-lb) of torque is applied to the flange nut (7). To meet the maximum requirement, there must be less than 276 kN (62,100 lb) of tension in the stud when 678 N-m (500 ft-lb) of torque is applied to the flange nut.

As shown in Figure 2, the clamping force generated by the flange nut must fall within the limits prescribed by the SAE. Fasteners that fall outside of the torque limits are not acceptable.

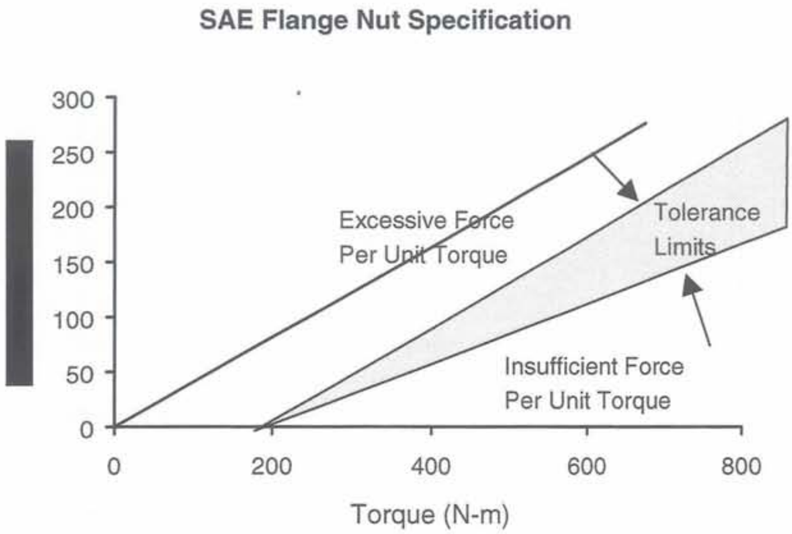

Figure 2: SAE Torque Clamping Force Performance Requirement

Anecdotal tests have shown that as the flange nuts age or when they are re-used, their torque/clamping force characteristics can diminish in the order of 50%. This means that when these flange nuts are tightened to a specified torque value, the achieved clamping force can be as little as 50% of the design value. Under these conditions the fasteners may not meet the SAE specifications and cannot produce sufficient clamping force to meet design requirements. Given that hub-piloted wheels depend exclusively on clamping force to prevent the wheel from separating from the hub, it is clear that such a reduction in torque/clamp force characteristics represents a significant risk to wheel separation. More work is required to better understand the torque/clamp force performance of these fasteners as a function of age and repetitive re-use so that industry can be more knowledgeable about wheel separation risk factors.

Heat Effects

After experiencing a wheel separation from an urban bus due to the loss of flange nuts, the Ottawa transit authority (OC Transpo) conducted and internal investigation on a new bus using a dynamometer (6, 8, 9). There was a suspicion that the problem may be linked to temperature change associated with braking. A moderate braking cycle was used to raise the temperature of the wheel assembly simulating normal brake duty cycles for urban busses. As the temperature increased, the flange nut required more rotational displacement to achieve the identical torque level. When the wheel cooled after being torqued at high temperature, the effect of thermal contraction resulted in the fastener being was significantly over-torqued. From this experiment, it was concluded that as the temperature of the wheel assembly increases, the clamping force diminishes significantly. Given that urban busses routinely experience very high wheel assembly temperatures due to frequent brake applications, the bus company increased the installation torque level from the manufacturer's recommended value of 644 N-m (475 ft-lb) to a range of 813 – 881 N-m (600 – 650 ft lb) as a counter measure against heat related wheel separations. OC Transpo also specified that torquing of the flange nuts must not take place when the wheel assembly is hot in order to prevent excessive clamp force and stud stress when the assembly cools.

The same problem will occur when wheels are installed or re-torqued at very cold temperatures. As the weather improves the change in temperature will result in a reduction in the clamping force.

Re-Torquing of Wheel Nuts

There are very few independent reports focusing on truck wheels. No literature was found that provided technical information that supported or refuted the 80 km to 160 km re-torque requirement. There was no variation in the re-torque specifications among the various wheel manufacturers. It appears that this number is arbitrary and may have been chosen by wheel manufacturers as a convenient way to at least give some rough parameters governing re-torquing intervals. There is no information available that would allow an independent party to determine if this distance requirement is an absolute requirement, a reasonable requirement or a requirement of convenience. This is an important consideration because the requirement to stop a truck at 80 km to 160 km from its origin presents a logistics challenge (there are many routes where there are no repair facilities within such a departure distance). The Professional Engineers Ontario report "Wheel Separations on Tractor-Trailers" recognized this limitation by stating that "checking the wheel nut torque after 100 km of travel can realistically only be done by the driver using a bar wrench, which is acceptable. All that is required is to ensure that there is no perceptible loosening of the nuts. This is the only practical method for checking wheel nut torque on the road." It must be stressed that despite these challenges, re-torquing of wheel fasteners after initial installation is an important task, the issue is, at what distance from original service should this be done.

There is no comprehensive source on industry practice that speaks to truck wheel re-torquing. In the absence of such a source, the best that can be done is to rely on anecdotal experience. The Canadian truck transport industry is conscious of the importance of re-torquing wheel flange nuts after the wheel has been installed. The zone of operation appears to be the main factor influencing the distance traveled before re-torquing. The probability of wheel attachment problems increases on rough and mountainous roads due to high wheel vibration levels and high braking demands. This results in variations among carriers in the distance traveled before re-torquing occurs. Transport resource haulers operating in northern sectors on unpaved rough roads, instruct their drivers to re-torque the wheels before traveling more than 250 km after a wheel has been installed. The re-torquing task is normally done by the driver at the side of the road with a standard wrench and extension bar rather than a torque wrench. These companies believe that the rough terrain is much harder on the wheel systems thereby requiring shorter re-torquing intervals. Line haul companies operating on better quality roads generally re-torque at their terminal following the first trip segment. The author estimates the re-torque distance intervals to be in the order of 400 km to 700 km.

In the US, on the basis of anecdotal evidence, the practice of re-torquing appears to be quite unusual. Of the US carriers contacted by the author, not one of them practices re-torquing of the wheels.

LEGAL ISSUES

The Ontario Highway Traffic Act deals with wheel separations in a simplistic way. If a wheel separates, the offender is guilty of an offense and may be fined up to $50,000. The Act makes it an absolute liability offense, that is, one where there is no defense, beyond the claim that the wheel did not separate. It is not open to the accused to prove that he or she took all reasonable measures to prevent the separation, which is the so-called defence of due diligence. From a forensic engineering perspective the inability to mount a defence means that comprehensive investigations into the cause of the wheel separation are not carried out and therefore the natural discover mechanism that is active in most court cases, ceases to exist. This deprives the engineering community of one of its most powerful retrospective analysis opportunities where potential design problems can be identified as a result of documented failures. Under the absolute liability rule where no defense is possible, the legal system inadvertently suppresses investigations of cause, which does not benefit potential defect discovery. Therefore in the absence of rigorous analysis, the legal system may be perpetuating the very problem that it is attempting to correct.

The notion of absolute liability for wheel separation is based on the assumption that truck wheel systems are properly designed and their failure mechanisms and causal factors are fully understood. It also implies that all wheel separations are preventable and are the result of poor maintenance practice. While poor maintenance is undoubtedly associated with some wheel separation cases, the evidence presented in this paper clearly show that these assumptions are not valid for all cases.

DISCUSSION

The Transport Canada study concludes with the following statement. "The fact that wheel separations are occurring over all wheel types, suggests that the expectations of current wheels are being exceeded, and that we may have reached the limits of current designs."

The Ontario Professional Engineer's report states the following: "It is said that the hub-piloted system is now used on all new tractor duals in Ontario, and on a high percentage of new trailer duals. This is evidence that the industry is making efforts to improve the situation. However, since this new wheel type has come into usage only recently, there is insufficient data to assess statistically the anticipated improvement or potential failure mechanisms."

Both of these independent reports express uncertainty about truck wheel systems. The Transport Canada report suggests that current wheel systems may have reached the limit of their design and the Ontario Professional Engineers report cautions against unknown failure mechanisms related to hub-piloted wheels. The significance of these observations and the possible problems with hub-piloted wheels constitutes an emerging issue.

Warnings contained in wheel manufacturers safety and service manuals clearly state, in prominent warning boxes, that dirt and contamination including thin layers of paint (greater than 0.0035") can result in wheel separation. According to the wheel manufacturers, these seemingly innocuous factors can have a profound effect on road safety. One can only conclude that safety factors inherent in the design of all other vehicle related parts are greatly diminished in the current design of the hub-piloted wheel system. It would appear that the owners and drivers of these vehicles are being asked to take responsibility for a design that is at its limit or is insufficiently robust to compensate for such factors.

The Professional Engineers of Ontario report concludes that "liberal axle loading allowances and eccentric axle configurations have undoubtedly contributed to wheel separation" and the report recommends that "vertical and lateral wheel loads should be examined on the basis of Ontario weight and dimension regulations; the effect of these loads on trailer performance and highway deterioration should be examined." This analysis was never conducted.

Ontario axle loads are among the highest in North America. All trucks operating on the US Interstate System are limited to a tandem axle group weight of 15,455 kg (34,000 lb) or 1,982 kg (4,250 lb) per wheel. In Ontario, the allowable tandem axle load for the vehicle in question is 17,900 kg (39,380 lb) or 2,238 kg (4,923 lb) per wheel. Therefore, the wheels in Ontario are loaded up to 13% greater than those in the US. Given that there are at least 10 times as many trucks operating in the US than in Canada, it can be concluded that the major market for wheels is in the US. It may be that the relatively small jurisdiction of Ontario inadvertently allows the hub-piloted wheel system to be operated more closely to its design limit and therefore increases the risk of wheel separation. It may also follow that the higher wheel loads permitted in Ontario exacerbate the sensitivity of the hub-piloted wheel system to such factors as paint thickness.

CONCLUSIONS

1. Despite harsh penalties and the enforcement of absolute liability legislation for wheel separation incidents, wheel separation continues to be a significant problem within the province of Ontario.
2. The majority of the wheel separations are caused by fastener failures on hub-piloted wheels.
3. The legal method that the province of Ontario has used to deal with the wheel separation problem is poorly structured as it is based upon the assumption that the wheel systems are without fault and any failure is always the result of failure to exercise proper care and due diligence. Detailed investigations of the specific cases presented in this paper challenge this view.
4. The evidence presented in this paper clearly shows that truck wheel separation mechanisms and causal factors are not fully understood and that the hub-piloted wheel system is vulnerable to the loss of flange nut fasteners that back completely off of the studs.
5. Wheel fastener integrity and the risk of wheel separation are affected by hub-piloted wheel system temperature variations associated with vehicle braking or installation at very cold temperatures.

6. For hub-piloted wheels, it may be necessary to vary the applied wheel fastener torque to obtain the proper clamping force depending upon operating thermal variations, and the condition of flange nuts.

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