APPLICABILITY STUDY OF FIFTH WHEEL SENSORS FOR MONITORING THE VEHICLE DYNAMICS IN ARTICULATED TRUCKS

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ABSTRACT

Today in the Brazilian cargo vehicle industry, there is a technological research for solutions to meet the CONTRAN Resolution 641:2016 [1], which made mandatory stability and anti-rollover control systems in cargo trailers and semitrailers in Brazil after 2024. Even though the government concern to reduce the truck's rollover accidents indices is very pertinent, there is another frequent occurrence which still don't have an efficient technological solution for it controls. By the way, in many cases, it is the main cause of the rollover accidents on long cargo vehicles: The Trailer Swing Effect.

This paper presents an applicability study of innovative sensors for the vehicle articulation (fifth wheel). These sensors will monitor the vehicle dynamics for identifying the Trailer Swing Effect. This technology will be fully present in the tractor vehicle, acting independently of the characteristics and the semitrailer technological level.

CONTEXT

Undoubtedly, innovations in the automotive sector provides a great competitive advantage to any company. However, the innovative process is not simple, due the technological and commercials uncertainties that a disruptive project presents. For these reasons, there isn't many innovative technology-based companies (*startups*) in this sector. Even in this scenario, the Truck Vision Company, a Brazilian *startup*, decided to innovate from a difficulty observed in the clients: Despite all the technology embedded, in some situations still required a great driver's skills to maneuver articled vehicles.

Batista et. al. [2] demonstrated that when the driver is maneuvering articulated trucks, sometimes when the truck is not aligned with the semitrailer, he loses the rear visibility completely. In this moment, the semitrailer obstructs the rear vision totally on the side rearview mirror.

This lack of visibility causes several accidents in conversions and maneuvers events, like in Figure 1, causing high losses to the transporters and damages to the vehicles.

Figure 1 – Accident due the lack of rear side visibility [2]

In order to present an innovative solution to this lack of visibility, this startup created and the *SMART MIRROR* product (*"RETROVISOR INTELIGENTE"* in Portuguese), an electronic kit that automatically adjusts the side rear-view mirror, provides total rear visibility in any conversion and maneuvering situations (Figure 2).

Figure 2 – Visibility in the side rear view mirror WITHOUT and WITH the Truck Vision *Smart Mirror* [3].

To this product be feasible, the system needed to measure the articulation angle between the truck and the semitrailer, to adjust the side rear view mirror according to this angle. Truck Vision developed a disruptive solution for measuring and calculating this angle, a simple and easy solution, which basically contains two components (Fig. 3):
- The Magnetic Disc (*Disco Magnético*), which contains some magnets that is attached to the Semitrailer King Pin;
- The 5th Wheel Magnetic Angular Sensor (*Sensor de Quinta Roda*), an electronic compass, positioned at the bottom of the truck fifth wheel.

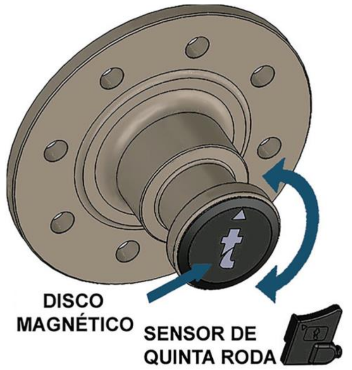

Fig. 3 – Magnetic 5th Wheel Sensor and Magnetic Disc [3].

This angular measurement system works in this way: When the vehicle is hitched, the King Pin and the Magnetic Disc rotates inside the fifth wheel. The angular measurement is made from the magnetic field variation caused by the disc rotation and is detected by the Fifth Wheel Magnetic Sensor [3]. The concept of the Magnetic Disk, besides simple and functional, is highly innovative, patented since 2013 by Batista et. al. [4].

JUSTIFICATION

It was after the *Smart Mirror* product release, that a demand for apply this fifth wheel sensing technology became interesting for other systems present in large cargo vehicles. As well as to automate the rear-view mirror, the concept of an angle sensor that monitor the articulation exclusively from the truck, should be necessary and useful for dynamics control and telematics systems.

However, on these days an efficient king pin monitor sensing is high needed from the automotive industry, and not only for the vehicle dynamics control, but this is a certainly demand for an announced future of autonomous driving vehicles. By the way, until now there is a shortage of automotive solutions that measure the truck articulation angle and also monitor the semi-trailer movements independently of any electronic devices installed in the semitrailer [5, 6].

Currently in Brazil, is becoming necessary that braking and dynamics control systems should be more efficient and assertive. This need is mainly because the CONTRAN 641:2016 resolution, which made mandatory the stability control systems on cargo vehicles after 2024. This resolution provides that semi-trailers vehicles must have the roll control function (anti-rollover) [1]. Because this more effective cargo vehicle safety systems necessity, motivated to develop some efficient semi-trailer monitoring technology, using sensors only present in the fifth wheel, like is applied on the *Smart Mirror* product.

This obligatoriness of the anti-rollover devices, shows a very relevant government concern for seeking artifices to reduce this very common type accident in Brazilian roads. However, there is another accident type that unfortunately is very frequent, the anti-rollover systems are ineffective to detect and sometimes, is the main cause of a subsequent rollover accident: The Trailer Swing Effect, popularly known in Brazil as "L" or "semitrailer closing L".

A serious accident between an empty "*cegonheira*" semitrailer and a passenger bus occurred on April 2019, in Santa Catarina's Hills/Brazil. This accident was caused by a semitrailer side slip into a wet curve, that came crashing into a bus that was traveling on the opposite lane (Figure 4). In this accident four people including the bus driver died and 10 were injured [7].


Figure 4 – Accident caused by a Trailer Swing Effect [7].

Other motivation of this study is that even with vehicles equipped with Antirollover Systems, this type of accident will not be avoided. Antirollover Systems is not able to detect the sudden yaw movements of the trailer, especially in bi-articled configurations ("*bitrens*" and "*rodotrens*") and in very long vehicles such as the "*cegonheiras*", both configurations very common in Brazil.

Knorr Bremse, one of the largest suppliers of braking systems for commercial vehicles, explains why bi-articulated vehicles still is a technical challenge for the stability control systems: "*Technical challenge: Unlike an articulated vehicle, the bi-articulated composition, (...) has, (...), two articulations. This additional level of freedom provides a variety of forces that must be considered when processing ESP*" [8].

The innovative fifth wheel sensing concepts presented on this paper, was designed for if it is combined with the current stability control systems will allow more effective braking performance and will guarantee better stability for the vehicles, even in long and bi-articulated compositions.

OBJECTIVE

The objective of this paper is to present an applicability study and the feasibility of sensing systems for Fifth Wheel/King Pin articulations. This disruptive technology will allow to monitor the dynamic movements of the semi-trailer with the sensors present only in the fifth wheel. The sensors will act independently of the technological level and the presence of any electronic devices in the semi-trailer.

ACCIDENTS OCURRED BECAUSE LATERAL INSTABILITIES ON ARTICULATED VEHICLES

Brazil has a logistics matrix highly dependent on the road modal, with a growing fleet of long cargo vehicles. Combined with human factors, poor maintenance of the vehicles and our roads, these points contribute for a high rate of accidents involving trucks in Brazil. According to the Brazilian Federal Highway Police (PRF) [9], in 2019 was around 25,000 accidents was involving articulated trucks. Table 1 shows the main types of this accidents.

Table 1 – Major articled trucks type accidents [9]

TYPE	%
Rollover	20,05%
Line Change	15,27%
Frontal Collision	9,28%
Rear Collision	17,93%
Lateral Collision	19,53%

Based on these data, can check a worrying indicator: About 20% of accidents involving trucks in Brazil, were a rollover occurrence. However, the type of the accident indicated by PRF in most cases, does not present the real truth cause of the occurrence, but shows only the final consequence. An example of this data, is the Santa Catarina's Accident (Fig. 4), that was classified by the PRF as: FRONTAL COLLISION - IN RAIN - WITH VICTIM.

Pamcary [10], a Brazilian insurance company presented a study of the main factors that influenced accidents involving articulated vehicles:

- Driver failure was present in 66% of the occurrences, which: 43% recklessness, 13% incompatible speed and 10% due to fatigue.

- Road conditions was present in 57% of accidents, of which: 20% due a sharp curve, 15% due of the poor road condition and 17% on a slippery road.

However, in United States there is concern to investigate the main cause of the accidents. An American research shows the accident's rates caused exclusively by lateral instabilities (Figure 5): Yaw Instability (Trailer Swing or Jackknife Effect), Turn-over (pure Rollover) and Yaw instabilities combined with Rollover.

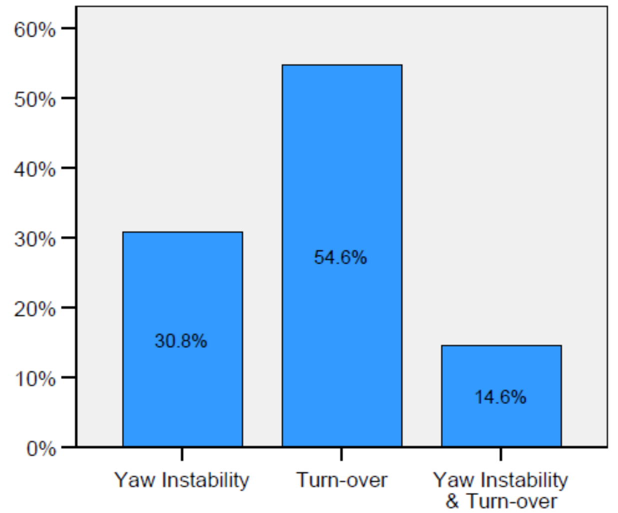

Figure 5 – Accidents due to lateral instabilities [11]

According to these data, 69.2% (54.6 + 14.6%) of the total of the accidents occurred Rollover. In 21% of the total Rollover cases, is occurred combined with some yaw instability. This research also indicates the most caused events of these accidents:

- Making a curve 35.5%;

- Evasive maneuver 21.9%;

- Hard braking 21.8%;

- Other factors: 20.8%.

THE ROLLVER INSTABILITY

Rollovers instabilities occurs when a lateral acceleration is applied on the vehicle and exceeds the rollover acceleration limit. When it exceeds, will cause the vehicle's CG (Center of Gravity) rotates over the point of the tire's ground contact, in external side of the curve. This limit is known on the literature as Static Rollover Threshold (SRT) [12]. The SRT value shows the maximum lateral acceleration, which could be applied in the vehicle (g's - acceleration of gravity) before the vehicle enters in an imminent rollover condition.

Cargo vehicles have SRT values normally between 0.4 and 0.6g [12], which can be is calculated using the following formula:

$$SRT = \frac{t}{2h}$$

Where “t” is the gauge (distance between the center of the tires on the same axle) and “h” is the height of the center of gravity, considering the vehicle fully loaded.

However, Winkler et. al. [12] affirmed that this SRT value is only theoretical and in most cases is overestimated, since other characteristics that also influence, such as: The flexibility of the tires; suspension and fifth wheel lashes; the torsional stiffness of the semitrailer structure; type of suspension (if it is mechanical by springs or pneumatic), the positioning of the load CG, among other factors. On sequence, is explained some these vehicles characteristics:

THE FIFTH WHEEL INFLUENCE - There is a gap in the articulation locking mechanism, which allows a slightly roll angle of the semitrailer in relation of the truck during a rollover. This angle is caused by the “Trailer lash” or the “Fifth Wheel Separation” [12] (Figure 6).

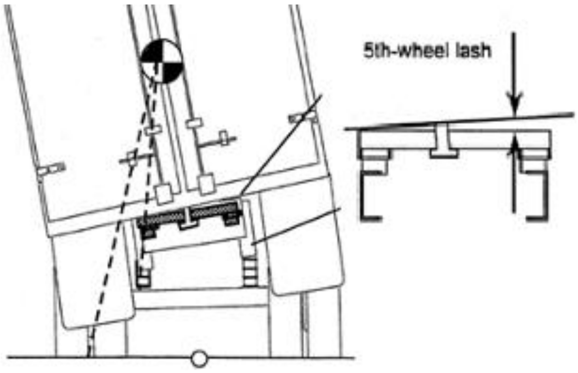

Figure 6 – Fifth wheel lash on the rollover [12]

Considering this fifth wheel influence, the rollover process happens in three stages [13]:

STEP 1: The semitrailer is completely supported on the ground and its mass that is supported on the fifth wheel is also equally divided between the edges (F1 and F2). On this stage the fifth wheel turns in solidarity with the semi-trailer [13] (Figure 7):

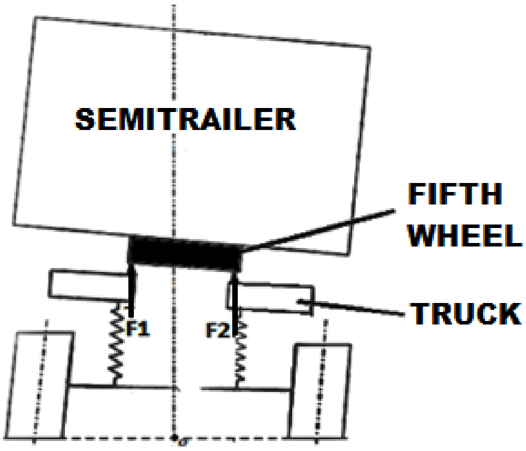

Figure 7 – Rollover STEP 1 [13].

STEP 2: There is a mass transfer on the fifth wheel for the rollover side (F1 + F2). At this moment, occurs the Fifth Wheel Separation of the semitrailer table and the fifth wheel face, creating a lash [13] (Figure 8).

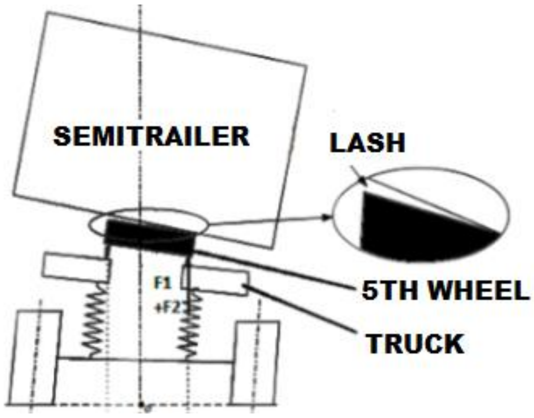

Figure 8 – Rollover STEP 2 [13].

In practical tests, La Clair et. Al. [14] verified this Trailer Lash Effect, during a maneuver nearby the rollover eminency. In Figure 9 can check this lash between the Fifth Wheel and the Semitrailer table.

Figure 9 – Fifth Wheel Separation during tests [14].

Arant [15] also verified in static tests that the semi-trailer table and kingpin can be considered rigid and without torsional deformations during a rollover event. According to the author, what definitely occurs during Step 2 is the lifting of the kingpin and the semi-trailer table. At this moment, there is a tendency to pull up the kingpin, sequenced by its rotation on the fifth wheel coupling point (Figure 10).

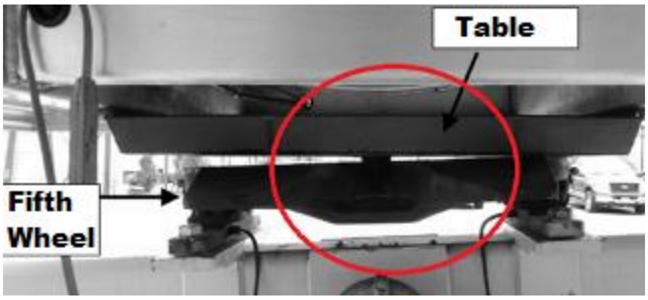

Figure 10 - Rotation and separation of the Fifth Wheel [15].

STEP 3: In this stage, the fifth wheel lash reaches its limit and the vehicle starts to roll together (truck and the semitrailer). At this moment the semi-trailer tends to lift the wheels off the ground and in the sequence, the rollover event becomes inevitable [14].

THE CHASSIS STIFFNEES INFLUENCE - The torsional stiffness of the semitrailer chassis is another relevant feature that directly influences the SRT value. Closed Bodies semitrailers (like vans and tanks) have a high torsional stiffness coefficient, up ten times greater than Open Bodies vehicles (flatbed, sider, dry loads, etc). Closed Bodies semitrailers can be considered rigid, since torsional behavior is practically zero during a rollover event [12, 13].

In rigid these cases, when the semitrailer entering into a rollover threshold (Step 3), it will pull and rotate the fifth wheel, twisting the truck's chassis (Figure 11).

Figure 11 – Rigid Semitrailers into a rollover situation.

By the way Open Body Semitrailers cannot be considered rigid, because it will tend to rotate initially the rear end, lift the wheels from the ground before rotating the front part attached on the fifth wheel [16] (Figure 12). In these cases, the imminent rollover cannot be detectable by the fifth wheel, only at the moment that the accident is inevitable.

Figure 12 – Semi-trailer with high torsional behavior.

THE YAW INSTABILITIES

Regarding lateral yaw instabilities, these can occur in three ways [17] (Figure 13):

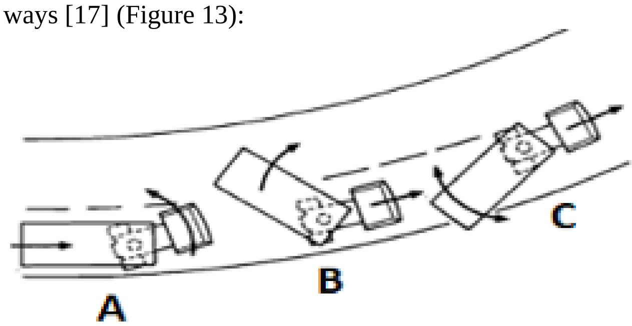

Figure 13 – Yaw instability modes [17].

A) The Jackknife Effect.

B) An unilateral yaw instability (Trailer Swing).

C) A Lateral oscillation (Trailer Swing).

Basically, yaw instabilities occurs when there is a force applied laterally on the vehicle's CG with an intensity higher the frictional force on the wheels. The mainly fact of these instabilities is the friction condition between tires and pavement, and is also influenced by the cargo weight and position, and the longitudinal and lateral vehicle speed [17].

In cases with high friction condition and high lateral acceleration, yaw instabilities are more difficult to occur, is more probable the direct rollover. However, if have a low friction coefficient, this type of instability can occur even with a small lateral acceleration, such as 0,1~0,2g [12, 17].

Dorion et. Al. [17], also verified the angle behavior in the articulation into a yaw instability situations. The author showed an experiment which the articulated vehicle made a low friction constant radius curve, at a certain point was applied an abrupt braking (Figure 14). As was shown previously, about 22% of the causes of yaw instabilities was caused abrupt braking [11].According to the author, the definition if the yaw instability will be a Trailer Swing or a Jackknife Effect depend not only on the of speed, friction conditions and radius of the curve, but also mostly of the CG load position and the length of the semi-trailer [17].

In Jackknife Effect, the yaw rate change is more abrupt, up to 65 degrees/s. In Trailer Swing is smaller, about 19 degrees/s. However, in both cases the author check that the vehicle can change its condition very abruptly, in less than 0.5s can move from a stable condition to any yaw instability [17].

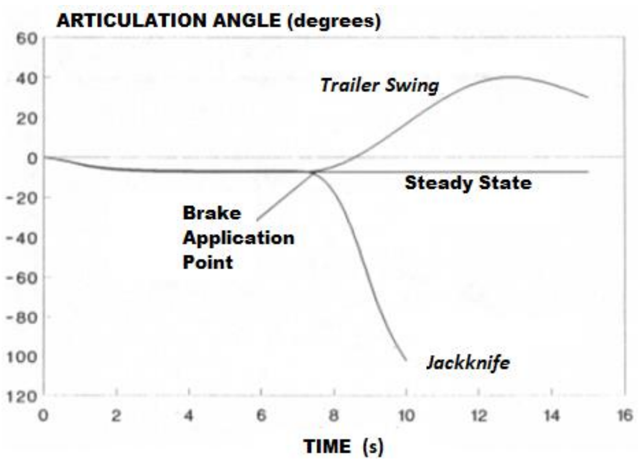

Figure 14 - Articulation angle behavior in yaw stability [17]

According to this author, short and loaded single article vehicles and long and empty vehicles, are more prone to Trailer Swing. This propensity, combined with a downhill slippery curve, a little braking force could be the cause of this yaw instability, just like happens in Santa Catarina's accident on Figure 4 and on the accident showed below on Figure 15.

Figure 15 – Trailer Swing on a slippery [3]

However, yaw instabilities can occur primarily, and be a cause of a subsequent rollover [11]. In these cases, when the vehicle loses grip and slides laterally, normally the driver in an attempt to regain the vehicle control, tries to braking even in an unstable condition. With the speed reduces, the vehicle returns to a minimal friction condition, but because the rear amplification, it enters in a sequential rollover. This type of accident usually occurs in a closed and slippery curve, with high loaded vehicles. An example of this accident occurred in a Brazilian Road, Figure 16.

Figure 16 – Vehicle rollover after a lateral slippery [3].

When there is yaw instability combined with rollover, it is a very difficult condition to control, due the conflicting necessities to correct simultaneous instabilities. The assertiveness way to correct is to detect and correct separately, first the primary instability [18].

THE CURRENT CONTROL STABILITY SYSTEMS

ELECTRONIC BRAKING CONTROL (EBS) - To avoid the vehicle rollover, the technology evolved significantly over the years, several sensors and actuators have been created to ensure the stability of the vehicle composition. The advent of this technology was the Electronic Brake Control (EBS, or TEBS when it is applied on trailers). TEBS (Figure 17) is a combined solution of the evolution of the anti-lock brake system (ABS) with the vehicle's Roll Control System (RSC or RSS) [8].

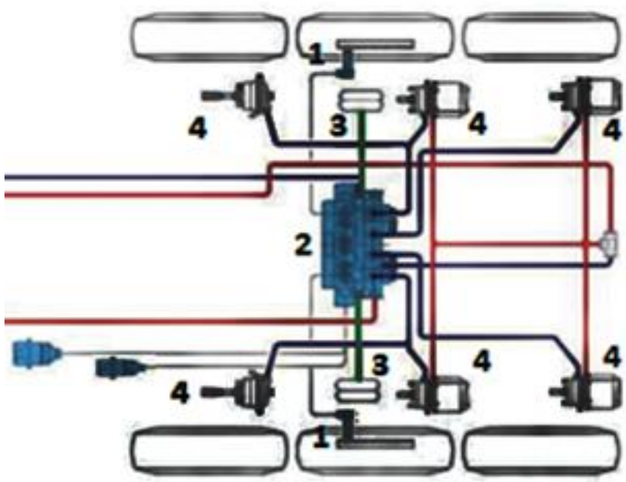

Figure 17 – TEBS System for semitrailers [19].

All TEBS systems has the RSC functionality. Basically, the RSC acts by constantly checking the speed in each wheel (1) on the semitrailer; the compression of the suspensions (3); and the lateral acceleration and roll sensors present on TEBS module (2). When the system verifies a rollover tendency the system acts automatically on each brake actuator (4) to avoid this unsafe condition [19]. A fundamental variable for efficient rollover detection is the suspensions compressions verification (3), which has an efficient and accurate sensor, normally applied in the air pocket of the pneumatic suspensions, standard on Europe.

However, less than 10% of the Brazilian cargo fleet has pneumatic suspension [41]. On this situation, load sensors (Figure 18) are currently used for monitor the mechanical suspensions compression, which doesn't have the same efficiency and accuracy the sensor for pneumatic suspensions. In addition, these load sensors showed in Figure 18, are notably fragile for application on Brazilian roads. By the way, the spring bundle is more rigid than the air suspension pockets, what also influences the accuracy and efficiency of these load sensors [19].

Figure 18 – Sensors for mechanical suspensions [19, 20].

As the initial rollover condition is usually generated by a semi-trailer instability [12], the majority presence of mechanical suspension and the use of these load sensors with low durability and efficiency, are the main technical limitation of Anti-rollover Systems application in Brazil to comply the CONTRAN legislation [1] after 2024.

ELECTRONIC STABILITY CONTROL (ESC) – The directional stability control (ESC or ESP) is a system present only on the tractor vehicle, which detects situations where there is a difference between the actual trajectory of the vehicle and the desired by the driver. The ESC has some specific sensors present only on the truck, not found on the semitrailer (the steering wheel sensor and a yaw sensor). When this system detects a lateral slip of the tractor vehicle, the system automatically controls the acceleration and braking on each wheel, to bring the vehicle to the desired route [8] (Figure 19).

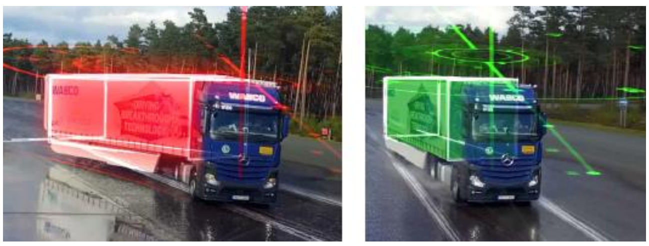

Figure 19 – Vehicle WITOUH and WITH ESC System [8].

When the tractor vehicle is coupled to the semitrailer with TEBS with electronic communication, if the system detects an over-steering (Jackknife Effect) of the truck it also can act on semitrailer's braking, to correct the tractor vehicle yaw instability. [21] (Figure 20):

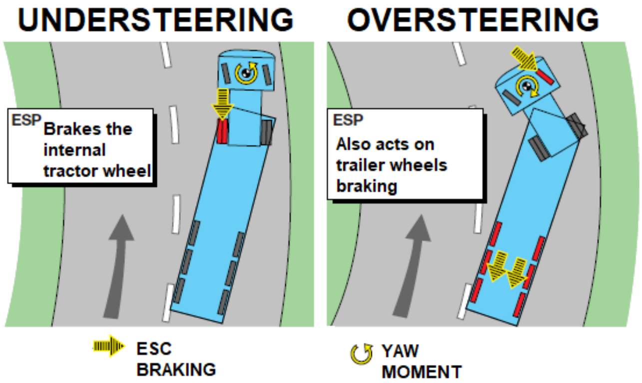

Figure 20 – Articulated Vehicle with ESC on truck [21].

Directly, it can be said that ESC is an "individualistic" system, which exclusively controls the yaw stabilities of the tractor vehicle and not on the entire composition. This system can prevent the Jackknife Effect of the truck but however, is not able to prevent and control the yaw instabilities of the semi-trailer as the Trailer Swing. This lack of a stability systems for control the yaw movements of the trailers is because at this time, there is no data and sensors able to monitor the yaw movements of the semitrailer relative to the tractor vehicle. "*There is no ESC system available for semi-trailers*" [22].

This lack of an effective technical solution for preventing the trailer slippery, took Volvo, a company notably recognized for seeking improvements for road safety, to develop the only system available on the market capable to prevent the Trailer Swing Effect: The "*Stretch Brake*". However, it is a passive system, which depends the driver perception of risk to activate it. When it is activated, the tractor vehicle will basically keep the trailer brakes activated on a pulsed way, to avoid it sliding on wet downhill curves [35] (Figure 21).

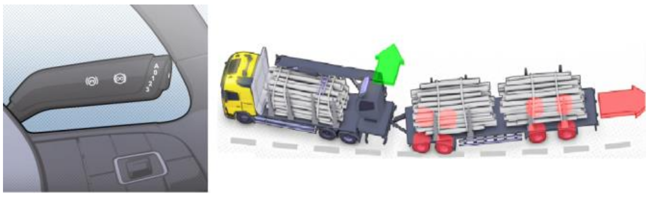

Figure 21 – "*Strech Brake*" System by Volvo [35].

Although it presents some effectiveness, this system could not be applied on a Brazil's scenario. In addition to the need of the driver's activation, the Brazilian fleet is mostly equipped with drum brakes [29] with low thermal capacity. The constant and pulsed action on brakes will lead an overheating of the trailer brakes and, consequently, a drastic decrease of its efficiency.

INTEGRATION OF THE STABILITY SYSTEMS - Iombriller et. Al. [23] presented the importance of preventing the combined vehicle compositions instabilities. Is known that the semitrailer and the truck are all of them, produced by different manufacturers that sometimes have different technological levels. This divergence, sometimes makes difficult to apply some solutions that need to have devices on both units to operate. Because this, could have vehicles with different technological levels in the same composition. Table 2 indicates which Stability Control systems will be in operation, even with a technological divergence is presented on a cargo vehicle composition.

Table 2 – Compositions with different technologies [19].

Vehicle model		SYSTEMS				
		ABS		EBS-RSS		ESC
ABS	-	yes	no	no	no	no
	ABS	yes	yes	no	no	no
	EBS	yes	yes	no	yes	no
EBS	-	yes	no	yes	no	yes
	ABS	yes	yes	yes	no	yes
	EBS	yes	yes	integrated via CAN		yes
-	ABS	no	yes	no	no	no
	EBS	no	yes	no	no	no

It is noted that the ideal situation is when there is the EBS system on the truck and on the semitrailer (TEBS), with CAN integration network. However, specially in Brazil this should be an unusual situation and will be more frequent to find a new technological truck, attached with an outdated semi-trailer. In this Brazilian scenario, this lack of technological convergence on vehicle composition and the lack of some solution to integrate them, undoubtedly will cause a poor accidents reduction index and below the government expectative with the Contran legislation [1].

THE EFFECTIVENESS OF CONTROL SYSTEMS

Even with limitations, it is recognized the evolution of articulated vehicles safety that these technologies had been provided. However, still have gaps that could be improved, mainly considering applications for Brazilian market.

In the USA (more favorable scenario than Brazil), the reduction of rollover accidents was lower than expected by the manufacturer Bendix (a Knorr Bremse company), which observed a reduction of only 4% in rates of rollover facts between 2008 and 2015 on United States [24]. The technologies divergence between the truck and the semi-trailer and the aging of the fleet was pointed by Bendix as the main factors that prevented a greater effectiveness of the stability control systems [24]. Bendix also points some facts that even with anti-rollover systems the effectives will be limited, as because the road geometry, excessive speed and the driver's imprudence. Bendix also points that the systems until have some technical limitations by itself [24]. However relevant study by NHTSA [25], demonstrated the real effectiveness that RSC and ESC could provide to prevent accidents on rollover, LOC (Loss of Control on yaw situation) and by a combined events (Table 3):

Table 3 - Effectiveness of RSC and ESC technologies [25]

Technology	Target Crashes	Effectiveness (%)
RSC	Rollover	37 - 53
	LOC	3 - 3
	Combined	21 - 30
ESC+RSC	Rollover	40 - 56
	LOC	14 - 14
	Combined	28 - 36

- About the mandatory anti-rollover system (RSC): It has high performance in preventing pure rollover, but inefficient for controlling yaw instabilities, with only 3% effectiveness in these cases.

- About RSC combined with ESC: Has practically the same rollover preventing performance, have better but still small performance to prevent LOC, only 14% effectiveness.

In both cases, these systems will have a very small probability to avoid the LOC accident, as occurred in Santa Catarina (Figure 4). It is worth to mention that this is an American study, where there is a standardization of semi-trailers with better maintenance, all with pneumatic suspensions and excellent conditions roads.

BIARTICLED VEHICLES - In addition to the technological divergence between vehicles, the growing fleet of long and bi-articulated vehicles in Brazil highlights a concern about the effectiveness of these systems in this type of vehicles. Heavier and shorter vehicles are more prone to rollover, but long and bi-articulated vehicles will be more susceptible to yaw instabilities due the higher rear amplification, as showed on Figure 22 [17].

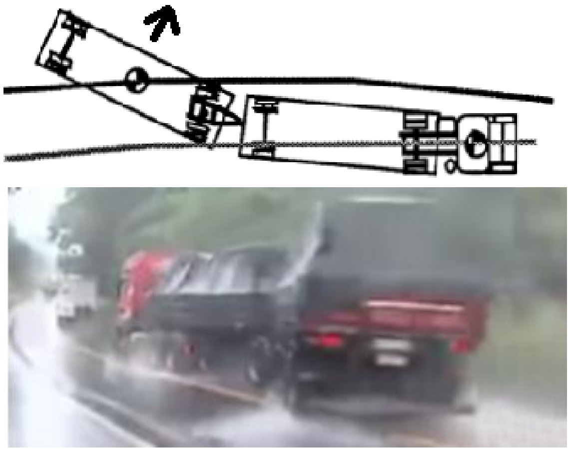

Figure 22 – Trailer Swing on biarticulated vehicle [30]

In another study, the vehicles dynamic characteristics were verified according of the country legislation (Table 4) [26]. The European (EU) configuration is similar to the Brazilian single articulation vehicle. The "*Brazil*" configuration, refers to a bi-articled 19.8m vehicle, which presented the worst stability condition on this study: The highest rear amplification and one of the worst damping rates for yaw instabilities.

Table 4 – Vehicle dynamics in each country [26]

	Rearward amplification	Yaw damping
US	1.18	0.55
EU	1.29	0.50
Scandinavia	1.81	0.39
South Africa	1.56	0.22
Brazil	1.88	0.36

Even if biarticulated compositions is equipped with ESC system, can be said this system has no effective, as shown by Bendix manufacturer, that presents the following note in its manual: "*The ESP Bendix system (...) is designed and optimized for tractor trucks that tow a single trailer. If the tractor truck equipped with Bendix ESP is used to drive combinations with multiple trailers (...) the effectiveness of the ESP Bendix system can be greatly reduced. Extremely careful driving is always necessary when towing bi and tri-articulated*" [27].

"CEGONHEIRAS" - Typically Brazilian semitrailer configuration for car's transport, a very long vehicle with only one articulation, that is:

- Very light when is empty, susceptible to Trailer Swing Effect [17], as occurred in Santa Catarina (Fig. 4).

- When is loaded, the cargo CG position may vary according to the layout and models of the cars transported (Figure 23), which can result in some situations, a high Rear Amplification, a relevant torsional behavior in curves and pre-disposition to rollover. This CG fluctuation also affects the effectiveness of TEBS, which is parameterized only for one CG position configuration.

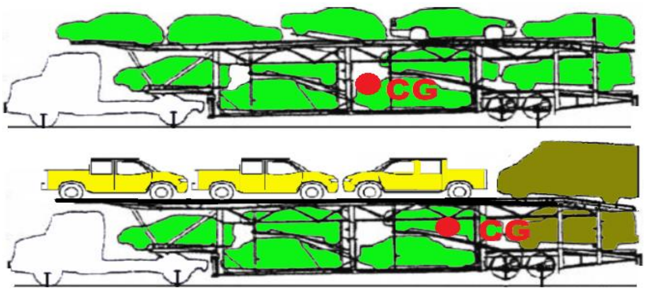

Figure 23 – CG positions in "Cegonheiras" Semitrailer

TYRES CONFIGURATION - Another technical issue that limits the effectiveness of control systems in Brazil is the majority presence of vehicles with double tires. Pezold et. al. [28], showed that this configuration presents less stability and a higher risk of aquaplaning than the configuration of single wide tires, adopted in the USA and Europe. Another peculiarity of the double tires is the possibility of present different calibrations in the same assembly, which is often imperceptible to the driver.

These divergences can cause the vehicle to lose grip during conversions on slippery tracks, especially on roads that have ripples and geometric flaws, common in Brazil [29] and that favor to aquaplaning.

SYSTEM VALIDATION - Finally, Iombriller et. al. [23] raises another important question: Even with the Contran [1] regulation, until now, there isn't a Brazilian standard that specifies validation tests to prove the effectiveness of devices for our semitrailer's configurations.

Therefore, from the points presented, it can be assured that the effectiveness of these Stability Control Systems is expected to be low in Brazil. Due to this presence of long, and bi-articulated vehicles, that are mostly equipped with mechanical suspension and double tires.

THE NECESSITY OF A FIFTH WHEEL SENSOR FOR STABILITY CONTROLS

The current safety needs and limitations of the current stability control systems, demonstrate the necessity of a vehicle's articulation monitor system. This need <u>creates demand</u> for a sensor that presents precision, independence and practical application to the fifth wheel, due to the points presented below:

<u>TEBS couldn't detect the trailer yaw instabilities:</u>

- The TEBS system with anti-rollover system (RSC) only has sensors that detect lateral accelerations, rollover movements and the speed of the wheels on the trailer [19].

- The Trailer Roll Angle is the same as in a Trailer Swing event (red) as in a stable situation (blue), Figure 24.

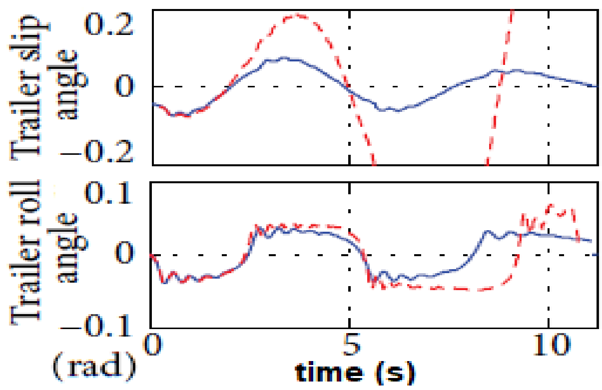

Figure 24 – Trailer Yaw (slip) and roll angle during the Trailer Swing Effect compared with a stable situation [34].

- While rollover occurs normally at 0.4g [12] of lateral acceleration, the Trailer Swing Effect can occur with only with a 0.1g depending of the friction's conditions, an identical value of a normally conversion [17].

- Without specific sensors and controllers, trailer yaw instabilities are impossible to detect with only TEBS/RSC systems.

<u>ESC detects only the tractor vehicle yaw instabilities:</u>

- The directional control system (ESC) is technical limited only for control tractor vehicle trajectory, using sensors present only on this vehicle [21].

- The Rear Amplification behavior of the one articulation vehicle is very different of the biarticulated that is very common in Brazil (Figure 25). As in multi-articulated vehicles the rear amplification is higher, they are more prone to the Trailer Swing than to Rollover [17].

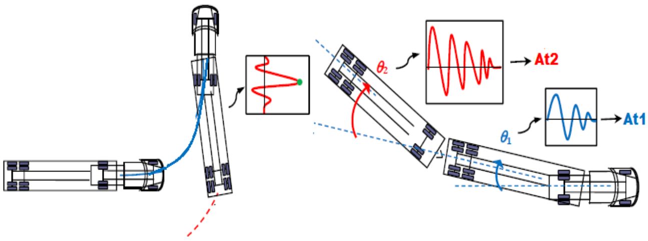

Figure 25 – Divergent rear amplification behavior (author).

- However, this current ESC systems are inefficient to detect Trailer Swing, mainly in multi-articulated vehicles, but if is monitored the articulation angles, the control of this type of instability becomes possible [30].

<u>For yaw control, the articulation angle is essential:</u>

- Several authors presents that the fundamental variable for control the yaw instabilities is the articulation angle. According to them, the analytical methods for estimating this angle are only palliative and complex methods, but are currently used because this lack of a practical and accessible commercial solution for a sensor to measure this angle [5, 6, 31].

- However this estimated methods, in addition of the complexity, it will depends of several variables from the semi-trailer, require knowledge of the friction condition between the tires and the road and it is not applicable to multi-articulated vehicles [5, 6, 31].

- In order to control the semitrailer yaw stabilities, is essential to know if this vehicle is following an expected trajectory. However, the expected trajectory for a semi-trailer is basically the length of an angular rotation, from a specific command coming from the truck. Bouteldja [31] and Chen [32] presented a diagram of directional control by the articulation angle.

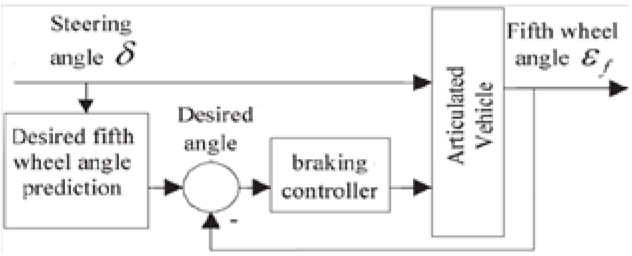

Figure 26 – Articulation angle control diagram [31]

THE NECESSITY OF A FIFTH WHEEL SENSOR FOR TRACKING (TELEMATICS) SYSTEMS

In addition of the geographical vehicle's indicated position, nowadays various sensors and telemetry components are added to the tracking systems to provide solutions for monitoring and managing the fleet in real time. By the way, vehicle's telemetry information creates a possible to have an Internet of Things (IoT) network for make a sustainable transport system with connected vehicles, that allows costs reductions, and provides better efficiency and greater safety indications [32].

The current (telematics) tracking systems already have some solutions that allow the control of the driver conduct, an essential act to ensure the road safety. This currently monitorable parameters are basically only the excessive speed and sudden braking events. Was still noted from this market that also have some necessities that is not attended by the current technology, that if have the fifth wheel information could be useful for a fleet management:

<u>Driver behavior management is limited:</u>

- It is only possible to monitor the driver's conduct in aggressive maneuvers with rollover tendency as in Figure 27, if the semi-trailer that has TEBS, which is not mandatory and until now, is little founded in Brazilian semitrailers fleet [29].

- Until now is not possible too, monitor the sudden yaw movements of the semi-trailer, caused by malpractice (Figure 15) or by imprudence (and irresponsibility) as in this purposeful maneuvers "*Quebra de Asa"* (Figure 27).

Figure 27 – "*Quebra de Asa*" ("Wing Break"): purposeful maneuver made by some irresponsible drivers in Brazil [33]

- Is not possible to manage if the driver performs was correctly or make a fully investigation of a the real cause of an accident, if the semitrailer's behavior during these occurrences was unknown.

THE NECESSITY OF A FIFTH WHEEL SENSOR FOR AUTONOMOUS VEHICLES

Thinking of a future already announced, autonomous vehicles will be a reality. This new scenario will bring several challenges for Engineering, due the necessity of the interaction between the artificial intelligence and the directional control of a vehicle, where all variables must be considered. However, fully automating an articulated vehicle is not a simple task and, of course, more complex than on small car. This difficulty is not only because its bigger dimension, but also due to the presence of a joint and the divergent dynamics, when loaded and when is empty. The existing autonomous technologies are:

- Waymo, Tusimple and Plus.AI: These companies already have autonomous articulated trucks, where the vehicles are basically monitored by cameras and radars. These proposals are limited for a cruise trips and in maneuver situations it must be operated by a driver.

- *Vera* [35] Volvo Prototype: Vehicle operated by a control center, designed to move semi-trailers over short distances and low speeds, with pre-determined routes and repetitive in flows (Figure 28).

Figure 28 – Autonomous truck – *Vera* [35]

- Directional axles automation on semi-trailers [36]: To automate the rotation of the semi-trailer wheels, a king pin sensor is normally used, which acts as follows: In rotation, the Turntable follows the movements of the king pin and an encoder sensor reads the hitch angle (Figure 29).

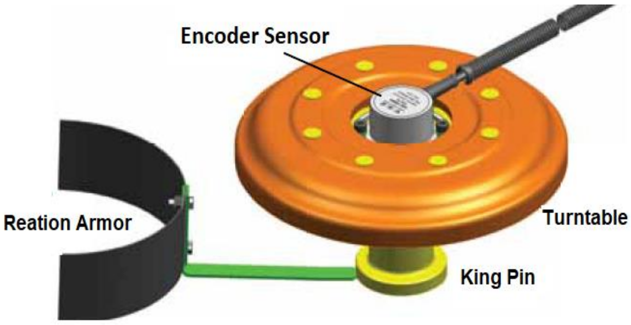

Figure 29 – VSE King Pin Angular Sensor [36]

<u>For Autonomous Driving the articulation angle must be controlled:</u>

- For the complete automation of an articulation vehicle where maneuvers are needed, among other parameters, the articulation angle is fundamental to control, as evidenced by authors of autonomous theme [37].

- Without a precise control of the articulation angle, maneuvers and automated driving on narrow streets will be very difficult to made on the autonomous program (as Waymo, Tusimple and Plus.AI cases).

<u>The actual kingpin sensor solution, limits automation:</u>

- The VSE's monitor sensor (Figure 29) [36] that is commercially available is mechanically complex, is fully present in the semi-trailer and requires considerable modifications in this vehicle for its application.

- The integral presence of the sensor in the semitrailer limits the autonomous tractor vehicle to operate only with this semitrailer which has this sensor.

- Unconventional trailer communication is required for the automated truck [6], for transmitting the information of the angle measured by the sensor.

- Does not allow the complete automation solution in cases that require constant change of trailers. Due to the sensor being present in the trailer and not in the automated tractor vehicle, there is no angle monitoring and it is only possible to operate on controlled routes and with operational supervision (*Vera*'s case).

SENSORS TECHNICAL PROPOSALS FOR MONITOR THE VEHICLE BY THE FIFTH WHEEL

For a better understanding this part of the study, a convention of Cartesian coordinates is presented (Fig. 30):

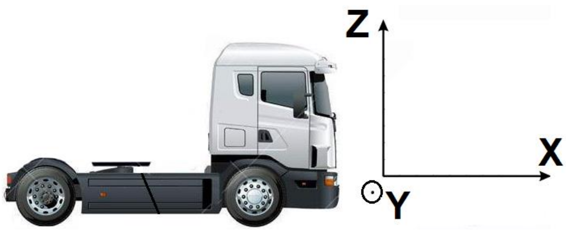

Figure 30 – Vehicle coordinate convention (author).

PREMISES – Performing practical tests, it was detected the existence of significant clearances between the king pin and the fifth wheel, which allows the translation movement of the pin (Figure 31). With the blue and white lines, is noted that the king pin travels on the X axis when the vehicle is braking and on acceleration, showing that have a considered clearence on the articulation mechanism.

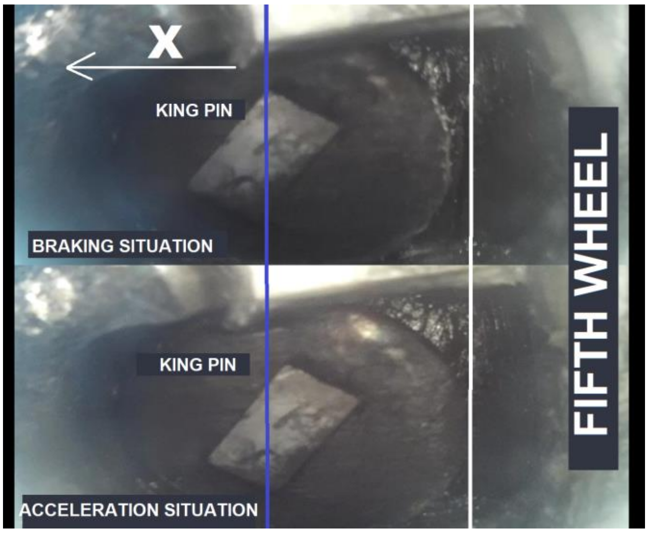

Fig. 31 – Gap between King Pin and 5th Wheel (author)

These clearances are caused by the natural wear of the kingpin, combined with a maintenance fault, without the periodic adjustment of the fifth wheel as recommended by the manufacturer [30]. Sometimes these clearances are imperceptible to the driver. In the condition of Figure 31, the following values were measured (Table 5).

Table 5 – Clearances measured by Kingpin/Fifth Wheel

Diameter Max/Min King Pin	Diamenter Kingpin Measured	5ª Wheel Clearance Measured	Clearance Total Max	Cleareance Total Measured
51/49mm	47mm	1,5mm	0,3mm	5,5mm

This real gap conditions may compromise the effectiveness of sensors that only perform angular measurement and do not consider this translation condition of the king pin on X axis. It should be noted that the solutions for monitoring articulations (commercialized [36] and patented [6, 39, 40]), are all for perform only the angular measurement between vehicles.

Based on these observations, the author proposes two technical solutions for the fifth wheel monitoring. These solutions must be practical for application, meets the indicated market necessities in this study and be effective even in these situations encountered by these practical tests.

CONTOUR CONDITIONS - To ensure effectiveness and reliability, the proposed sensors must:

- Detect the rotation of the King Pin on Z axis (articulation angle): Minimum Accuracy 0.5 deg. for Stability Control and Automation and 2.0 deg. for Telematic Systems.

- Detect the rate of change of the angle in Z (joint angle): Minimum frequency of 20 Hz [6].

- Detect translation movements of the King Pin in X (clearances) and Z (tendency to rollover) axis: Minimum accuracy minimum 1.0mm.

TELEMATIC SYSTEMS SENSOR PROPOSAL - For tracking systems, the solution needs to be easy to apply on vehicles in circulation and no structural modifications needed. For this market, the author presents a new version of the Truck Vision *Smart Mirror* sensor.

This fifth-wheel sensor that monitor the movements of the Magnetic Disc attached to the Kingpin, in addition of the angular measurement, can also will measuring its translations movements in X and Z (Figure 32).

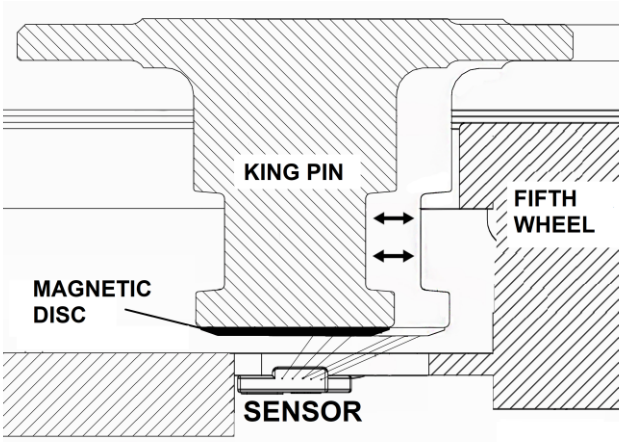

Fig. 32 – Fifth Wheel Sensor and Magnetic Disc (author)

This magnetic disk that makes a spatial reference to the fifth wheel sensor. Other alternative for this solution is to put a magnet into kingpin body, but this last proposal must be normalized and regulated.

However, the presence of a disc on the kingpin has some advantages for tracking systems, such as:

- Obtain the electronic coupling and disengagement by the magnetic disc presence close to the fifth wheel sensor, with easy application in vehicles already in circulation.

- The presence of a disc on the king pin for reference to the sensor, allows to add other features. This part could have a RF code, if have this could also serve to identify the which is coupled semi-trailer, a relevant application for tracking systems.

STABILITIES AND AUTONOMOUS SYSTEMS SENSOR PROPOSAL - For these applications, are required that the monitor sensing to have greater precision and totally independence of the semi-trailer. For these cases, the author presents a fifth wheel sensor solution that is coupled to the king pin by an electromagnet device and is fully presented on the fifth wheel (Figure 33 and 34).

This solution will act as: When the kingpin is hitched in the fifth wheel, it detects the presence of the pin and on sequence, an electric current will be induced on the electromagnet that will be coupled by magnetic attraction to the kingpin.

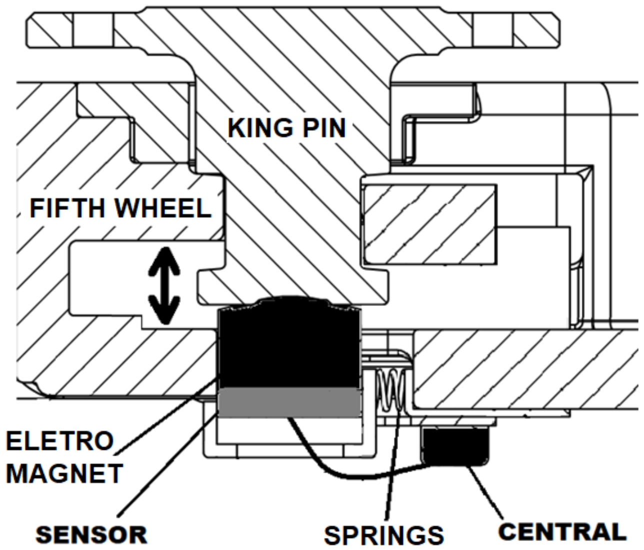

Figure 33 - Sensor with Electromagnet coupling in section view of the fifth wheel (author).

Once coupled, accelerometers and gyroscopes present below the electromagnet will detect rotations and translations movements on the X, Y and Z axes of the kingpin. For decoupling, another sensor will detect the unlocking of the fifth wheel and the electric current will be interrupted by the electromagnet, also decoupling it from the king pin.

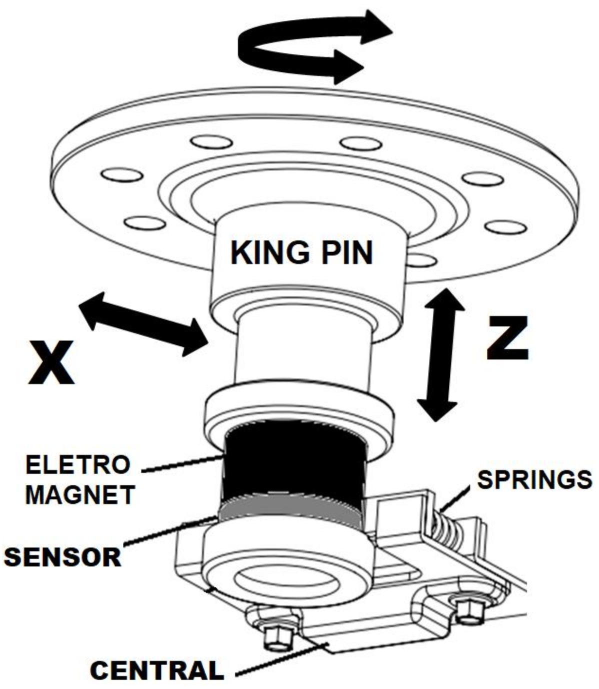

Figure 34 - Sensor with electromagnet coupling with the fifth wheel hidden (author).

Despite has more mechanical complexity than the first solution presented, this proposal will guarantee total independence, accuracy and will allow the fully monitoring of king pin movements, with greater precision and less software processing complexity than the previous solution.

OTHER OPTIONS FOR THE ANGLE MONITORING

As well as presented, due to this essential necessity of control the articulation angle, in addition to the technical proposals indicated by the author, others available patented solutions are presented above:

- First Option: VSE King Pin Angular Sensor [36] (Figure 29) used on semitrailers for electronic control of directional axles. Is a complex mechanical solution fully present on the semitrailer, which demands of a considerable modifications on this vehicle for its application.

- Second Option: Wenova system [39] (Figure 35): It has a magnetic marker (13) on the king pin (5) and a sensor (11) in a mechanical device (19) present on the fifth wheel (9). When the vehicle is hitched, this mechanical device (11) brings the sensor (11) in a closest position to the king pin (5) and only in this condition, the system can make the angular measurement. This system will be inefficient when have mechanical clearances between the king pin and the fifth wheel and for detect the translations of the king pin on the Z axis.

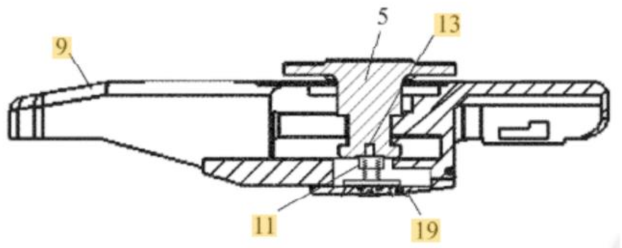

Figure 35 – Wenova Fifth Wheel Angular Sensor [39]

This inefficiency is because the sensor is technically limited only to read angle in only a very close condition to the magnetic marker. Those limitations are indicated by its own manufacturer, in the patented state of the art.

- Third Option: Due the speed difference between the wheels [40] (Figure 36): Cargobull/Knorr Bremse presents a system that uses the wheel speed sensors of the EBS to measure the angle between vehicles. This system calculates the angle by the difference of the speeds between the left and right wheels of the semi-trailer (AL and AR), in relation to the wheels speeds of the tractor (VL and VR).

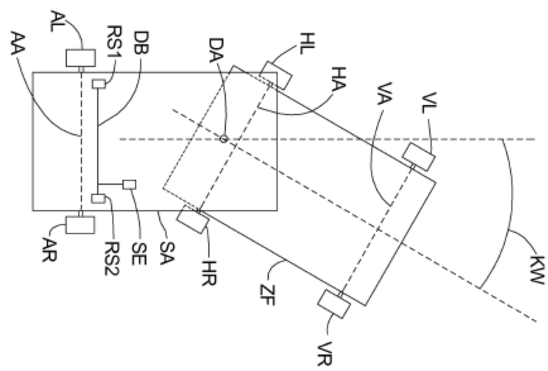

Fig. 36 – Angle calculation by wheel speed difference [40]

Although is functional, it also depends of information from the both vehicles and will work only if both units have EBS. Another limitation is that this system is only applied for maneuver situations and if all wheels have friction against the road. In a slippery road situation, the wheels will have similar speeds close to zero, making impossible to calculate the angle between vehicles with this system.

- Fourth Option: Angle monitor by cameras [6] – Figure 37: The use of sensors without contacts, without structural modifications and outside the fifth wheel is defended by some authors that consider the articulation hostile environment for electronics devices. Is proposal a system for angular measurement by cameras positioned behind the cabin. Although have a simple implementation, presents a complexity software processing, the camera can accidentally be covered up, requires a calibration at each coupling and is not applicable for open semitrailers.

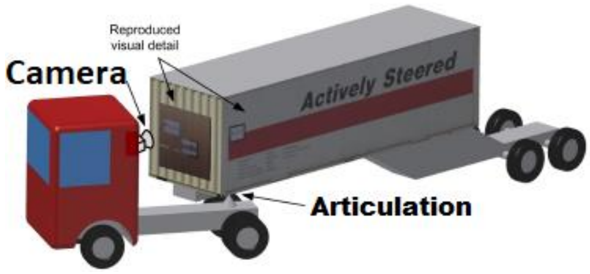

Figure 37 - Calculation the angle by cameras [6]

CONCLUSIONS

From this study, it was verified the high necessity of the angular monitoring systems for the fifth wheel articulation. Even with these high necessities, there was a lack of a robust, precise and at the same time accessible and easy to apply sensor solutions that meet these demands. The concern for better road safety indexes from government and also from the author, motivated this research for presenting viable and plausible solutions to these technical gaps found.

The commercial solution for angular monitoring, initially developed for the electronic directional axles control on the semi-trailer [36] is now used as a palliative in systems that necessarily need this information. By the way, the others solutions [39, 40, 6] are still complex and with several technical limitations. The use of palliative systems or the empirical and complex methods, which depends of many variables [5, 31], are adopted too, due to this lack of a most practical and precise angular sensor, only presents in the tractor and not in the semi-trailer.

This lack of articulation solutions monitor creates limitations, especially for the stability control systems. However, if this useful angular monitoring existed, other relevant features could be added and the stability control, would present a better technical performance. Beyond the applicability in safety devices, other functionalities and facilities could be added for tracking and the autonomous systems, as the integral driver conduct control.

These two sensors proposals aim to meet not only a technical demand, but a primary objective for have a solution for this limited effectiveness that the stability control systems will have in Brazil. Therefore, from the state of the art founded for the angular monitoring solutions, it can be concluded that the sensors technical proposals on this study are interesting options, for the technical gaps founded. As the sensors proposals are shown to be simpler, independent, practical and for monitor all variables presents on the king pin/fifth wheel articulations.

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