Off-road Vehicle Rollover and Field Testing of Stability Index

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Abstract

Off-road vehicles are often operated in unstable situations and on rough terrain where operators may be subjected to high-risk conditions. Tractor stability and the reduction of injuries related to tractor rollovers are areas that need to be addressed.

This article presents typical tractor rollover tests and analyzes tractor stability in terms of the stability index developed by authors. Three radio-controlled tractors were used to complete the tests. Tractors' dynamic state variables, such as roll and pitch angles, roll and pitch velocities, and ground speed, were recorded by the measuring system of tractor stability developed by authors, concurrently the image from videotape was used to identify the stability status of the tractors.

The effect of velocity, ramp height, slope, and turning radius on tractor stability was studied. Rotation velocities can also significantly contribute to tractor rollover. The results indicate the validity of the stability index model.

Keywords. Tractor safety, Off-road vehicle stability, Overturn, Field tests.

Tractor accidents and costs resulting from them have been reported and statistically studied by official agencies and institutes. Among tractor-related accidents, tractor overturns are the largest portion of fatal tractor accidents, accounting for approximately one-third to one-half of all fatal injuries but only constituting about 5 to 10% of total nonfatal farm injuries (Murphy, 1990, 1992). Pratt, Kisner and Helmkamp (1996) pointed out that tractors had both the highest frequency and fatality rate of all machinery types, according to the National Traumatic Occupation Fatalities (NTOF) surveillance system of the National Institute for Occupational Safety and Health (NIOSH) from 1980 to 1989. From 1985 to 1989, tractor overturns averaged 49% of all tractor fatalities (National Safety Council, 1990). According to the National Safety Council (1996), tractor overturns accounted for an average of 51% of tractor-related fatalities from 1985 to 1995, with an annual rate of 5.4 deaths per 100,000 tractors in 1995.

Tractor rollover tests have been used to investigate tractor overturns and validate mathematical models. Davis and Rehkugler (1974) designed a physical one-twelfth scale-model of a tractor with ROPS to verify their mathematical model, and investigated the procedure for the accurate recording of three-dimensional motions for subsequent analysis. The scale-model study of wheel-tractor overturn was to

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provide data for systems having variable values with the range of both the physical model and prototype, and to predict the prototype response. Using a mirror, a three-dimensional view of the scale-model tractor-terrain system was built. They used a high-speed movie camera and grid arrangement to record the tractor overturning motion. In their study, the verification of the mathematical model was provided by comparing the tractor motions predicted by the digital computer simulations to those observed experimentally for the equivalent model tractor and terrain condition. Wray and Kamm (1977) and Wray and Kwitowski (1983) considered the pitch and roll angles of a front-end loader as input in a model to calculate the position of a front-end loader and to develop a criterion of stability and a simplified overturn indictor (stability indictor) incorporating speed and/or acceleration effects.

Uneven ground and complicated terrain play important roles in causing a tractor overturn. A steep slope is a critical factor for tractor stability. Whitaker (1973) pointed out that half of the tractors lost control while sliding down a hillside before overturning. According to Willsey and Liljedahl (1969), among 145 cases studied 120 were side overturns, 21 rear overturns, and four were front overturns.

The reality of the above crucial facts has prompted government agencies, researchers and engineers to investigate the causes of tractor rollover and to develop proper methods to assess the stability of agricultural tractors. NIOSH and its partners in the public and private sectors have developed the National Occupational Research Agenda (NORA) to provide a framework to guide occupational safety and health research into the next decade.

A quantitative value referred to as a stability index and a relevant measuring system have been developed from tractor physical operating conditions and tractor dynamics (Liu et al., 1995; Liu and Ayers, 1996, 1997, 1998; Liu, 1998). The authors have investigated the principle of a tractor rolling over using video technology and full-size radio controlled tractors. Based on tractor center of gravity, wheelbase, tread width, body angles, rotation velocities, turning radius, ground speed, static and dynamic stability index models were developed. To evaluate the stability index concept, 35 field tests were conducted on variety of slopes and operating conditions at the Agricultural Engineering Research Center, Colorado State University.

This article presents typical tractor rollover tests, and analyzes tractor stability in terms of the stability index developed by the authors. Typical tractor overturn tests were conducted in accordance to ASAE S519. Three radio-controlled tractors were used to complete the tests. Tractors' dynamic state variables such as roll and pitch angles, roll and pitch velocities, and ground speed, were recorded by the measuring system of tractor stability. Concurrently the images from videotape were used to identify the tractor stability status. The effect of velocity, ramp height, and slope on tractor stability was studied.

Tractor Stability Index

The actual status of a moving tractor on a slope can be simplified into a stationary tractor with a dynamic action applied. Based on an energy point of view, the tractor may be overturned by its kinetic energy. When the tractor is excited by either traveling over uneven ground or sharply turning to cause the rotations around a tipping axis, the tractor's kinetic energy must be transferred into other kinds of motions or energy. It may accelerate the tractor, or may be transferred into potential energy. The latter can result in a rise of the center of gravity of the tractor and the angular displacements such as roll and pitch angles. Particularly, when the tractor's kinetic energy about a tipping axis is large enough to raise the center of gravity to a static critical angle, the tractor overturn is likely. In terms of the directional axis system (fig. 1) used to analyze tractor kinematics and dynamics, the tractor static and dynamic stability indices were defined (Liu, 1998). The physical tractor characteristics and the stability models produce an index from 0 to 100. A stability index of 100 indicates the highest stability in which a tractor may be stationary or move at a constant velocity on level ground. A stability index of 0 indicates a tractor operating under conditions where an upset or instability is likely. They can be principally expressed by a static stability index SI. Multiplying by a dynamic factor $U_d(t)$ produces the dynamic stability index, SI′(t),

$$SI = \left(1 - \frac{U}{U_{cri}}\right) \times 100$$

$$SI'(t) = SI \times U_d(t) \qquad (1)$$

where U is a state variable, U_{cri} is a threshold of the state variable, and $U_d(t)$ is a dynamic factor depending on a variation of rotation kinetic energy of the tractor. Because the rotational kinetic energy is a second-order function of a rotating velocity around an axis, so the $U_d(t)$ is defined as:

$$U_d(t) = 1 - \left(\frac{U'}{U'_{cri}}\right)^2 \qquad (2)$$

where U′(= ω) is a rate of state variable with respect to time, and can be determined by following equations with respect to X, Y, and Z axes, respectively,

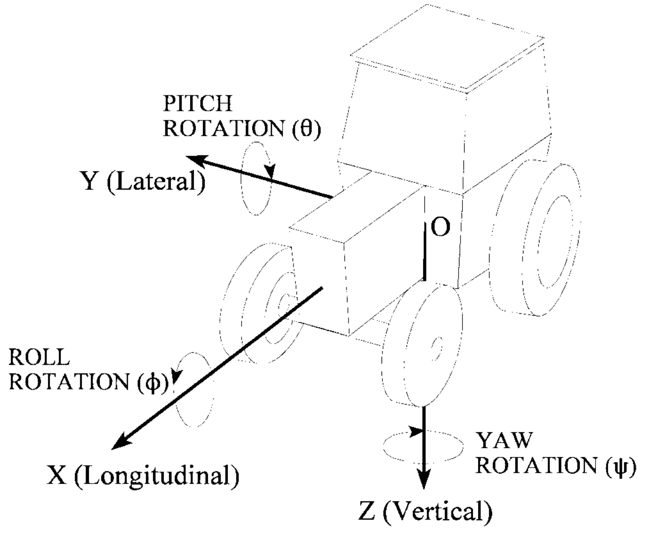


Figure 1–Definition of variables describing vehicle motion in three dimensions.

$$\omega_{xx} = \phi' = \frac{d\phi}{dt} \quad \text{(X axis)}$$

$$\omega_{yy} = \theta' = \frac{d\theta}{dt} \quad \text{(Y axis)} \qquad (3)$$

The U_{cri}' is defined as a critical rate of the state variable of the tractor on a slope. Based on the balance of mechanical energy, the value of the critical rate will be derived in different cases. For a tractor lateral stability, if roll angle and velocity are measured, then a static lateral stability index, defined as SI_{LATS}, and its dynamic index, defined as SI_{LATS}', can be calculated by the equation:

$$SI_{LATS} = \left(1 - \frac{\phi}{\phi_{cri}}\right) \times 100$$

$$SI_{LATS}' = \left(1 - \frac{\phi}{\phi_{cri}}\right)\left[1 - \left(\frac{\phi'}{\phi'_{cri}}\right)^2\right] \times 100 \qquad (4)$$

Similarly, a longitudinal stability index of the tractor can be calculated. A summary of stability indices is presented in table 1. Full development of the stability index approach is found in Liu (1998).

Tests and Equipment

Tractor stability is affected by many factors, and it is very complicated if all of the variables are considered in a model. Consequently, several major variables, such as slope and speed, were selected as control variables in the experiment. Besides the standard tests such as the side upset and the rear upset tests according to ASAE Standards S519, a series of ramp tests in fields were involved in this research.

The experimental results should be comparable or repeatable. A full size tractor is an effective tool to solve the conflict among costs, multiple tests of overturn, potential damage, risk to operator, and realistic rollover data. The ASAE Standard S519 was used to design the overturn bank and to guide the execution of some overturn tests.

Lateral Stability Test

Tractor lateral stability is mainly influenced by roll angle and velocity. For the Ford 800, three different lateral angles less than the critical lateral angle of the tractor were considered when the tractor was driven on three different ramps (fig. 2). Side overturn tests based on ASAE S519 were executed by John Deere A, tricycle Farmall M [Farmall M (3)], and wide-front axle Farmall M [Farmall M (4)]. A total of 10 lateral stability tests are summarized in table 2.

Table 1. Comparison of indices of tractor stability

Stability Index	Steady-state or Static	Dynamic State
Lateral	$SI_{LATS} = (1 - \phi/\phi_{cri}) \times 100$	$SI_{LATS}' = (1 - \phi/\phi_{cri}) \times [1 - (\phi'/\phi_{cri}')^2] \times 100$
Longitudinal	$SI_{LONGS} = (1 - \theta/\theta_{cri}) \times 100$	$SI_{LONGS}' = (1 - \theta/\theta_{cri}) \times [1 - (\theta'/\theta_{cri}')^2] \times 100$

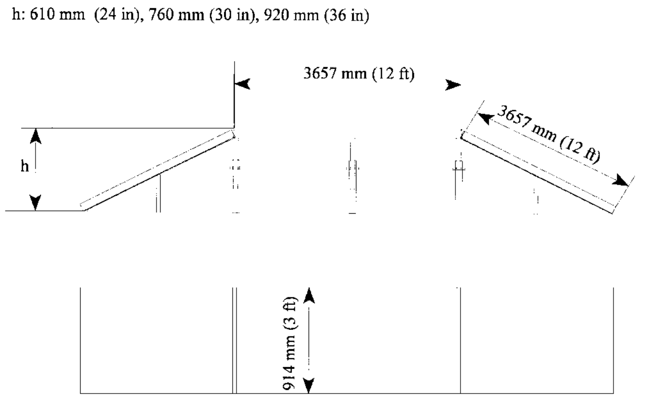


Figure 2–Diagram of ramp for lateral tests.

Table 2. Lateral tests and tractor

Test Type or Site	Height or slope angle mm or (°)	Number of Tests	Gear	Tractor
Ramp	610 (26)	3	2nd, 3rd, 4th	Ford 800
	760 (32)	3	2nd, 3rd, 4th	Ford 800
	920 (41)	1	2nd	Ford 800
ASAE S519		1	3rd	John Deere A
Site 1		1	3rd	Farmall M (3)
Site 1		1	3rd	Farmall M (4)

Longitudinal Stability Test

A series of longitudinal ramp tests on the field slopes of 15, 30, and 40° were conducted. A wide-front axle Farmall M was used to perform these tests at different speeds on the slopes. A total of nine longitudinal tests are summarized in table 3.

Testing System

The measuring system of tractor stability (MSTS) (Liu, 1998) was installed above the PTO of the tractor and used in all of the tests. The data acquisition program in 21X micrologger was run to test each of six channels, which were used to input roll angle, pitch angle, roll velocity, pitch velocity, yaw velocity and ground speed, respectively. Timing for MSTS with 21X and video camera was manually set the same as that of the video camera.

Table 3. Longitudinal tests and tractors

Test Type or Sites	Slope Angle (°)	Number of Tests	Gear	Tractors
Ramp	15	2	2nd, 3rd	Farmall M (4)
	30	2	2nd, 3rd	Farmall M (4)
	40	2	2nd, 3rd	Farmall M (4)
ASAE S519	60	1	3rd	John Deere A
Site 2	60	1	3rd	Farmall M (3)
Site 2	60	1	3rd	Farmall M (4)

Result and Discussion

Tractor stability has been analyzed in many different ways by modeling, simulation, and experiments. Full-size tractor tests can directly provide more information for verification of modeling and simulation. In order to study loss of tractor stability and the effect of major factors on tractor stability, it is necessary not only to analyze the tractor stability based on dynamics, but also to perform tractor upset tests and verify the stability model in fields. From the point of view of mechanical energy balance, the tractor overturn demonstrates exchange between kinetic energy and potential energy. A static stability index only represents the change of potential energy, and a dynamic stability index involves the approximate translation of two kinds of energies. The experimental results of stability indices are presented with variation of testing time as X axis, which only presents the interested period.

Lateral Stability Index

Ramp Tests of Ford 800. Side roll occurs in most tractor rollovers, and roll angle and velocity are of major concern. The Ford 800 with ROPS was used to perform ramp tests in three different heights and velocities. Figure 3 presents the stability index of Ford 800 traveling in 4th gear on the second height of the ramp. The ramp resulted in a roll angle of 32° and/or the calculated SI_{LATS} = 20 for the Ford 800. However, when the tractor traveled in 4th gear through the intersection between the slope and the horizontal top of the ramp, the SI_{LATS}' suddenly dropped to 15. Traveling velocity did not significantly affect the static stability index in second and third gear.

As the ramp height was increased to the third height, it resulted in a roll angle of about 40° and/or calculated SI_{LATS} = 15 for Ford 800. This ramp experiment indicates the SI_{LATS} of Ford 800 as low as 5 and SI_{LATS}' of 2.5, but the tractor still did not roll over because the stability index is more than zero.

Table 4 presents the comparison of the minimum lateral stability indices when the Ford 800 was tested at three different speeds on the three heights of the ramp. It shows that as the ramp height increases, the minimum SI decreases. At 2nd and 3rd gear, there is not significant difference between a calculated SI and measured SI on the first and second heights of the ramp. However, at 4th gear, the measured SI

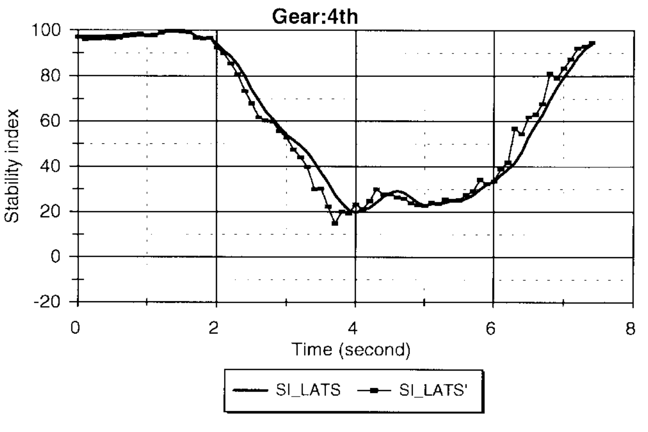


Figure 3–Lateral stability index of Ford 800 at second height of ramp.

Table 4. Comparison of the minimum lateral stability indices of Ford 800

Height (roll angle) mm	(°)	Measured SI (SI′) at Three Gears 2nd	3rd	4th	Calculated SI
610	(26)	41 (41)	42 (42)	37 (37)	45
760	(32)	18 (15)	18 (17)	20 (15)	20
920	(40)	5 (2.5)	-	-	15

- Tractor could not go up slope in this gear.

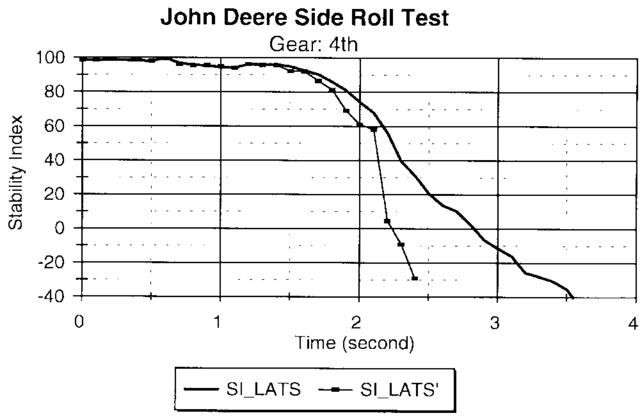
value is approximately 5 to 8 index than the calculated SI value. The SI_{LATS}' is obviously less than SI_{LATS}.

Test results on the ramp at the first and second height depict that dynamic factors, such as roll velocity and ground speed, slightly affect tractor stability indices but do not contribute to the lowest stability index. The dynamic lateral stability index (SI_{LATS}') is almost the same as the static lateral stability index (SI_{LATS}) except that when the tractor approached the top of the ramp, where SI_{LATS}' was less than SI_{LATS}. While the tractor was traveling through the intersection between the slope and horizontal top of the ramp, its roll velocity obviously changed, and it resulted in the decrease of the stability index during a period of time. High tractor velocities result in larger differences between SI_{LATS}' and SI_{LATS}. Figure 3 shows their differences to be as large as an index of 10. However, the dynamic factors did not significantly influence the lowest stability index of traveling courses on the ramp.

ASAE S519 Side Upset Tests of John Deere A and Farmall M

Figure 4 presents the stability index when the John Deere A was in a side rollover according to ASAE S519. From 1.5 to 2 s, the stability index decreases slowly, then decreases quickly for another 0.5 s. The lateral static stability index is zero after it is continuously decreased for 1.3 s. When the stability index reached zero, the tractor rolled over. After that time, the stability index continues to decrease. This figure illustrates a comparison of John Deere A static and dynamic stability indices and roll velocity. As the tractor was rolling over, the roll angle and velocity increased. Therefore, the roll velocity played an important role in decreasing the stability of the John Deere A. The SI_{LATS}' is less than SI_{LATS} during side overturn after the tractor began to roll slightly due to the high roll velocity. Although the SI_{LATS} indicates that the tractor rolled over at 2.8 s when the roll angle equals the lateral critical angle (or $SI_{LATS} = 0$), SI_{LATS}' shows that the tractor lost its stability at 2.3 s when SI_{LATS} is 47. In fact, as the absolute value of the roll velocity quickly increases at 2.1 s, the kinetic energy was increasing, and the center of gravity of the tractor was lowering. So, the tractor side overturn could not be avoided. In this test, the SI_{LATS}' can indicate a loss of the tractor stability 0.6 s earlier than the SI_{LATS}. Conclusively, the loss of lateral stability is the major reason of the tractor side overturn. SI_{LONGS} contributes little to the instability of the tractor.

Farmall M with ROPS, configured as a tricycle tractor and as a four-wheel tractor, was used to conduct side overturn tests at site 1 according ASAE S519. Figure 5 gives the variation of stability or moving states when the tractor was overturned to the side, and indicates occurrence of side overturn. The tricycle Farmall M showed very similar rolling characteristics to the John Deere A. The lateral stability index has a quite linear relationship with time during the tractor rollover. When the tractor was running at a speed of about 22 km/h (13.75 mph), the tractor took approximately 0.6 s to roll to the lateral critical angle, which was a much shorter time than for the John Deere A.



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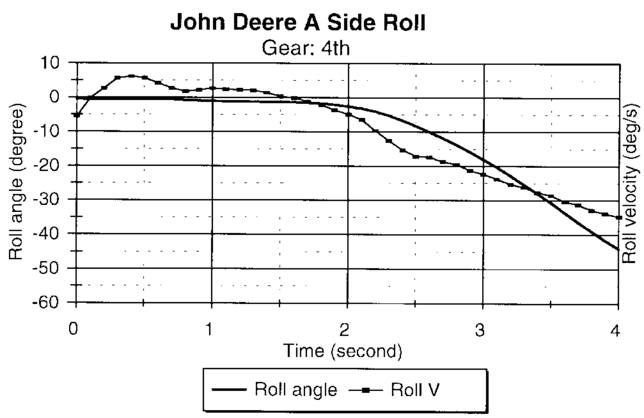


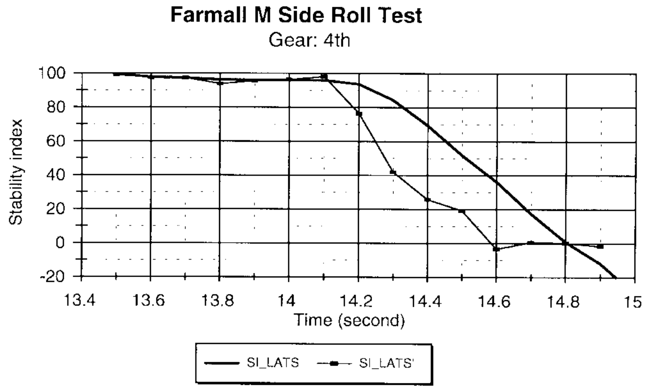
(b)

Figure 4–Lateral stability indices of John Deere A side rollover.

Figure 5a presents a comparison of the SI_{LATS} to the SI_{LATS}'. Because of roll velocity, the SI_{LATS}' is less than SI_{LATS}. When the SI_{LATS}' indicates that the tractor lost its stability ($SI_{LATS}' = 0$), SI_{LATS} still equals 35. In fact, at this moment, the tractor's roll velocity reached 75°/s while the roll angle equals 37°.

Videotape (fig. 5b) provides more detailed information, and aided in identifying the tractor stability indices with the tractor position. Each image corresponds to a stability index. When $SI_{LATS} = 0$, the image indicates that the tractor is rolling over.

This upset test showed the roll velocity significantly contributed to the loss of the tractor stability. As the rear right wheel of the tractor was driven up on the ramp, the tractor rotation produced a large roll velocity. Then, as the tractor was continuously rotated, and the center of gravity was lowering, the roll velocity and kinetic energy increased. They further accelerated the tractor rolling over.



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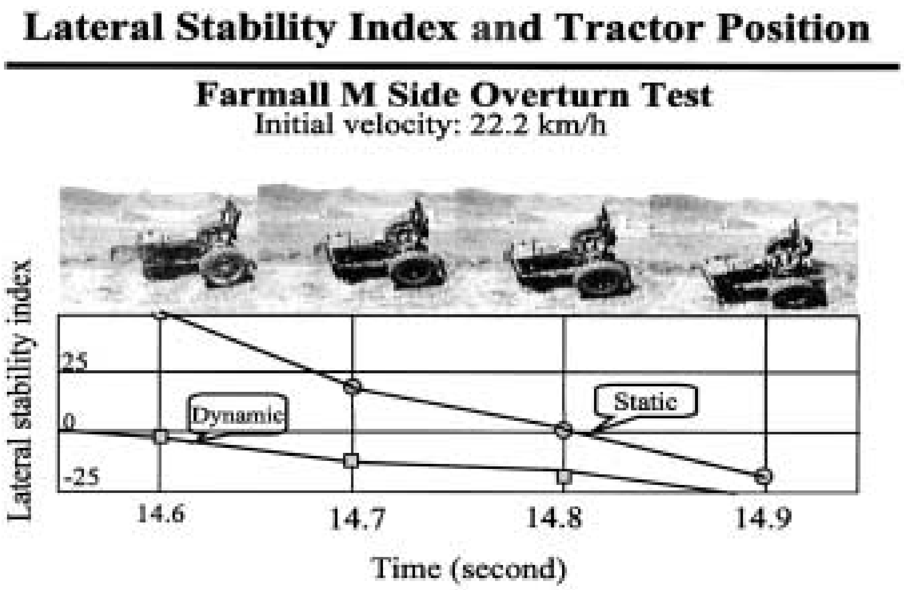


(b)

Figure 5–Comparison of stability indices during tricycle-type Farm M side overturn.

Longitudinal Stability Index

Ramp Tests of Farmall M. The longitudinal stability of ramp tests was conducted on three different slopes (15, 30, and 40°). The Farmall M with wide front track was used to perform the tests.

Figure 6 shows the longitudinal stability index when the tractor was running at two speeds on the slope of 30°. Comparison of minimum SI_{LONGS} at two different speeds shows that there is little difference or almost the same that $SI_{LONGS} = 32$. However, the velocities significantly affected dynamic longitudinal stability indices. When V = 9.1 km/h, ΔSI_{LONGS} (= $SI_{LONGS}' - SI_{LONGS}$) is about 30, and SI_{LONGS}' approaches zero. The SI_{LONGS}' calculation predicted a near rollover that

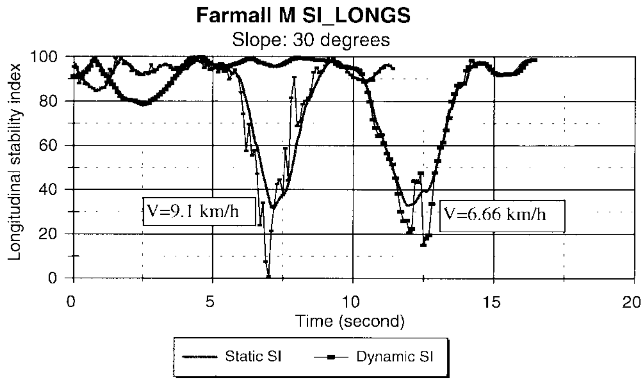


Figure 6–Longitudinal stability indices of tractor versus time during Farmall M rear overturn test at two different speeds.

did not occur. When V = 6.66 km/h, ΔSI_{LONGS} = 20. The SI_{LONGS}' at the two speeds demonstrates a large difference. The SI_{LONGS}' when V = 9.1 km/h is 15 less than that when V = 6.66 km/h, and it indicates high pitch velocity will reduce stability.

Table 5 summarizes the comparison of the minimum longitudinal stability index when the wide-front axle Farmall M was tested at two different speeds on the three slopes of the ramp. Based on the definition of SI_{LONGS}, the minimum SI_{LONGS} has a negative linear relationship with a pitch angle. The table shows that as the ramp slope increases, the minimum SI decreases. SI_{LONGS}' is less than SI_{LONGS}, and calculated SI_{LONGS} is more than the measured SI_{LONGS} on the slopes of 15 and 30°. But on the slope of 40°, the calculated SI_{LONGS} is less than the measured SI_{LONGS} because the measured maximum slope angle is less than the designed slope of 40°.

ASAE S519 Rear Upset Tests of John Deere A and Farmall M

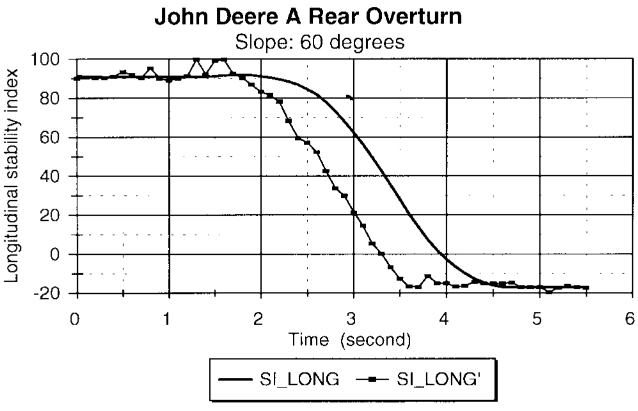
Figure 7a shows the longitudinal stability index when a John Deere A was climbing to a slope of 60° at a speed of 6.38 km/h. The rear overturn of the John Deere A occurred at this test. As the tractor began to climb from the bottom of the slope, the tractor's pitch angle and velocity increased slowly for about 0.7 s. Then, the pitch angle increased linearly with time.

A comparison of SI_{LONGS} to SI_{LONGS}' illustrates that pitch velocity results in the decrease of stability index of 40. When SI_{LATS}' = 0, SI_{LATS} = 41, the dynamic stability index depicts loss of stability 0.6 s earlier than the static stability index does. Therefore, the speed significantly affects the stability of the tractor when the tractor is going uphill.

Table 5. Comparison of the minimum longitudinal stability index of Farmall M

Slope Angle (°)	Measured SI (SI′) at Gears		Calculated SI
	3rd	4th	
15	66.9 (64.6)	65.6 (63.3)	66.7
30	32.9 (0.7)	31.4 (15)	33.3
40*	22.4 (14.4)	15.7 (4.4)	11.2

* The measured maximum slope angle was less than the designed slope of 40°.



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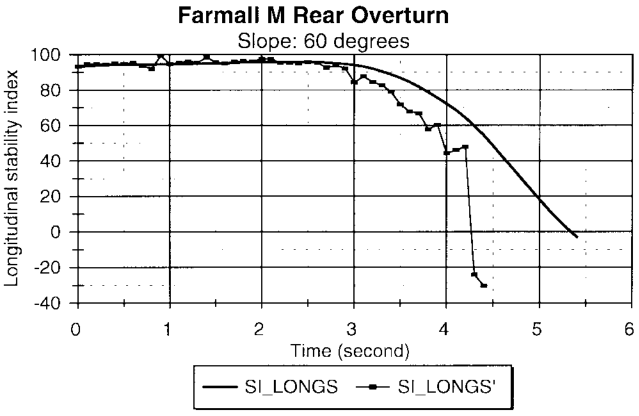

(b)

Figure 7–Longitudinal stability indices versus time during rear overturn of tractors.

The rear upset of the Farmall M produced similar results. Its stability index was strongly affected by pitch velocity. While the tractor was running on the slope from 2.8 s to 4.6 s, the SI_{LONGS}' is less 20 than the SI_{LONGS}. The SI_{LONGS}' indicates the loss of the tractor stability 1.1 s earlier than SI_{LONGS} does.

Conclusion

Tractor stability under different conditions in real-time was studied by a stability monitoring system and relative stability assessment. In order to obtain practical and efficient experimental data pertinent to the stability index model, three radio-controlled tractors (Ford 800, John Deere A and Farmall M) were modified, and equipped with the stability monitoring system and field data acquisition. In terms of roll, pitch, yaw and speed sensors, the stability monitoring system has been developed to measure the pitch and roll angle, their velocities, yaw velocity and ground speed. They have been successfully used in the tractor upset tests in the field and in the study of tractor stability. Video technology was applied to validate the stability index concepts, to investigate how a tractor rolled over, and to determine the time at which the deployment of a safety device should be initiated.

To verify the stability index concept and tractor overturn characteristics, more than 20 different stability tests were completed. The tractor upset tests such as side overturn and rear overturn according to ASAE S519 were performed in the standard banks. A series of lateral and longitudinal field tests were conducted on slopes ranging from 15 to 60°.

Tractor stability is mainly determined by tractor dimensions and center of gravity when the tractor is either operating slowly or at a constant state. In this case, a static stability index can be used to evaluate the tractor relative stability. Tractor overturning is due to exceeding critical positions such as lateral and longitudinal critical angles. From an energy point of view, it only presents the change of potential energy or instability of position without consideration of kinetic energy transformation.

A dynamic stability index can indicate the tendency of tractor stability and overturn. The experimental results show that a dynamic stability index is lower than a static stability index in most cases. In lateral and longitudinal stability tests, the body rotation velocities increase the possibility of tractor overturn and decrease tractor stability. The effect on stability of the tractor crossing an obstacle or a bank presents a typical impulse signal to the tractor and causes the tractor to jump into the air. As soon as the effect results in enough increase of roll and/or pitch velocities, the dynamic factor including the rotational velocity may become zero and indicate the tractor will overturn. When the tractor overturned, the dynamic stability index reached zero earlier than the static stability index.

The lateral turning overturn and its stability index of a tractor was also studied in terms of dynamic analysis and field upset tests. The results of these tests were reported by Liu (1998).

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