Accident Analysis and Prevention 41 (2009) 839–848

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A parametric study of golf car and personal transport vehicle braking stability and their deficiencies

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ARTICLE INFO

Article history:
Received 19 February 2009
Received in revised form 14 April 2009
Accepted 16 April 2009

Keywords:
Golf car
Low speed vehicle
Braking
Yaw stability
Downhill braking
Rollover

ABSTRACT

This paper describes research and parametric analyses of braking effectiveness and directional stability for golf cars, personal transport vehicles (PTVs) and low speed vehicles (LSVs). It is shown that current designs, which employ brakes on only the rear wheels, can lead to rollovers if the brakes are applied while traveling downhill. After summarizing the current state of existing safety standards and brake system designs, both of which appear deficient from a safety perspective, a previously developed dynamic simulation model is used to identify which parameters have the greatest influence on the vehicles' yaw stability. The simulation results are then used to parametrically quantify which combination of these factors can lead to yaw induced rollover during hard braking. Vehicle velocity, steering input, path slope and tire friction are all identified as important parameters in determining braking stability, the effects of which on rollover propensity are presented graphically. The results further show that when vehicles are equipped with front brakes or four-wheel brakes, the probability of a yaw induced rollover is almost entirely eliminated. Furthermore, the parametric charts provided may be used as an aid in developing guidelines for golf car and PTV path design if rear brake vehicles are used.

1. Introduction

1.1. Golf car accident statistics

It is estimated that there were, on average, approximately 13,000 golf car related injuries requiring emergency room treatment in the US per year from 2002 to 2007. The estimated number of accidents steadily increased from roughly 11,000 in 2002 to over 17,000 in 2007 (CPSC, 2007). Of these, approximately 10% (1300 per year on average) involved a car rollover and these accidents were typically more likely to cause injuries requiring a hospital stay than non-rollover accidents (CPSC, 2007). Of the cases where the location of the injury was reported, approximately 70% occurred at sports or recreational facilities (e.g. golf courses) while the remainder occurred at locations such as private homes or public streets, implying that personal transport vehicles (PTVs), which are often virtually indistinguishable from golf cars, are included in these estimates. In light of these statistics, rollovers represent a significant number of serious golf car and PTV related accidents, the reduction of which would significantly improve occupant safety (McGwin et al., 2008; O'Brien et al., 2005; Watson et al., 2008). As such, it is important to identify potential causes of rollovers as well as what can be done to reduce their frequency of occurrence.

1.2. Root causes of rollovers

Rollovers often occur when the driver loses control of the car while traveling downhill and applying the brakes (Annese, 2007; Contra Costa Times, 2007; Devanney, 2001; GreenvilleOnline.com, 2008; Journal Times, 2007; Zbrandt, 2007). As will be discussed in the remainder of this paper, this is often caused by the current industry practice of building golf cars and PTVs with brakes on only the rear axle wheels. It is obvious that a rear brake design (i.e. one with brakes only affecting the rear wheels) offers reduced braking effectiveness when compared to four wheel braking, particularly on a downward slope. This is partly because rear brake designs provide only half as many braked tires. Additionally, traveling downhill and decelerating both cause forward weight shift, which reduces the normal force, and thus the available traction, on the rear tires. Most importantly, a vehicle with skidding rear tires and rolling front tires is directionally unstable, resulting in a tendency of the vehicle to "fishtail" (i.e. rotate in the yaw direction) (Allen et al., 1991; Collins, 1979; Pacejka, 2006; Seluga and Ojalvo, 2006); this tendency is hereafter referred to as "yaw instability." These hazards have been understood for approximately 100 years and, as a result, four-wheel automo-

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doi:10.1016/j.aap.2009.04.017

tive brake designs have been in use just as long (Farwell, 1922; Loughead, 1923; Olen, 1934; Perrot, 1924; Schipper, 1922). The hazards of rear-wheel-only brakes are especially pronounced on steep slopes, slippery surfaces or at high speeds. On relatively level ground with good traction and at typical golf car speeds (i.e. less than 15 mph), this instability will not generally manifest itself in significant vehicle yaw rotations. However, as will be discussed below, this instability has the potential to present a serious rollover danger when any of these three conditions are not met.

Reduced braking effectiveness on a downhill slope can lead a driver to falsely perceive a brake problem, causing him to press harder on the brake pedal, thus locking the wheels and triggering the yaw instability. This hazard is aggravated at locations that incorporate hilly terrain, steep, narrow car paths, sharp turns and unpaved surfaces, as golf courses often do. The prevalence of such conditions makes it desirable to create golf cars with good braking characteristics (i.e. properly balanced brakes on all four wheels) for use on existing courses, many of which have downhill slopes of 10° or more. In addition to traditional golf cars that are driven on golf courses, many resort and retirement communities as well as local municipalities in the United States now allow golf cars, personal transport vehicles (PTVs) and low speed vehicles (LSVs) on streets as primary means of local transportation (IIHS, 2002, 2003; Passaro et al., 1996; Suhr, 2008). The same braking hazards are relevant to PTVs, which are often very similar, if not identical to, golf cars, as well as to LSVs when rear brake designs are employed.

1.3. Vehicle standards

Industry and government standards for the design of golf cars, PTVs and LSVs differentiate vehicles based on maximum level ground speed and intended usage, which can sometimes lead to confusing or ambiguous vehicle distinctions (see Table 1). For example, ANSI standard Z130.1-2004 "Golf Cars–Safety and Performance Specifications" (ANSI, 2004a) applies to vehicles "specifically intended for and used on golf courses for transporting golfers and their equipment", while ANSI Z135-2004 "Personal Transport Vehicles—Safety and Performance Specifications" (ANSI, 2004b) applies to vehicles "operated on designated roadways, or within a closed community where permitted by law or by regulatory authority rules" not including golf cars. As a result, a golf car used on a golf course is covered by ANSI Z130.1, but the same vehicle used elsewhere (e.g. a school campus), would be covered by ANSI Z135. This is a common circumstance as retired fleets of used golf cars are often resold for use at locations other than golf courses. Similarly, Federal Motor Vehicle Safety Standard (FMVSS) #500 "Low-speed vehicles," (US DOT, 2003) applies to 4-wheeled motor vehicles with a maximum speed of 32–40 kph (20–25 mph) operated on public roads.

None of the above-mentioned standards require four wheel brakes or dynamic downhill braking tests. The ANSI Z130.1-2004 standard for golf cars and ANSI Z135-2004 standard for personal transport vehicles (PTVs), Sections 9.6.4 and 9.7.4.1, respectively, state that service brakes must be capable of bringing the car to a stop from its top speed with an average deceleration between 0.27 and 0.50 g[1] with a brake pedal application force of no more than 556 N (125 lbs). This translates to a maximum allowable braking distance of 8–15 m (28–50 ft) on level ground from a top speed of 24–32 kph (15–20 mph), respectively. This test is conducted on a surface having a minimum tire–ground coefficient of friction of 0.8; however, the required braking deceleration is significantly lower than what could be easily achieved with brakes on all four wheels (i.e. 0.8 g on a 0.8 COF surface), or even with brakes on one axle. For comparison, at these speeds a typical passenger car with four wheel brakes would produce a braking distance of approximately 3–5 m (9–17 ft) on dry pavement. Furthermore, 0.8 is near the upper range of expected tire friction coefficient on dry pavement, and the actual available friction on unpaved or wet surfaces will be significantly lower; thus, cars in service will routinely encounter conditions significantly more demanding than those specified in ANSI braking tests. In addition, while these standards require that a vehicle's maximum speed not exceed a particular value on level ground, that speed can easily be exceeded when traveling downhill (E-Z-GO, 2005a,b). The dichotomy between golf car design standards, which specify dynamic braking tests on high friction level ground, and the often steep paved and unpaved golf car paths encountered in the field, leads to golf cars routinely being driven on terrain that is not addressed by the ANSI golf car standard.

Under Federal Motor Vehicle Safety Standard (FMVSS) #500 (low speed vehicles), the only braking requirement for low speed vehicles is that they must be equipped with a parking brake, defined as "a mechanism designed to prevent the movement of a stationary motor vehicle." This standard does not contain any explicit requirement for a braking system capable of stopping the vehicle while it is in motion, nor do any of the other FMVSS braking standards apply to LSVs. For comparison, FMVSS 135—Passenger Car Brake Systems, which applies to the braking performance of passenger cars under normal and emergency conditions, states in Part S5.1.; "Service brake system:. . .Each vehicle shall be equipped with a service brake system acting on all wheels."

ANSI Z130.1-2004 requires a warning label to be affixed to all golf cars stating "Drive slowly straight up and down slopes." However, it is highly foreseeable that drivers will sometimes not drive 'slowly' down hills or will be unable to regulate the car's speed due to ineffective brake performance (as discussed below). Therefore, it is prudent to provide a golf car braking system that can effectively and safely reduce the car's speed while traveling downhill at or above its maximum level ground speed.

1.4. Current brake designs

The great majority of the golf cars and personal transport vehicles (PTVs) currently produced by the major manufacturers (e.g. Yamaha, EZ-Go and Club Car) are equipped with brakes on only the rear axle wheels using either rear wheel drum brakes (Club Car, 2008a; E-Z-GO, 2005a,b), an internal means of braking the rear drive axle (Yamaha, 2006a,b, 2008) or an electric braking system in the case of some electric cars (E-Z-Go, 2007). In contrast, most low speed vehicles (LSVs) are equipped with brakes on all four wheels, and often make use of hydraulic brakes (Columbia, 2008; Elias, 1998; GEM, 2008; MILES, 2008; ZENN, 2008). In addition, many of the utility and transport vehicles (which are similar to golf cars) manufactured by the major golf car manufacturers are equipped with brakes on all four wheels either as standard or optional equipment (Club Car, 2008b; E-Z-Go, 2008; Yamaha, 2003, 2004). A summary of some of these vehicles and their brake system specifications is provided in Appendix A. Some golf

Table 1
Brief comparison of golf car, PTV and LSV safety standards.

	Max. speed kph (mph)	Location	Safety standard
Golf car	<24 (15)	Golf course	ANSI Z130.1
PTV	<32 (20)	"Designated roadways"	ANSI Z135
LSV	<40 (25)	Public roads	FMVSS #500

[1] It should be noted that the 1999 revision of ANSI Z130.1 required a minimum braking deceleration of 0.47 g, with no limit on the maximum allowable deceleration.