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Three Wheeled vs. Four Wheeled Turf Work Trucks

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ABSTRACT

Confusion and misconceptions regarding the utility and safety of turf work trucks are addressed in this paper. Sources of this confusion include media stories of related vehicles and advertisements. The maneuverability, including both turning ability and traction performance, as well as lateral-stability characteristics of three- and four-wheeled turf work trucks are evaluated based on experimental tests and mathematical models.

Experiments with the three most popular heavy-duty turf work trucks from Cushman® and Toro® show that the three-wheeled model maintains a distinct advantage over the four-wheeled models with respect to maneuverability in tight spaces as measured in clearance-circle tests. Traction-performance tests with these vehicles show there to be considerable variations in traction performance between vehicles, test conditions, and loading states.

The analyses of the lateral-stability characteristics of three- and four-wheeled turf work trucks, using a mathematical model, indicate that the optimum four-wheeled vehicle is more laterally stable than the three wheeler for equal track widths. However, among vehicles of equal clearance-circle performance, the optimum three-wheeled vehicle stability surpasses that of the four wheeler.

This paper continues with the analysis of the effects of a simple load on three- and four-wheeled vehicle stability which shows qualitatively different effects of loading on the two vehicle configurations. Finally, this paper evaluates the need for and implementation of a rollover protective structure (ROPS) system.

Among the conclusions reached is that both three- and four-wheeled turf work trucks are required to achieve all of the performance goals found in the workplace.

INTRODUCTION

Although intended primarily for turf-care applications, today's turf work truck has evolved and found its way into other uses which include farming, ranching, horticulture, and facilities maintenance. Its unique combination of payload capacity, maneuverability, and durability has made this vehicle indispensable for efficiently and economically performing many tasks. Due to its size, power, and maneuverability, it can work over, between, and around practically all outdoor terrain features which include grass, sand, trees, and grades. The turf work truck's large tires permit this vehicle to operate over manicured terrain without scarring the delicate surface. The turf work truck can carry over 900 kilograms (approximately 2000 pounds) of payload as well as provide a platform for power take off (PTO) torque, electric power, and hydraulic power for many

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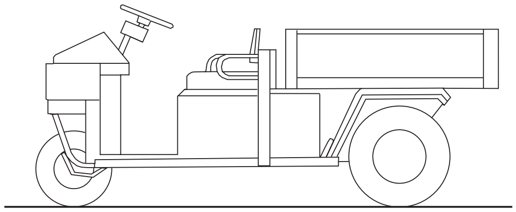

Figure 1. Cushman Turf-Truckster Model 630

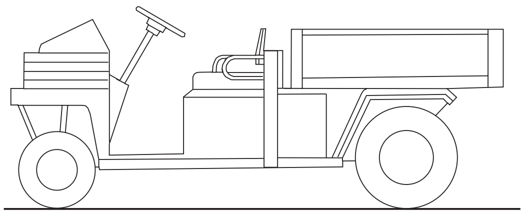

Figure 2. Cushman Turf-Truckster Model 632

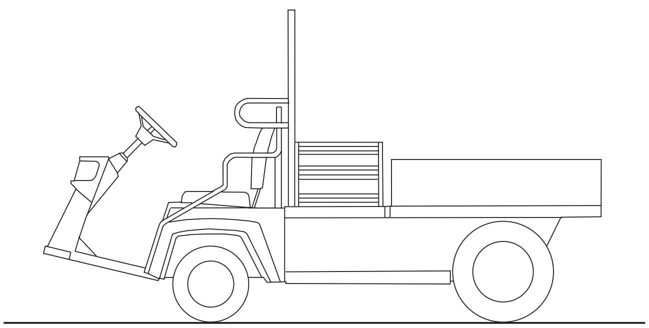

Figure 3. Toro Workman Model 3200

attachments. Implements and attachments used with turf work trucks include sprayers, spreaders, dressers, groomers, aerators, lifts, compressors, washers, and harvesters.

Not surprisingly, a variety of vehicle models are available among turf work trucks, each with its own set of characteristics. The most striking difference between models of turf work trucks is the number of wheels — some have three; others have four.

The three vehicles shown in Figs. 1, 2 and 3 represent the vast majority of commercial heavy-duty turf work trucks sold in the world today; the Cushman® three-wheel Turf-Truckster® (model 630), the Cushman four-wheel Turf-Truckster (model 632), and the Toro® Workman® (model 3200). Specifications from the manufacturers of these vehicles are contained in Table 1. All vehicles in the table are rear-wheel drive, gasoline powered, and liquid cooled although other engine options are available.

Turf work truck manufacturers have been using ASME/ANSI Standard B56.8 for personnel and burden carriers [1, 2] for guidance in the design and construction of these vehicles, although this standard is not fully applicable. A personnel and burden carrier is to operate “on indoor and outdoor improved surfaces” whereas turf work trucks usually operate on unimproved terrain and loose soil. An SAE standard (J2258) specifically for turf work trucks is scheduled for presentation in 1996. Considerable debate has arisen regarding the maneuverability and stability differences among turf work trucks, especially between the three- and the four-wheeled models. This paper addresses these characteristics. Also included are issues regarding turning ability, traction performance, lateral stability, vehicle loading, comparisons to other types of vehicles, and operator protection.

MANEUVERABILITY

Since turf work trucks operate in confined spaces, around trees and between sand traps for example, the ability to make tight turns can be a critical aspect in the use of these vehicles. These vehicles must also negotiate uneven, loose, and sloped terrain. Therefore, both clearance circle and traction are important considerations in the design of turf work trucks.

The tight turning maneuverability of the three aforementioned heavy-duty turf work trucks are experimentally determined through measuring the outside clearance-circle diameter for each vehicle. This is an industry metric for measuring turning ability of a vehicle. The results of these tests are summarized in Table 2.

Table 2. Clearance-circle diameters for turf work trucks

#	Vehicle	Diameter		
1	Cushman 3 Wheel	200”	(16’-8”)	5.08 m
2	Cushman 4 Wheel	260”	(21’-8”)	6.60 m
3	Toro 4 Wheel	250”	(20’-10”)	6.35 m

The clearance-circle diameter of the Cushman three wheeler is 5.08 m at the outermost point of its body. The corresponding clearance circle of the Cushman four wheeler is 6.60 m; the Toro produces a clearance circle of 6.35 m. Figure 4 clearly illustrates the superior turning capability of the three-wheeled vehicle over either of its four-wheeled counterparts. The clearance-circle diameters of the Toro and Cushman four wheelers are 25% and 30% larger, respectively, than that of the three wheeler. This demonstrated turning advantage no doubt contributes to the popularity of the three wheeler.

The first set of traction tests performed was a static-obstruction experiment in which the front wheels of the turf work trucks are positioned up against a common parking-lot stop whose

Table 1. Manufacturer specifications for turf work trucks

#	Vehicle	Model	Wheels	Overall Length	Wheelbase	Rear Track	Base Weight	Max. Weight	Engine Power	Engine Displ.
1	Cushman Turf-Truckster	630	3	2.57 m (101 in)	2.0 m (78 in)	1.3 m (50.5 in)	557 kg (1228 lbs)	1695 kg (3728 lbs)	20 kW (27 hp)	846 cc (51.6 ci)
2	Cushman Turf-Truckster	632	4	2.76 m (109 in)	2.1 m (84 in)	1.3 m (50.5 in)	612 kg (1350 lbs)	1795 kg (3950 lbs)	20 kW (27 hp)	846 cc (51.6 ci)
3	Toro Workman	3200	4	3.38 m (133 in)	1.8 m (70 in)	1.2m (47.75 in)	636 kg (1400 lbs)	1814 kg (4000 lbs)	20 kW (27 hp)	657 cc (40 ci)

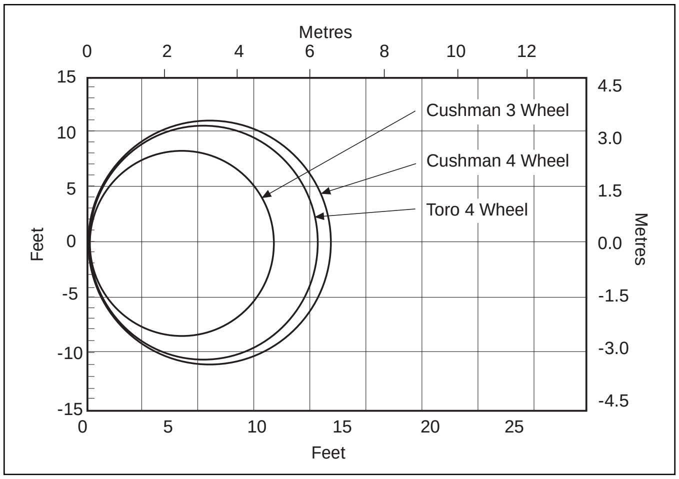

Figure 4. Clearance circles for turf work trucks

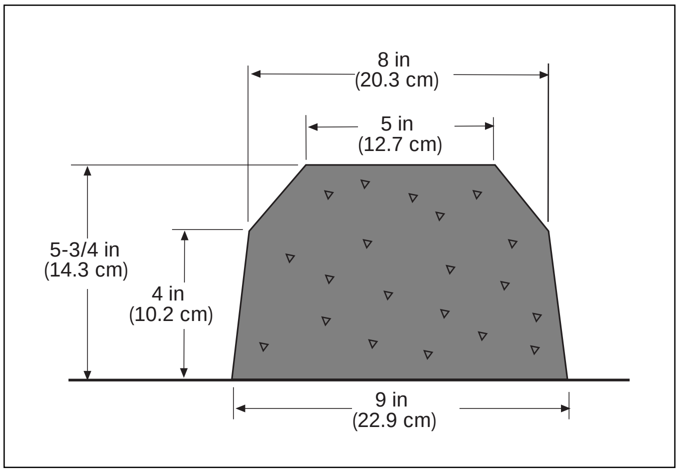

Figure 5. Cross sectional view of static obstacle for traction tests

cross section is shown in Figure 5. The turf work trucks then attempt to climb the stop in both unloaded and loaded states. The load used during the testing is 2000 pounds (909 kilograms) of uniformly distributed sand.

A second set of tests measured the traction of turf work trucks on a large tilt table. The tilt table used measures 4.6 m x 4.6 m (15 ft x 15 ft). In these tests, a cable is attached to each vehicle at axle height to restrain the vehicle as it pulls on the cable which is parallel to the tilt table surface. The cable tension upon the start of tire slip is recorded for unloaded and loaded vehicles with the tilt table level and with it inclined to a 30% (16.7°) grade. Inclined tests were conducted to measure cable tension for turf work trucks attempting to climb the tilt table both in forward and in reverse gears.

The results from the first set of traction tests are contained in Table 3. Since the Toro comes equipped with a locking differential, the Toro is tested in two states — with the differential unlocked and with the differential locked.

Table 3. Results of forward static-obstacle traction tests

#	Vehicle	Unloaded	Loaded
1	Cushman 3 Wheel	Climbed	Climbed
2	Cushman 4 Wheel	Climbed	Climbed
3	Toro (Differential Unlocked)	Not Climbed	Climbed
4	Toro (Differential Locked)	Not Climbed	Climbed

These results indicate that the two unloaded Cushmans are able to climb the obstacle on blacktop while the unloaded Toro cannot. When the Toro is tested with its differential in the unlocked position, one drive wheel spins; when tested with the differential in the locked position, both drive wheels spin. All vehicles can negotiate the obstacle when they are loaded with the sand. None of the vehicles is able to climb the obstacle in reverse gear when the tests are repeated regardless of whether or not they are loaded with the sand.

The results of the second set of tests are listed in Tables 4, 5, and 6 which show the data from the forward-gear level, forward-gear inclined, and reverse-gear inclined tests, respectively. These numbers are the arithmetic means of several measurements. The traction test results on the level tilt table shown in Table 4 indicate that, in both unladen and laden states, the Cushman four wheeler has the largest pulling capability. The Cushman three wheeler has greater pull than the Toro when loaded and, on average, the same as the Toro when unloaded. The Toro did not have the torque to slip both wheels and engine stall resulted when the differential was locked and the vehicle was loaded. Although the Toro wheels did not slip, the cable tension was comparable to the unlocked differential tension.

Table 4. Results of tilt-table traction tests — forward and level.

#	Vehicle	Unloaded	Loaded
1	Cushman 3 Wheel	4.1 kN (927 lb)	11.7 kN (2625 lb)
2	Cushman 4 Wheel	5.1 kN (1153 lb)	12.3 kN (2775 lb)
3	Toro (Differential Unlocked)	4.0 kN (900 lb)	10.2 kN (2290 lb)
4	Toro (Differential Locked)	4.2 kN (943 lb)	Stalled

Table 5. Results of tilt-table traction tests — forward and inclined

#	Vehicle	Unloaded	Loaded
1	Cushman 3 Wheel	2.6 kN (587 lb)	4.8 kN (1080 lb)
2	Cushman 4 Wheel	2.9 kN (643 lb)	5.7 kN (1283 lb)
3	Toro (Differential Unlocked)	2.3 kN (516 lb)	5.0 kN (1130 lb)
4	Toro (Differential Locked)	2.5 kN (567 lb)	Stalled

Table 6. Results of tilt-table traction tests — reverse and inclined

#	Vehicle	Unloaded	Loaded
1	Cushman 3 Wheel	2.4 kN (547 lb)	3.8 kN (847 lb)
2	Cushman 4 Wheel	1.6 kN (350 lb)	4.6 kN (1023 lb)
3	Toro (Differential Unlocked)	0.4 kN (87 lb)	2.2 kN (490 lb)
4	Toro (Differential Locked)	0.4 kN (83 lb)	2.5 kN (570 lb)

Table 5 shows the results from the forward-gear tests on the inclined tilt table. The Cushman 4 wheeler has the highest pulling ability among tested vehicles. The Toro has greater pull when loaded in this situation than does the Cushman three wheeler. When unloaded, the Cushman three wheeler is slightly better than the Toro. The Toro, in this test program, experiences engine stall when the vehicle is loaded and the differential is locked.

The results from tests in which turf work trucks attempt to back up an inclined tilt table are contained in Table 6. Here the Cushman four wheeler is capable of the greatest pulling performance among loaded vehicles. The Cushman four wheeler is followed by the Cushman three wheeler and the

Toro. When unloaded, however, the Cushman three wheeler produces the largest pull followed by the Cushman four wheeler and then the Toro. The values of cable tension for the unloaded Toro are quite small compared to the other two turf work trucks. The difference between these two values of Toro pulling performance is negligible.

The coefficient of friction μ for each surface was calculated, using experimental measurements, by the following formula where W is the weight of a stationary turf work truck with locked wheels and F is the maximum tension developed in a horizontal cable attaching a turf work truck to a tug vehicle which slowly pulls on the turf work truck until sliding takes place.

$$\mu = \frac{F}{W} \tag{2.1}$$

Several measurements of force were used to calculate mean values for F. The resulting coefficients of friction between the turf work truck tires and the traction test surfaces are 0.86 for the blacktop and 0.87 for the tilt table. These surfaces were chosen for testing since repeatability would be much better than with using a soil or grass surface.

The overall results of the traction tests conducted indicate that the Cushman four wheeler has the greatest traction and pulling capacity. The Cushman four wheeler is followed in traction by the Cushman three wheeler in almost every case. The Toro comes in last. When loaded and restrained, the Toro is prone to stall when the differential is locked even with the transmission in first gear and low range. The unloaded Toro also develops cable-pull values which were substantially smaller than either of the other two unloaded turf work trucks under the reverse-gear condition. Although the locking differential is intended to increase traction, the results of these tests show little if any difference between the unlocked and locked differential traction measurements. It should also be mentioned in this discussion of traction and pulling capability that Table 1 shows the Toro to have the largest maximum vehicle weight of the three vehicles tested while possessing the smallest engine in terms of displacement.

It is not difficult to imagine an unloaded turf work truck encountering an obstructed downhill path requiring the vehicle to reverse its course and back up the uphill slope. This scenario could pose a problem to the Toro with its limited traction. The obvious solution to the clear weight-distribution problem and two-wheel drive (2WD) is the four-wheel drive (4WD) option available for this vehicle. Although the 4WD Toro was not tested in either turning or traction tests, its manufacturer states that the 4WD vehicle "turning geometry" is reduced to 50° from the 2WD turning geometry of 70° [3]. Therefore, an increase in traction comes at the expense of turning ability.

The results of the traction tests are important to the issue of maneuverability since many turf work truck operations involve traversing loose or sloped terrain in addition to turning within confined areas. Therefore, both maneuverability and traction are elements which must be taken into consideration for the most effective use of turf work trucks.

STABILITY

Stability of a vehicle is an important aspect of the overall safety of the vehicle/operator/environment system. There are several types of vehicle stability. Longitudinal stability involves a vehicle's behavior under the influence of forward and rearward accelerations. Lateral stability involves vehicle responses under lateral accelerations which may ultimately lead to spin out or vehicle tipover. Only lateral stability is studied in this paper. This is because longitudinal stability is not viewed as a problem with turf work trucks and because there may be significant variations in longitudinal stability characteristics existing between turf work trucks based solely on the particulars of the design, load, and terrain.

The debate on lateral stability appears to be clearly drawn along the lines of the three-wheeled vehicle versus the four-wheeled vehicle. In fact, one manufacturer of turf work trucks has advertised that almost 80 percent of rollover accidents recalled by golf course superintendents involve three-wheeled vehicles [4]. Since this statistic is not weighted to account for the preponderance of three-wheeled turf work trucks already in service, this number provides no meaningful information regarding the relative stabilities of the three and four wheelers and is misleading. The same advertisement, on the other hand, also acknowledges the need for the maneuverability provided by a three-wheeled turf work truck.

Two cases of lateral stability will be investigated here. The first case compares three- and four-wheeled vehicles having equal compactness defined by track width. The second case compares three- and four-wheeled vehicles having equal maneuverability defined by clearance-circle diameter. The compactness of a turf work truck is important not only in the operation of the vehicles in narrow passageways, but also in their off-season storage where less compact vehicles would require greater storage space. The importance of the clearance circle has already been discussed.

In order to evaluate the relative stabilities of comparable three- and four-wheeled turf work trucks, a theoretical static model is developed. Top views of the vehicles, together with their important parameters are shown in Figures 6 (A) and 6 (B). Rear views of the three- and four-wheeled vehicles in left-hand turns appear as Figures 6 (C) and 6 (D), respectively.

Since the equal compactness case is studied first, it is assumed that both vehicles share the same wheelbase L and the same trackwidth T. The stability analyses in this case show that a smaller-magnitude side force vector $\overline{F}$, resulting from lateral acceleration, is necessary to upset the three-wheeled turf work truck than is necessary to upset the four wheeler assuming that both vehicles also share the same center-of-gravity height H.

Figures 6 (C) and 6 (D) which show rear views of the three- and four-wheeled vehicles, respectively, and the forces acting in the transverse vertical plane on those vehicles as the inside wheels begin to lift off and lose contact with the ground. (The tire-force vectors in these figures are idealized in the figure as acting at a single rear wheel.) The gravitational acceleration acting on the vehicle centers of gravity are vectors $\overline{W}$ and

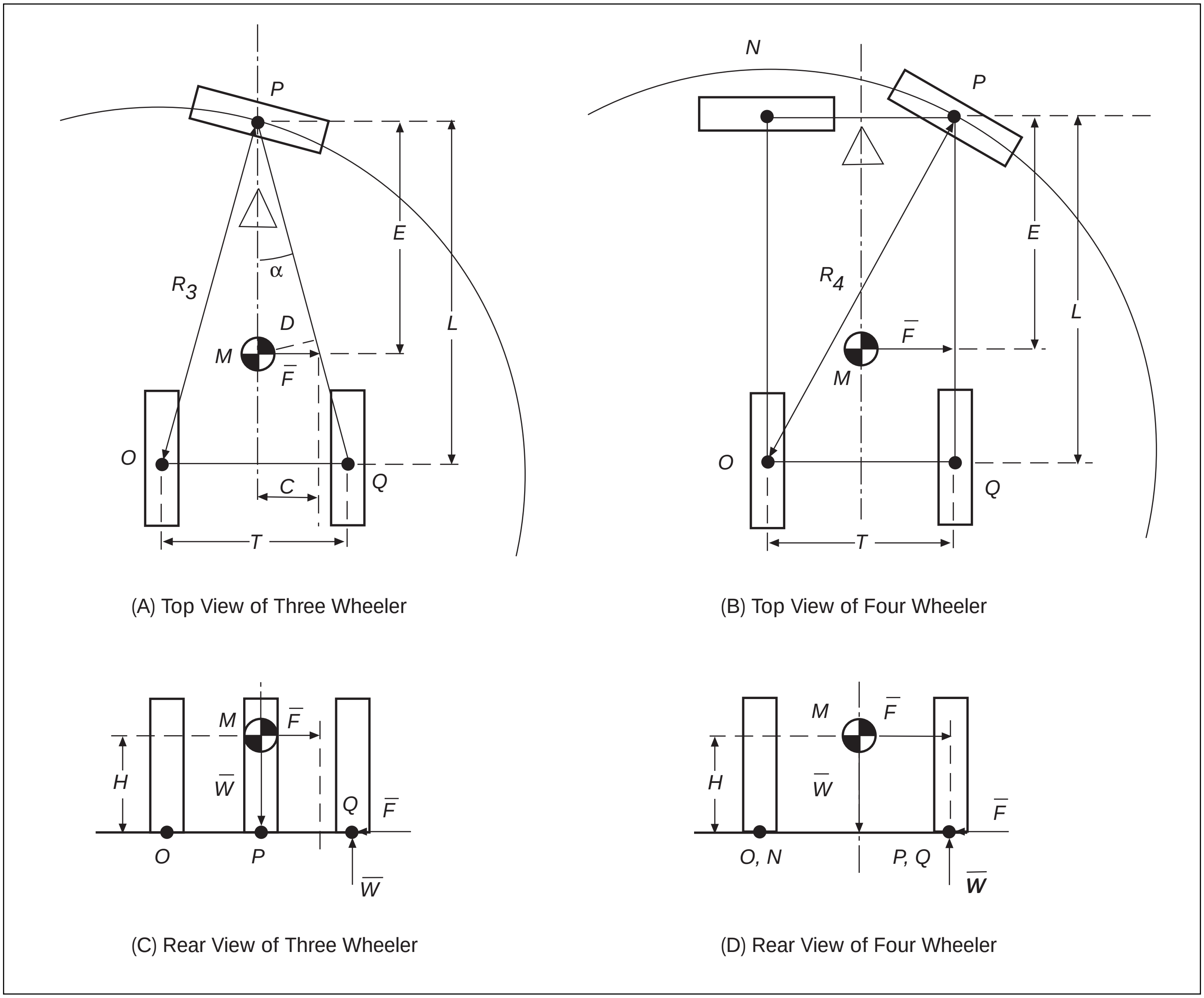

Figure 6. Views of three- and four-wheeled vehicles

function as the restoring forces. For the purposes of these analyses, it is assumed that the distance rearward of the vehicle centers of gravity is two-thirds of the wheelbase. Thus,

$$E = \frac{2}{3}L \tag{3.1}$$

For the three wheeled vehicle,

$$\frac{C}{2/3\,L} = \frac{T/2}{L} \tag{3.2}$$

$$C = \frac{T}{3} \tag{3.3}$$

Here, the vehicle will not tip if the restoring moment about the line $\overline{PQ}$, WD, is greater than the overturning moment, $HF \cos \alpha$. Thus,

$$WD \geq HF \cos \alpha \tag{3.4}$$

$$WD = WC \cos \alpha = W\frac{T}{3} \cos \alpha \geq HF \cos \alpha \tag{3.5}$$

$$(F)_{3-Wheel} \leq \frac{TW}{3H} \tag{3.6}$$

In the case of the four-wheeled vehicle, the restoring moment about the line $\overline{PQ}$ is $WT/2$; the overturning moment is HF. The vehicle will remain stable if

$$W\frac{T}{2} \geq HF \tag{3.7}$$

or

$$(F)_{4-Wheel} \leq \frac{TW}{2H} \tag{3.8}$$

Comparing the maximum achievable side forces, we find a 50% advantage for the four-wheel truck; thus,

$$(F)_{4-Wheel} = \frac{3}{2}(F)_{3-Wheel} \tag{3.9}$$

when the track widths, the weights and the heights of the centers of gravity are equal. Of course, both vehicles will have to be designed with sufficient lateral stability to perform safely; this absolute criterion is normally provided by a code or standard.

The stability comparison of three- and four-wheeled turf work trucks continues with the analyses of vehicles with equal clearance circles. In doing these analyses, it must be realized that the limiting case in turf work truck maneuverability is that in which the vehicle pivots about one of its rear wheels thereby producing the smallest clearance-circle diameter possible. If it is assumed that there is no chassis overhang beyond the wheels of the vehicle, the clearance circle becomes the turning circle which is the circle made by the outermost wheel of the vehicle. Figures 6 (A) and 6 (B) show the Ackerman geometry needed for steering the vehicle front wheels in the three- and four-wheel cases, respectively. The radius of the turning circle for a left-hand turn will be the distance from the inner wheel, represented by point *O*, to the front wheel or outside front wheel, represented by point *P*.

Given the present assumptions of equal wheelbase and track width, the diameter of the three wheeler's clearance circle will be smaller than that of the four wheeler since the minimum clearance-circle radii for the three and four wheelers are limited to R_3 and R_4, respectively, where

$$R_3 = \sqrt{\left(\frac{T}{2}\right)^2 + L^2} \tag{3.10}$$

$$R_4 = \sqrt{T^2 + L^2} \tag{3.11}$$

Therefore,

$$R_3 < R_4 \tag{3.12}$$

The inequality is even stronger in practical situations since the four wheel truck cannot achieve the sharp turn depicted in Fig. 6 (B).

Now, the stability of the three wheeler is investigated for the case in which it has the turning ability of the four wheeler as measured by the clearance circle. If the turning ability of the three wheeler is made equal to that of the four wheeler by widening the track width *T*, then the following is the result if all other parameters remain constant: setting $R_3 = R_4$, the new track width T' of the wider three wheeler increases to $2T$.

$$T' = 2T \tag{3.13}$$

When T' is used in Eq. 3.6 for the three-wheeled vehicle the comparison to Eq. 3.8 becomes

$$(F)_{3-Wheel} = \frac{4}{3}(F)_{4-Wheel} \tag{3.14}$$

Thus, the three-wheeled turf truck has 1/3 greater lateral stability than the four wheeler when their turning capacities are equal. This result is valid whenever the turning radius $R_3 \geq T'$; otherwise, the clearance-circle radius is governed by T' rather than R_3. This implies that

$$\sqrt{\left(\frac{T'}{2}\right)^2 + L^2} \geq T' \tag{3.15}$$

or

$$T' \leq \frac{2}{\sqrt{3}}\,L = 1.155\,L\ (very\ wide\ vehicle) \tag{3.16}$$

or

$$\alpha \leq 30^o \tag{3.17}$$

Shown here is that among equal width turf work trucks, the four wheeler will be more stable than the three wheeler on a level surface. Therefore, the four-wheeled turf truck should be selected unless a tight turning radius is crucial for an application; in this situation, an equal-width three wheeler should be chosen for maximum effectiveness on the job. This being the case, manufacturers should continue to provide both three- and four-wheeled vehicles to customers. It was also shown that a three-wheeled turf work truck is more stable than a comparably steering four-wheeled vehicle.

The analyses presented are based upon simple models not on experimental tests. These models assume rigid-vehicle steady-state motion by neglecting the relative-roll angle between sprung and unsprung masses as well as tire deflections. There are also several practical issues which restrict the widths of vehicles as well as feasible steering geometries used on vehicles. These factors notwithstanding, the models and analyses remain illustrative. In addition, operator decisions and subsequent actions further complicate the issue of real world tipover analysis as do terrain effects. These effects were not analyzed here.

EFFECTS OF VEHICLE LOADING

The versatility of the modern turf work truck has already been mentioned as a recognized feature of this vehicle. There exist a wide variety of attachments and implements available to the owner of the turf work truck which further add to the utility of the vehicle. Each piece of equipment is different and brings with it unique characteristics such as weight and position with respect to the vehicle which can significantly alter the behavior of the vehicle carrying or pulling the equipment. Therefore, it is impossible to generalize the effects of all types of equipment on the handling and stability of all vehicles. It is possible, however, to analyze the primary qualitative effects of one simple, yet common, type of loading on the stability of three- and four-wheeled turf work trucks.

The loading investigated herein consists of a heavy, rigid, homogeneous solid placed in the cargo beds of three- and four-wheeled turf work trucks. These two vehicles are shown in Figure 7 (A) and (B) with identical wheelbases and track widths. The centers of gravity (CGs) for the unloaded vehicles are represented by points *A* which shift rearward to points *B* as the loads are added to the beds of the vehicles.

Assuming that no changes other than rearward shifts in CG take place in these vehicles when loaded, the static stabilities of the two vehicles are affected in different ways. In the case of the four wheeler shown in Figure 7 (A), the lateral stability

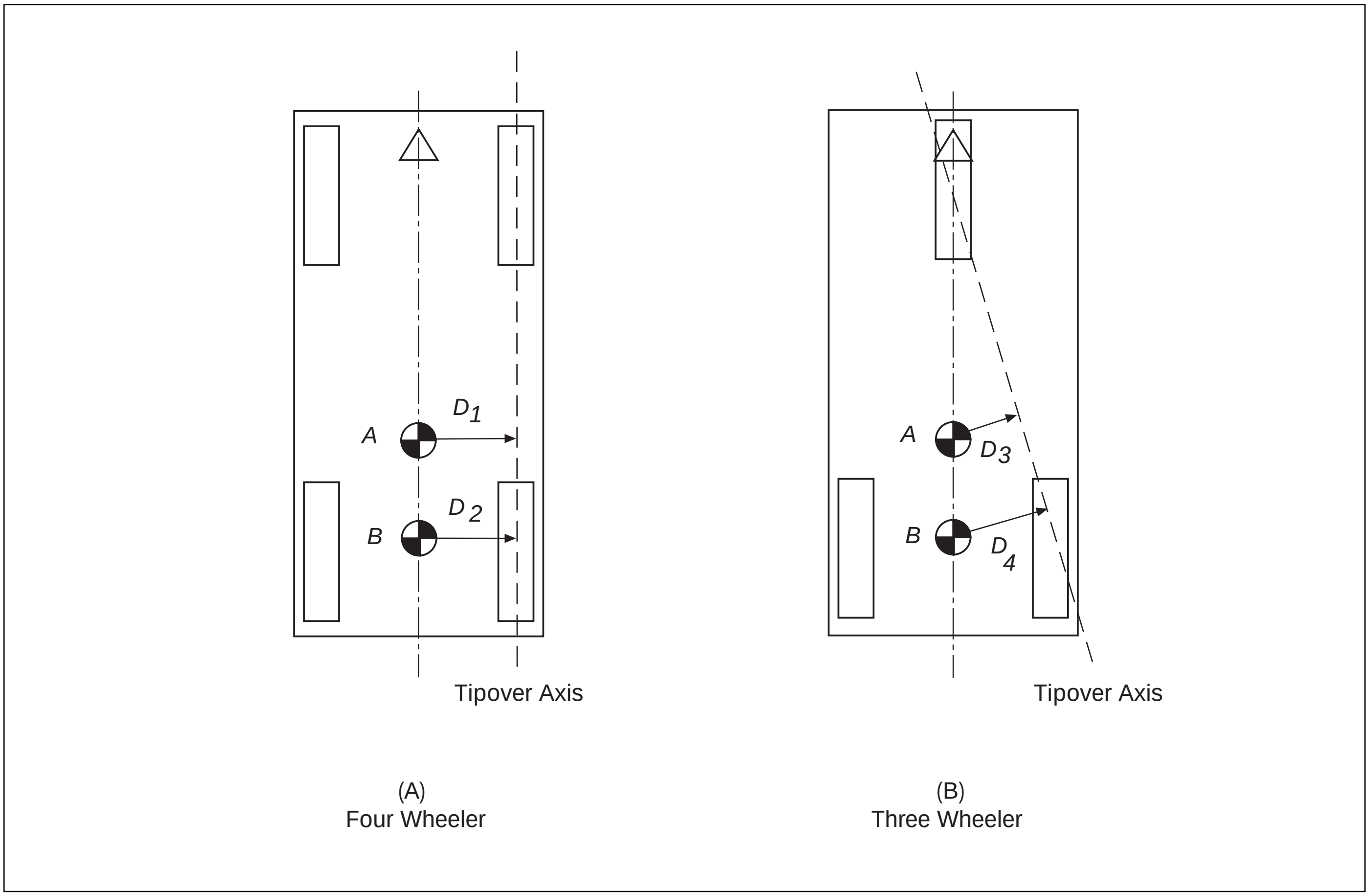

Figure 7. Effects of vehicle loading on four- and three-wheeled vehicles

is affected only in the restoring force, represented by vector $\overline{W}$ in Figure 6 (D). This is because as the CG of the four wheeler shifts rearward from *A* to *B*, the distance from the CG to the tip-over axis remains constant since $D_1 = D_2$. In the case of the three wheeler shown in Figure 7 (B), however, not only is the restoring force, represented by vector $\overline{W}$ in Figure 6 (C), increased, but the moment arm *D* through which the restoring force acts increases as well. It is clear that as the three wheeler CG moves from *A* to *B* the distance from the CG to the tip-over axis increases from D_3 to D_4.

Therefore, the stability effects of loading a three-wheeled vehicle are qualitatively different than those of a four-wheeled vehicle. While the loading of the four-wheeled vehicle portrayed in this example led to no change in its static stability, the loading of a three-wheeled vehicle did improve its static stability when changes in CG height are neglected.

TIPOVER PROTECTION

Because of significant factors beyond the designer's control, such as uneven and sloped terrain and operator actions, tipover accidents will continue to take place with both three- and four-wheeled vehicles. Having recognized that all vehicles can tip over, many researchers have directed their efforts regarding forklift trucks, agricultural tractors, and other specialty vehicles to the design and analysis of rollover protective structure (ROPS) systems [6, 7]. Among the chief conclusions of this work is that a ROPS system should not compromise operator safety by itself becoming a hazard. A ROPS system can injure or kill an operator of a vehicle in a tipover situation if the operator leaves the protective zone provided by the ROPS and becomes pinned between the vehicle and the ROPS. On unimproved surfaces, most researchers recommend the use of seat belts to protect the occupants from the crushing hazard associated with ROPS. Because seat belt usage remains low, we still face the following dilemma: Is it better to provide no ROPS protection or to provide ROPS knowing that seatbelt usage is low?

Another phenomenon has been studied extensively on improved surfaces — the "flyswatter effect." The use of a seatbelt propels an operator's head laterally at higher speeds than those associated with freefall. Where a restrained operator can contact a concrete slab, for example, the Head Injury Criterion (HIC) numbers for seatbelted operator's are usually in the range of devastation. Fortunately, turf work trucks do not face this difficult problem because they usually work on unimproved terrain.

A ROPS system has an adverse affect on the static stability of a vehicle by raising its center of gravity. Furthermore, ROPS and seatbelts compromise visibility.

An objective analysis of the need for a ROPS system is necessary if such a system is not required by local or national standards and regulations. A suitable method of safeguard evaluation should be employed [8] to assess the benefits and downsides of ROPS systems.

CONCLUSIONS

The maneuverability tests using the clearance circle clearly indicate the superiority of the three-wheeled turf work truck to either version of the four wheelers studied. The traction tests show significant differences in climbing and pulling performance between various turf work trucks which would affect vehicle maneuverability. However, for these traction tests, the differences are apparent between the two four-wheeled vehicles tested and not between three- and four-wheeled vehicles in general. The locking differential which is used to solve traction problems makes no discernible difference in traction performance on dry, hard surfaces. The other ready solution to the traction problem, four-wheel drive, significantly reduces the turning performance according to the manufacturer of the vehicle studied.

The stability analyses of three- and four-wheeled vehicles show that the four-wheeled vehicle has an advantage over the three-wheeled vehicle when measured in terms of equal compactness or width. Although a three wheeler can be made significantly more stable than an equally maneuverable four wheeler according to theory, there may be practical reasons why such designs cannot be pursued.

The qualitatively different effects of vehicle loading on three wheelers and four wheelers were demonstrated in an example. A simple load is added to the analytic models of three- and four-wheeled vehicles to show that only the restoring force is increased in the four-wheel case, while for the three-wheel case, both the restoring force and the moment arm through which the restoring force acts are increased.

The findings of this paper indicate that manufacturers of turf work trucks should continue to provide both three-wheeled or four-wheeled models to their customers to accomplish all of the required tasks. The two configurations of turf work trucks must be seen as complementary designs, not as competing designs.

Overseers of turf-work-truck operations should persist with the employment screening, training, and supervision of operators necessary for the most effective and safest utilization of these vehicles. Because the turf work truck is a versatile vehicle which must operate in a wide variety of configurations and environments, it is impossible to design a machine that will be immune to tipover accidents. For this reason the ROPS must continue to be studied as a possible candidate for minimizing the adverse consequences of rollover accidents.

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