International Journal of Automotive Research, Vol. 9, No. 4, (2019), 3110-3124

Iran University of Science and Technology

International Journal of Automotive Engineering

Journal Homepage: ijae.iust.ac.ir

ISSN: 2008-9899

Approaching Effective Parameters of Multi-Trailer Articulated Vehicles in S-Turns with Co-simulation of TruckSim and Taguchi Method

Sina Sadeghi Namaghi[1*], Nima Sadeghi Namaghi [2]

[1*] Department of Mechanic, Engineering Faculty, Ferdowsi University of Mashhad, Azadi Square, Mashhad, Iran.

[2], Department of Water Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Azadi Square, Mashhad, Iran.

ARTICLE INFO

Article history:

Received : 24 April 2019

Accepted: 28 Nov 2019

Published: 1 Dec 2019

Keywords:

Lateral Stability

Rearward Amplification

Drive Simulation

TruckSim

Taguchi Method

ABSTRACT

Heavy articulated vehicles have low performance with respect to stability analysis due to their multifaceted geometry and dynamics especially when it comes to non-linear maneuvers. In this study in order to find out which statistical and dynamical factors have the most effect on stability of this type of vehicle without getting involve with their complex mathematical theory, combination of drive simulation and Taguchi method is used. Since the number and variety of factors are extensive, multi-step Taguchi method used. This method applied on values of modified rearward amplifications of each units of vehicle as a criterion of lateral stability. Results show the high effect of suspension and load geometry of Vehicle Units on lateral stability and safety

1. Introduction

Safety is a common concern for all roads users. It is challenged by the traffic density and driving conditions, which have increased substantially over the past years and is expected to continue to rise in the future. Prevention of Multi-Articulated Vehicles (MAV) overturning events is an essential concern too. Only in United Kingdom nearly 60 injury crashes per year involving truck overturns at roundabouts is reported [1]. In a French study, 39 roll-over crashes occurred on 27 roundabouts were analyzed. In 95% of cases, the vehicle was an articulated lorry swiped over outside the ring, on its right side [2]. Most of these crashes are not reported in statistical crash records because they are usually not serious and the speed of involved vehicles is usually low [3]. Nevertheless, these events have economic consequences due to road damage, lorries damage and subsequent traffic disruptions. Langwieder et al. [4] investigated the benefit of electronic stability control functions in real accident situations involving cars and trucks. The purpose of these control functions was to prevent rollovers and lateral instability [5]. The latter concluded that improving the safety of trucks considerably contributes to road safety as they are involved in 16 % of the fatal accidents. Up to 9 % of the serious accidents involving trucks could have been positively influenced or even prevented with electronic stability control functions. Such functions have already been introduced for tractor semitrailer combinations [6].

Several researchers have considered the influence of the suspension, tires, chassis, and fifth-wheel on the lateral, vertical and longitudinal location, which affects the vehicle dynamic behavior in turnings and maneuvers [7]. Moreno et al. analyzed the last trailer of MAV’s, and reported that the static rollover threshold factor represents a three-dimensional phenomenon, and

*Corresponding Author
Email Address: sinasadeghinamaghi@um.ac.ir
http:// tlx.doi.org/10.22068/ijae.9.4.3108

[DOI: 10.22068/ijae.9.4.3108]

that longitudinal parameters and lateral load transfer play important roles in relation to the factor calculation [8]. On the other hand, an improperly loaded trailer can result in a poor trailer stability, overweight on axles, tires deterioration, and damage of the pavement [9]. To calculate the three-dimensional swipe threshold factor for a trailer, the previous work developed a three-dimensional simplified model that considers different characteristics of trailers, such as the suspension, tires, fifth-wheel, chassis and trailer/trailer angle [10]. In these studies for measuring sensitivity and stability (lateral and roll over) are done by using GPS and sensors attached to MAV's body, however their main points went on suspension and geometrical factors [11].

In non-experimental researches Rearward amplification appears to be the dominant performance property distinguishing the yaw response of multi-articulated vehicles from that of other commercial vehicles. This approach has been used in many studies to quantify dynamic behavior of articulated vehicles [12-14]. During transient turning maneuvers, the lateral acceleration of each trailing unit exceeds that of its preceding unit. As a result, the last trailer in a vehicle train has the tendency to swing out excessively which can lead to roll-over [13]. Two methods for calculating the value of rearward amplification are as bellow: 1) rearward amplification is calculated by using lateral accelerations of each unit tails [15], and 2) rearward amplification is defined in the frequency domain as the ratio between the lateral acceleration gains of the last trailer to the towing vehicles front wheel steering angle [16]. Since these studies were experimental and based on quantity of lateral acceleration or frequency amplitude gained by sensors in critical time (depend on lateral safety criterion) they were discrete, so for more precious time line measurement with fine time step is needed.

In conclusion previous researches were lack of two main points. First extensive and variety of MAV's dynamical, statically and geometrical factors must be reconsidered since previous studies absorbed on general ones. Second point goes for a precious and functional method for defining and computing lateral error of units (not only the tail of them) and can be applied even for simulation studies. In the present study, to approach the most effective design parameters including suspension, chassis, tire, and engine factors in S-turn maneuver a specific type of MAV is selected. TruckSim simulation data for proposed vehicle is validated by "Vehicle Standard Guidelines" [17]. To find rearward amplification value for lateral deviation of tails of each trailer, a new modified method along with Multi-Step Taguchi method apply.

2. Approach

In this study a tractor with two articulated trailers jointed by two 5th wheel hitches is chosen (Figure 1 B). The application of this type of Ecocomobi is for super heavy loads and it allows having maximum number of hitches (5th wheel or other types) and since it has commercial usage in road networks, it can put the travel safety at the high risk [18]. Longer and heavier vehicles have been allowed for many years outside Europe, for example in Australia, South Africa, Mexico, Canada and the USA but it should be noted that Ecocombi's have not been permitted officially in most European countries yet, except Sweden and Finland [19]. Of course there are other combinations and articulations sets but lack of study in two articulated MAVs because of their complex and coupled dynamics give enough reasons to choose this type of MAVs in this study as representative of other multi articulated vehicle.

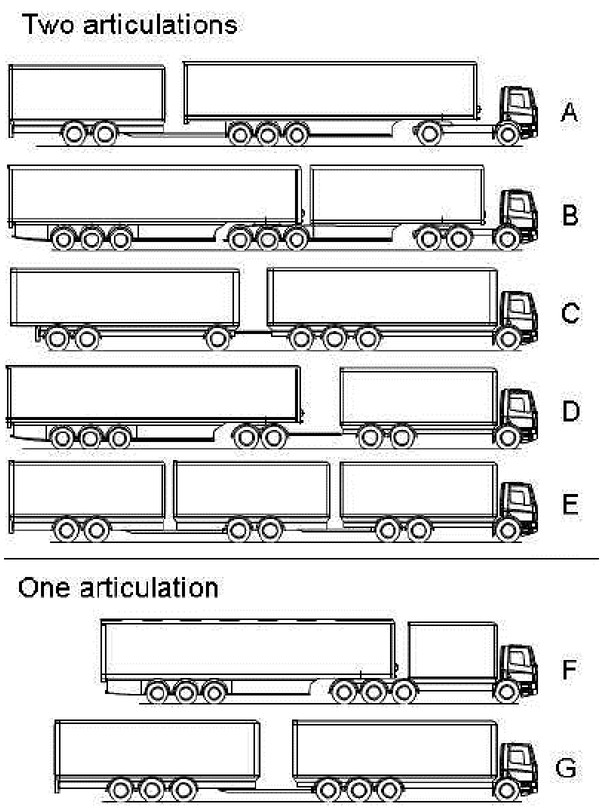

Figure1: One/Two Articulated Vehicles (Ecocombi)

[DOI: 10.22068/ijae.9.4.3108]

Each unit of the vehicle (Tractor and two Trailers) have their own independent parameters. Since the number of parameters is great enough to handle by applying one step Taguchi Method, it is rational to categorize them into smaller classes. The proper classification in this research is based on two-step Taguchi. In each step effective factors of every mechanical and geometrical parameters tables are selecting by analyzing the SNR result of Taguchi method and top ones of each table form the second step with different boundary value. Boundary value of each parameters in this method are defined my 6σ process which will be explained in section 3.2. As it will be discuss later the reason of designing the study in two step of classification and not more is limitation of boundary value of vehicle's parameters which leads to mechanical and physical interference.

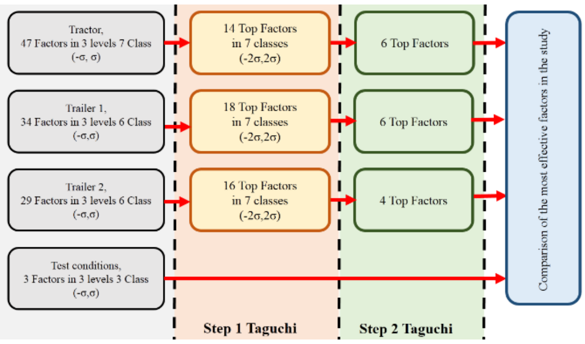

Figure 2 shows an overall view of approach and paper's goal.

Figure 2: Overall View of Approach used in this study.

2.1. Parameters Classification of MAV Units

Classification of each unit parameters are based on TruckSim Software configurations which is also follows vehicle's mechanical components and characteristics. Sections 2.1.1 to 2.1.3 describe these categorizations in form of tables for each unit of two articulated vehicle simulated in TruckSim.

2.1.1. Tractor Parameters

Tractor parameters according to TruckSim Vehicle Configuration sections are organized in Tables 1-9.Needless to mention all axles used in this study are symmetric.

Table1: Tractor Geometric Parameters

	Factor
1	Sprung Mass of Tractor
2	Height of Tractor
3	Length of Tractor
4	Axle 2 Longitudinal Distance
5	Axle 3 Longitudinal Distance

Table2: Tractor Tire Parameters

	Factor
1	Tire Type (Touring,Trailer,Truck)

Table 3: Tractor Powertrain Parameters

	Factor
1	Wheel Drive (WD)
2	Powertrain Type
3	Gear Ratio (Axle 1 to 2 and 2 to 3) Open Differential

Table 4: Tractor Hitch Parameters (5^{th} wheel)

	Factor
1	Roll stiffness
2	Pitch stiffness
3	Yaw stiffness

Table 5: Tractor Steering Axle 1 Parameters

	Factor
1	Nominal Steering gear ratio (Axle 1)
2	Wheel steering kinematics (Right=Left)
3	Caster Angle (Right=Left)

A Tractor Suspension system of axle 1 is different from axles 2 and 3. Axle 1 is steering system and have air springs while two other axles are driving and leaf springs ones. So, Suspension Kinematics and Compliance Factors are divided to 2 parts.

Table 6: Tractor Axle 1 Suspension Kinematics

	Factor
1	Axle 1 Suspension Kinematic Type
2	Unsprung mass of suspension system
3	Axle roll and yaw inertia
4	Spin inertia for each side
5	Lateral distance between wheels
6	Static toe angles
7	Static Camber angles
8	Dive (Caster) Angles

[DOI: 10.22068/ijae.9.4.3108]

Table7: Tractor Axle 2 and 3 Suspension Kinematics

	Factor
1	Axle 2 Suspension Kinematic Type
2	Unsprung mass of suspension system
3	Axle roll and yaw inertia
4	Spin inertia for each side
5	Lateral distance between wheels
6	Static toe angles
7	Static Camber angles
8	Axle 3 Suspension Kinematic Type

Table 8: Tractor Axle1 Suspension Compliance

	Factor
1	Suspension Compliance Type (Axle 1)
2	Spring compression/Jounce Ratio (Axle 1)
3	Upper seat height adjustment (Axle 1)
4	Damper force vs compression rate (Axle 1)
5	Stroke (Axle 1)
6	Jounce & Rebound Ratio (Axle 1)
7	Auxiliary Roll Moments (Axle 1)
8	Auxiliary roll damping (Axle1)

Table 9: Tractor Axle 2and 3 Suspension Compliance

	Factor
1	Suspension Compliance Type (Axle 2&3)
2	Spring compression/Jounce Ratio (Axle 2&3)
3	Upper seat height adjustment (Axle 2&3)
4	Damper force vs compression rate (Axle2&3)
5	Stroke (Axle 2&3)
6	Jounce & Rebound Ratio (Axle 2&3)
7	Auxiliary Roll Moments (Axle 2&3)
8	Auxiliary roll damping (Axle2&3)

2.1.2. Trailer 1 Parameters

Likewise previous section, Trailer 1 parameters according to TruckSim Vehicle Configuration sections are organized in Tables 10-15. No need to mention that unlike Tractor Unit, the 3 axles of Trailers are identical in properties.

Table 10: Trailer 1 Geometric Parameters

	Factors
1	Height of CG unladen Trailer Bed
2	Height of Hitch point of Trailer Bed
3	Sprung mass of Trailer Bed
4	Longitudinal Distance of CG Trailer Bed
5	Length of Trailer Bed
6	Axle 1 Longitudinal Distance
7	Axle 2 Longitudinal Distance
8	Axle 3 Longitudinal Distance

Table 11: Trailer 1 Tire Parameters

	Factors
1	Tire Type (same for all/Duality)
2	Tire Space of Duality (all same)

Table12: Trailer 1 Hitch Parameters (5th wheel)

	Factor
1	Roll stiffness
2	Pitch stiffness
3	Yaw stiffness

Table 13: Trailer 1 Suspension Kinematics Parameters

	Factors
1	Dynamic Load transfer coefficients
2	Suspension Kinematics Type (All axles are same)
3	Unsprung mass of suspension
4	Axle roll and yaw inertia
5	Spin Inertia for each side
6	Lateral Distance between wheels of axle
7	Static toe angle
8	Static Camber angle
9	Caster Angle Type

Table 14: Trailer 1 Load Parameters

	Factors
1	Height of Load
2	Mass of the Load
3	Longitudinal Distance Load CG

[DOI: 10.22068/ijae.9.4.3108]

Table 15: Trailer 1 Suspension Compliance Parameters

	Factors
1	Suspension Compliance Type
2	Spring compression/Jounce Ratio
3	Upper seat height adjustment
4	Damper force vs compression rate
5	Damper compression/Jounce Ratio
6	Stroke
7	Jounce & Rebound Ratio
8	Auxiliary Roll Moments
9	Auxiliary roll damping

2.1.3. Trailer 2 Parameters

Similar to Trailer1, Trailer2 parameters according to TruckSim Vehicle Configuration sections are structured in Tables 16-20.

Table 16: Trailer 2 Geometric Parameters

	Factors
1	Height of CG unladen Trailer Bed
2	Height of Hitch point of Trailer Bed
3	Sprung mass of Trailer Bed
4	Longitudinal Distance of CG Trailer Bed
5	Length of Trailer Bed
6	Axle 1 Longitudinal Distance
7	Axle 2 Longitudinal Distance
8	Axle 3 Longitudinal Distance

Table 17: Trailer 2 Tire Parameters

	Factors
1	Tire Type (same for all/Duality)
2	Tire Space of Duality (all same)

Table18: Trailer 2 Suspension Kinematic Parameters

	Factors
1	Dynamic Load transfer coefficients
2	Suspension Kinematics Type (All axles are same)
3	Unsprung mass of suspension
4	Axle roll and yaw inertia
5	Spin Inertia for each side
6	Lateral Distance between wheels of axle
7	Static toe angle
8	Static Camber angle

Table 19: Trailer 2 Load Parameters

	Factors
1	Height of Load
2	Mass of the Load
3	Longitudinal Distance Load CG

Table 20: Trailer 2 Suspension Compliance Parameters

	Factors
1	Suspension Compliance Type
2	Spring compression/Jounce Ratio
3	Upper seat height adjustment
4	Damper force vs compression rate
5	Damper compression/Jounce Ratio
6	Stroke
7	Jounce & Rebound Ratio
8	Auxiliary Roll Moments
9	Auxiliary roll damping

3. Method

Before Applying Multi-Step Taguchi, Number of Levels, their value boundary for each Factors and a new modified method for calculation of rearward amplification must be set.

3.1. Modified Rearward Amplification

As it was explained briefly, Rearward Amplification (RA) seems to be the dominant performance property distinguishing the yaw response of multi-articulated vehicles from that of other commercial vehicles. It has been used in many studies to quantify the dynamic behavior of articulated vehicles. Two Methods of calculating RA are common in literature. In the first Method, rearward amplification is calculated by using maximum value of lateral accelerations ot each unit's tail, which presents in equation [20] (1):

$$RA_t = \frac{Max\left(abs\left(a_{yn}\right)\right)}{Max\left(abs\left(a_{y1}\right)\right)} \tag{1}$$

The second method defines rearward amplification in the frequency domain as the ratio between the lateral acceleration gains of the last trailer to the towing vehicle's front wheel steering angle. In other word, in the second definition for rearward amplification the lateral acceleration due to steering wheel angle $H_{a_{y_n},\delta 1} = \left|\frac{a_{yn}}{\delta_1}\right|$, and the lateral acceleration due to steering wheel angle

[DOI: 10.22068/ijae.9.4.3108]

gained by the towing vehicle $H_{ay_1,\delta 1} = \left|\frac{a_{y1}}{\delta_1}\right|$ are used [21]. Equation (2) shows formulation of this method:

$$RA_f = Max\left|\frac{H_{ay_n,\delta 1}}{H_{ay_1,\delta 1}}\right| \quad (2)$$

In these methods, depending on MAV's Type (Figure 1) and road conditions, Value of RA has critical boundary, which if the absolute value of rearward amplification exceeds, it will be considered as failure and crash. Figures 3 and 4 show the maximum allowable rearward amplification of MAV with 2 trailers in dry road condition for both mentioned methods [20].

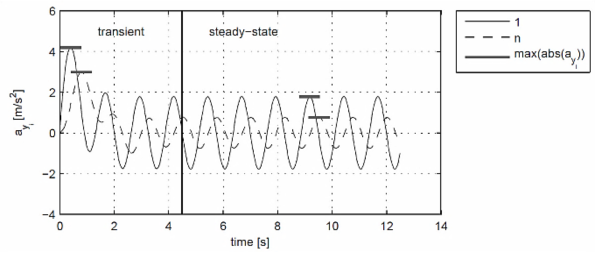

Figure3: Maximum Allowable rearward amplification by First Method; RA_t = 1.4

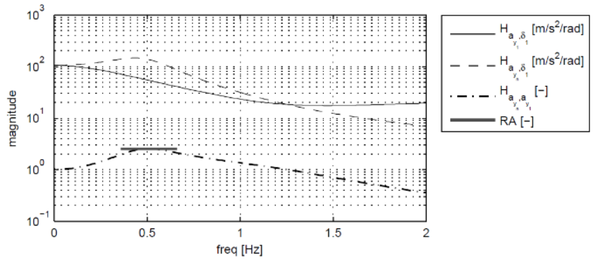

Figure4: Maximum Allowable rearward amplification by Second Method; RA_f =2.5

The second method based on analyzing of Frequency Response Function (FRF) which requisite the definition of motion equations, state space matrices and leave it to the MATLAB System Identification Toolbox. This method however is more accurate and its initial data are more accessible for this research, but depending on the number of freedom degree of modeling and linearization in simulation study bring errors in calculating rearward amplification value.

The new modified method is based on the second method. But by using TruckSim real-time Simulator software which simulate the MAV non-linear and independent of its freedom degree of modeling, one can have more accuracy in computing lateral accelerations and steering angles. Since in S-turn maneuver lateral accelerations of trailers fluctuate, the rearward amplification value computes through equation 2 for every 0.01s (Minimum available time step of TruckSim simulation).

Similar to previous studies, this method has its own critical boundary name RA_s. For the test conditions in this research, the safe RA_s boundary is:

$$1 \le RA_s \le 2.5 \quad (3)$$

RA_s=1 indicates the situations when units are aligned and it's the research target. Due to standard road width (3m) and maximum allowable hitch orientation angle to avoid jackknifing (60 Degree), if RA exceeds 2.5 it will assume as failure and crash [17]. To apply Taguchi method for each test, a numerical value is needed to express the deviation error of rearward amplifications from RA_s = 1 as criterion. To find out deviation error or similarity of two vector of arrays dozens of methods have been proposed and applied in mathematical and genetics fields [22]. Most of these methods based on giving a percentage value of having 0 or 1 for being different or exact similar respectively. These methods cannot be applied in this study since having identical value between i-th number two arrays (Vector RA_s=1 and Unit's RA_s Vector during the path) are almost zero. So in this study "Pairwise distance between two sets of observations" methods, in precise "Euclidean distance" method apply which one can function it by "D=pdist2" command in MATLAB [23]. With this command similarity or deviation error of these vectors results as format of one number (Called "D" Value) and operational to apply for Taguchi method's goal column. Figures 5-6 and Table 21 brings the results of running an example test to clarify the process discussed above.

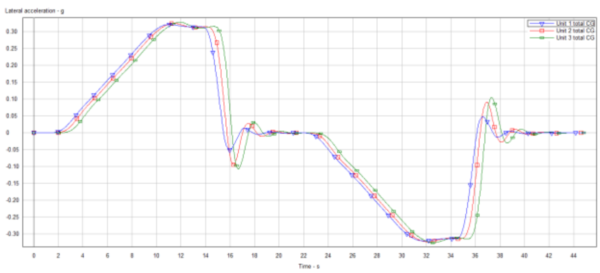

Figure5: Lateral Acceleration of CG's Units for an example Test

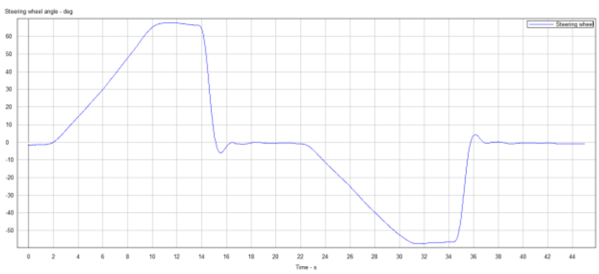

Figure6: Steering front wheel angle for an example Test

Table 21: Results of Unit's RA and Calculation of "D" Value for 10 time step

	a_y Unit 3 (g)	a_y Unit 2 (g)	a_y Unit 1(g)	Steering Wheel Angle (deg)	Max RA_s	Target RA_s=1
1	0.001	0.0009	0.0007	2	1.4285	1
2	0.021	0.0189	0.0157	4.58	1.3375	1
3	0.041	0.0369	0.0307	7.16	1.3355	1
4	0.061	0.0549	0.0457	9.74	1.3347	1
5	0.081	0.0729	0.0607	12.32	1.3344	1
6	0.101	0.0909	0.0757	14.9	1.3342	1
7	0.121	0.1089	0.0907	17.48	1.3340	1
8	0.141	0.1269	0.1057	20.06	1.3339	1
9	0.161	0.1449	0.1207	22.64	1.3338	1
10	0.181	0.1629	0.1357	25.22	1.3338	1
	D = 1.322					

3.2. Levels Design

Back to parameter classification section, classes have 1 to 9 factors. Due to limitation of MINITAB program for Taguchi designing, 3 levels are the utmost steps it can be considered. To find a proper data interval for levels in each factor, Tolerance Interval Tool in MINITAB software applied. As an example, Factor "Longitudinal Distance between Axles" for proposed vehicle can vary between 0.1m to 1.3m due to Vehicle Standard Guideline [17]. By considering (0.1, 1.3) as lower and upper boundary value for this factor and proceeding Tolerance Interval Tool, 6σ intervals yield. It's important to mention that number and their value of data use between the interval boundaries of each factor are arbitrary. Note that for factors which enough data can not be accessible through manufacture's guidelines to build intervals are conceded to TruckSim application. In this research (-σ, σ) and (-2σ, 2σ) intervals applied for first and second step of Taguchi respectively. Table 22 and figures 7 show the results of this example. (Mark * represent the default value)

Table22: Example longitudinal distance between Trailer's Axles Interval and related D Value

	Longitudinal distance between Trailer's Axles (m)	D Value
1	0.1	0.512
2	0.2	0.600
3	0.5	0.650
4	1	1.000
5	1.1	1.012
6	1.2	1.110
7	1.27*	1.220
8	1.3	1.530

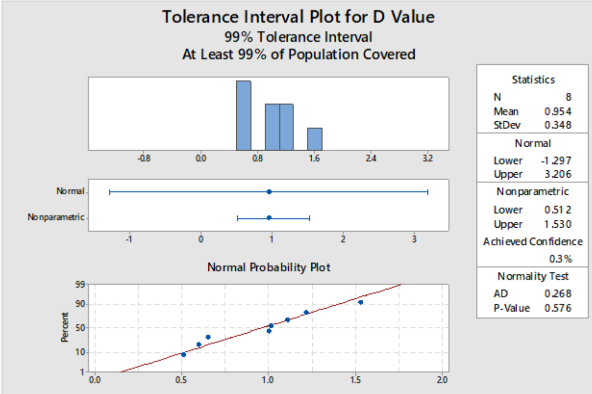

Figure 7: Tolerance Interval plot for D Value

Referring to Figure 7, (-σ, σ) and (-2σ, 2σ) interval of D value are equal to (0.606, 1.32) and (0.258, 1.65). Longitudinal Distance of Axles intervals related to these D values are (0.19, 1.275) and (N/A, N/A). N/A occurs when related interval for factors interfere with vehicles dynamics or design guidelines.

3.3. Test Conditions

In order to find the effect of driving and test conditions, a one-step Taguchi process applied. Levels are designed base on JASO (Japanese Standard Organization) program for heavy vehicles [24]. The * mark in table 23 resembles default road and driving condition in TruckSim Simulator.

Table 23: Test Conditions Levels

	Level 1	**Level 2**	**Level 3**
Test Speed	30 Km/h	50 Km/h	*80 Km/h
Road Friction	0.2	0.5	*0.85
Bank Degree	*0 Deg	10 Deg	20 Deg

4. Results

The results of applying the first and second step of Taguchi's Method for each unit parameters classes are presented in sections 4.1 to 4.3.

[DOI: 10.22068/ijae.9.4.3108]

4.1. Tractor Unit Results

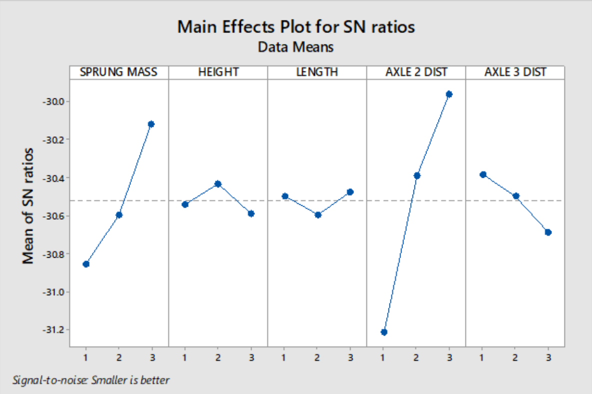

Figure8: First Step Taguchi for Geometric Factors

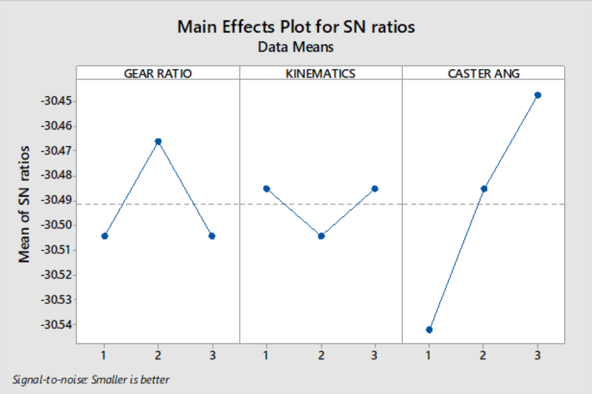

Figure9: The First Step Taguchi for Powertrain Factors

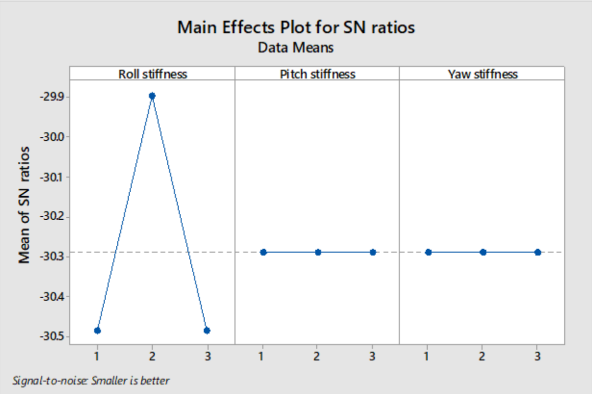

Figure10: First Step Taguchi for Hitch Factors

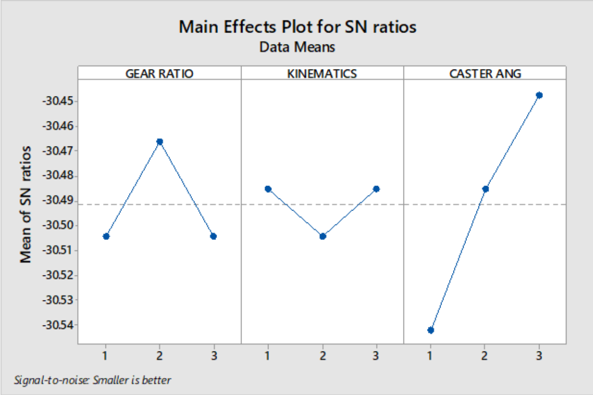

Figure11: First Step Taguchi for Steering Factors

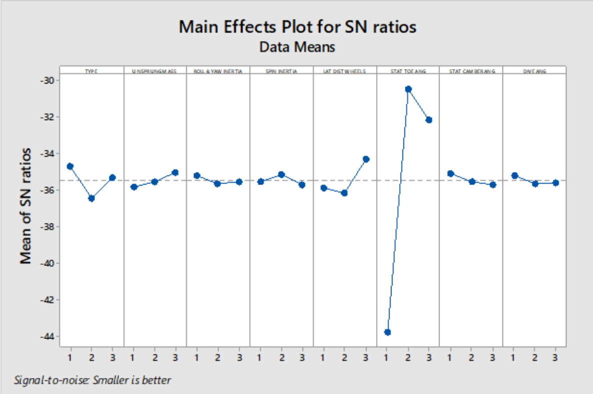

Figure12: First Step Taguchi for Suspension Kinematics of Axle 1

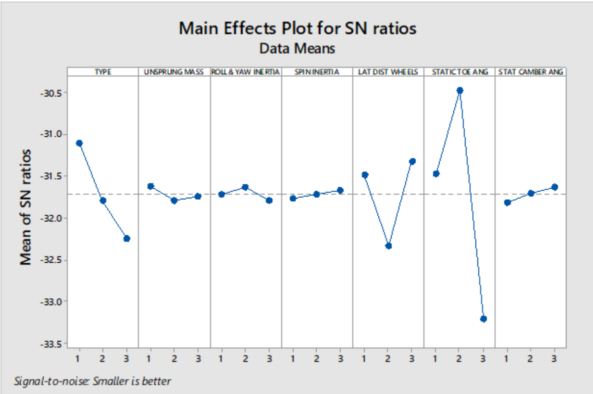

Figure13: The First Step Taguchi for Suspension Kinematics of Axles 2 and 3.

[DOI: 10.22068/ijae.9.4.3108]

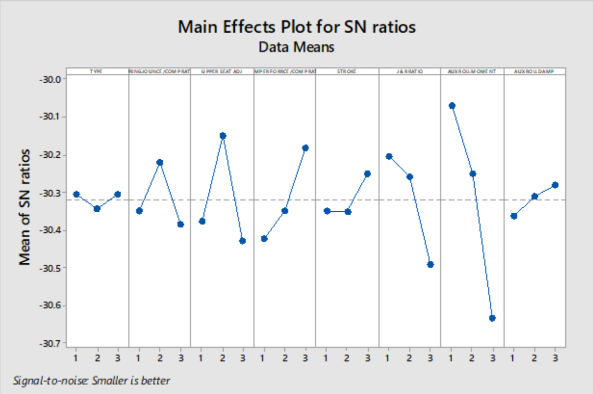

Figure14: First Step Taguchi for Suspension Compliance of Axle 1

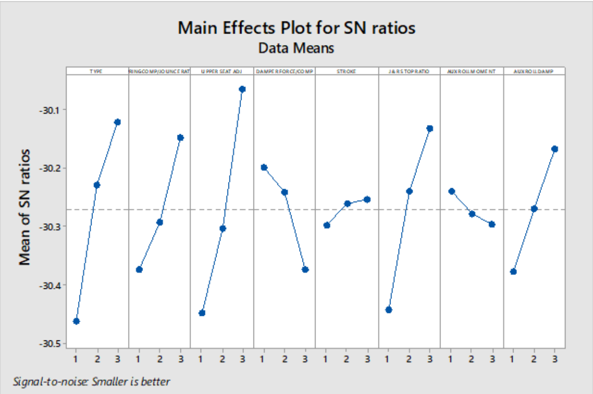

Figure15: First Step Taguchi for Suspension Compliance of Axles 2 and 3

No need to mention Tire Parameters consist of only one factor, so Taguchi Method didn't apply and consider it for the next step. Effective Factors of each class are represented in Table 24.

Table 24: Effective Factors of the First Step Taguchi for Tractor Unit

No.	Class	Tops
1	Geometry Factors	Sprung mass
		Axle 2 Distance
		Axle 3 Distance
2	Tire Factors	Types
3	Powertrain Factors	WD
		Type
4	Hitch Factors	Roll Stiffness
5	Suspension kinematics Factors	Toe angle
		Lateral distance between the wheels
		Type
6	Suspension compliance Factors	Damper force /compression ratio for axles
		Axle Type
		Jounce and rebound stop ratio for axles
7	Steering Factors	Caster Angles

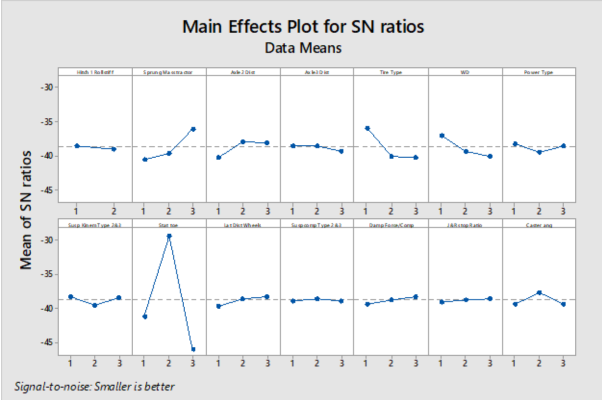

Figure16: Second Step Taguchi for Effective Factors of the First Step.

Table 25: Effective Factors of Second Step Taguchi for Trailer Unit

	Class	Factor
1	Geometry Factors	Sprung Mass
2	Tire Factors	Tire Type
3	Suspension Kinematic Factors	Type
		Toe Angle
4	Powertrain Factors	WD
5	Steering Factors	Caster Angle

4.2. Trailer 1 Unit Results

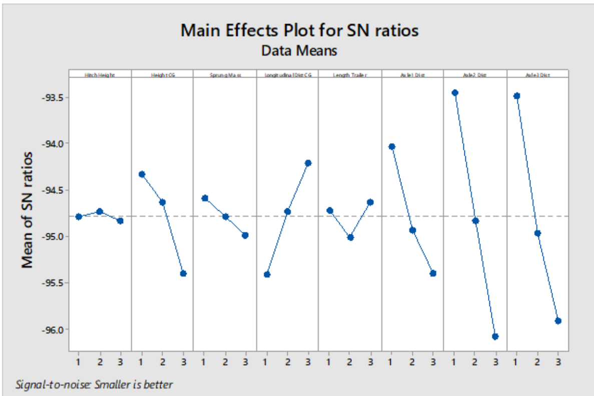

Figure17: The First step Taguchi for Geometric Factors

[DOI: 10.22068/ijae.9.4.3108]

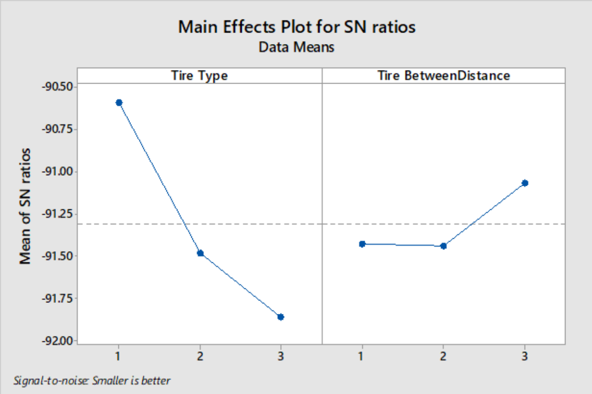

Figure18: First Step Taguchi for Tire Factors

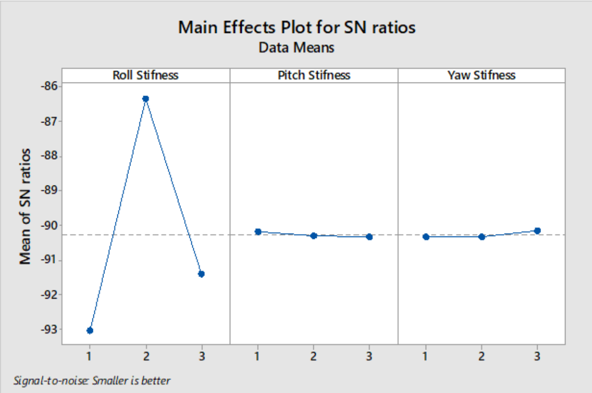

Figure19: the First Step Taguchi for Hitch Factors

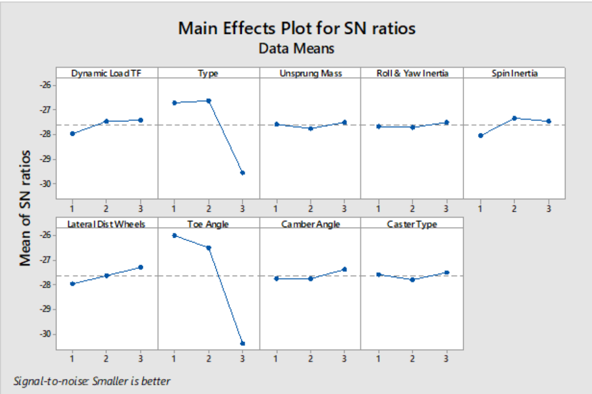

Figure20: First Step Taguchi for Suspension Kinematic Factors

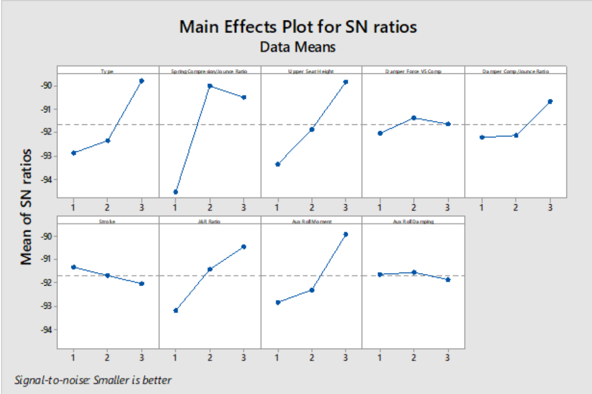

Figure21: First Step Taguchi for Suspension Compliance Factors

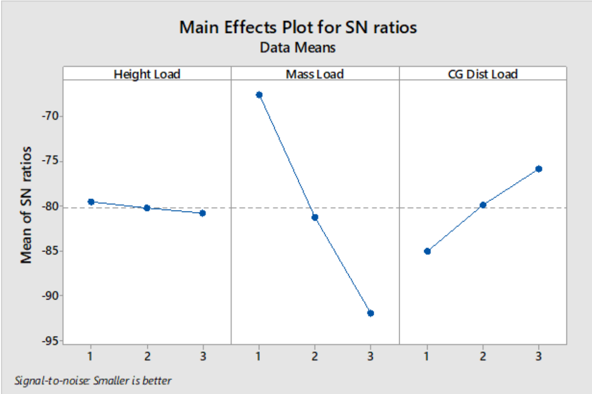

Figure22: First Step Taguchi for Load Factors

Table 26: Effective Factors of the First Step Taguchi for Trailer 1 Unit

	Class	Effective Factors
1	Geometry Factors	Height of CG unladen Trailer Bed
		Sprung mass of Trailer Bed
		Longitudinal Distance of CG Trailer Bed
		Axle 1 Distance
		Axle 2 Distance
		Axle 3 Distance
2	Tire Factors	Tire Type
3	Hitch Factors	Hitch 2 Roll stiffness (5th wheel)
4	Suspension Kinematics Factors	Suspension Kinematics Type
		Static toe angle (L=R)
5	Suspension Compliance Factors	Suspension Compliance Type
		Spring compression/Jounce Ratio
		Upper seat height adjustment
		Damper compression/Jounce Ratio

[DOI: 10.22068/ijae.9.4.3108]

		Jounce & Rebound Ratio
		Auxiliary Roll Moments
6	Load Factors	Mass of the Load
		Mass Center of Load

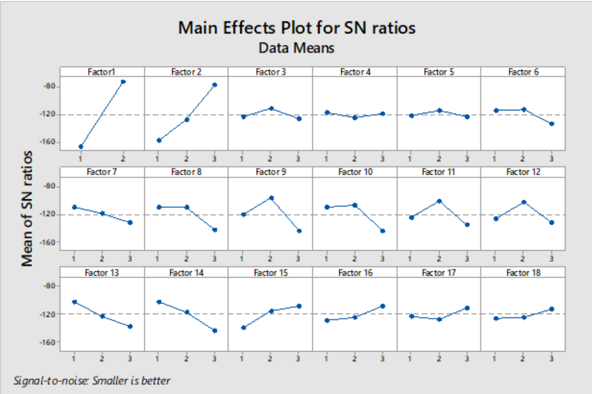

Figure23: Second Step Taguchi for Effective Factors of the First Step

Table 27: Effective Factors of Second Step Taguchi for Trailer 1 Unit

	Class	Effective Factors
1	Geometry Factors	Height of CG unladen Trailer Bed
		Axle 3 Distance
2	Tire Factors	Tire Type
3	Hitch Factors	Hitch 2 Roll stiffness (5th wheel)
4	Suspension Kinematics Factors	Suspension Kinematics Type
		Static toe angle (L=R)
5	Suspension Compliance Factors	Suspension Compliance Type
		Spring compression/Jounce Ratio
6	Load Factors	Mass of the Load
		Mass Center of Load

4.3. Trailer 2 Unit Results

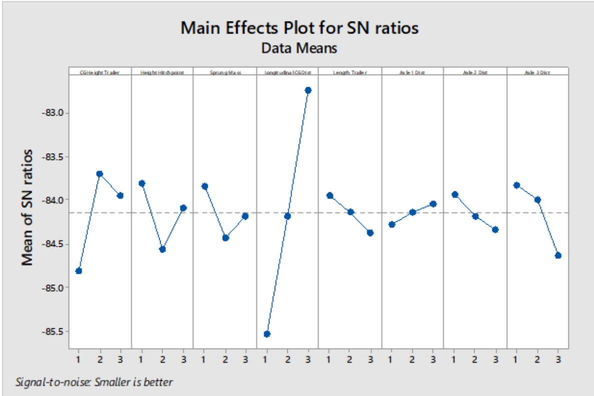

Figure24: The First Step Taguchi for Geometric Factors

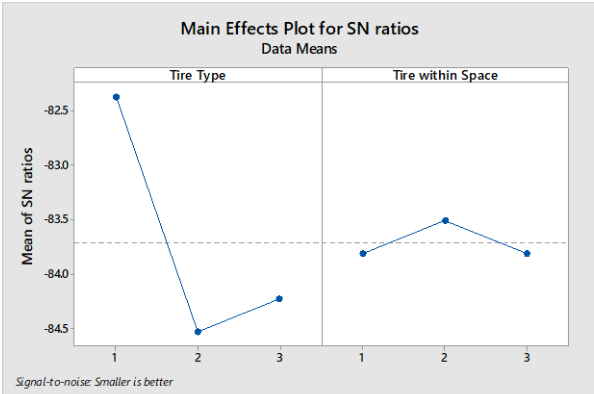

Figure25: First Step Taguchi for Tire Factors

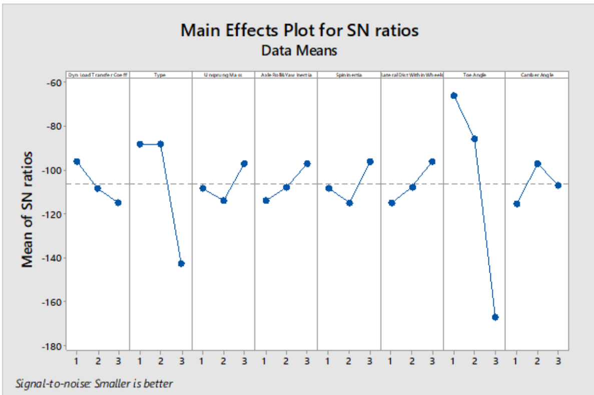

Figure26: First Step Taguchi for Suspension Kinematic Factors

[DOI: 10.22068/ijae.9.4.3108]

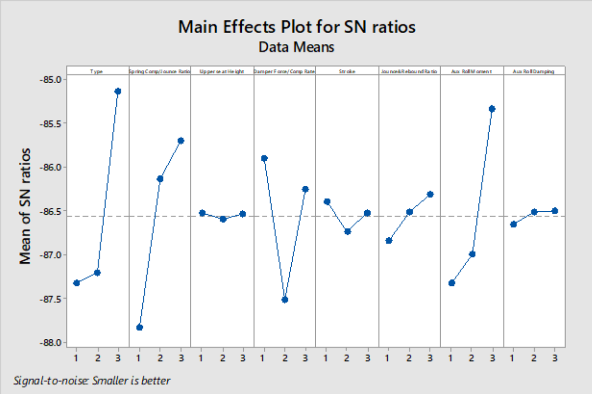

Figure27: First Step Taguchi for Suspension Compliance Factors

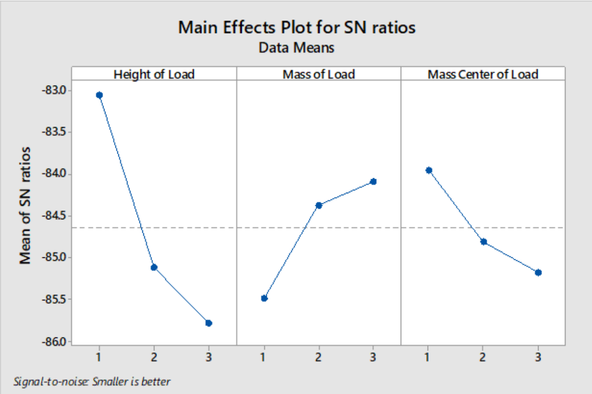

Figure28: The First Step Taguchi for Load Factors

Table 28: Effective Factors of First Step Taguchi for Trailer 2 Unit

	Class	Factors
1	Geometry Factors	Longitudinal Distance of CG Trailer Bed
		Height of CG unladen Trailer Bed
		Axle 3 Distance
2	Tire Factors	Tire Type
3	Suspension Kinematics	Dynamic Load Transfer Coefficient
		Suspension Kinematic type
		Toe Angle
		Lateral Distance within wheels
		Axles Roll & Yaw Inertia
4	Suspension Compliance	Suspension Compliance Type
		Spring Compression/Jounce Ratio
		Damper Force/Compression Rate
		Auxiliary Roll moment
5	Load Factors	Height of Load
		Mass of the Load
		Mass Center of Load

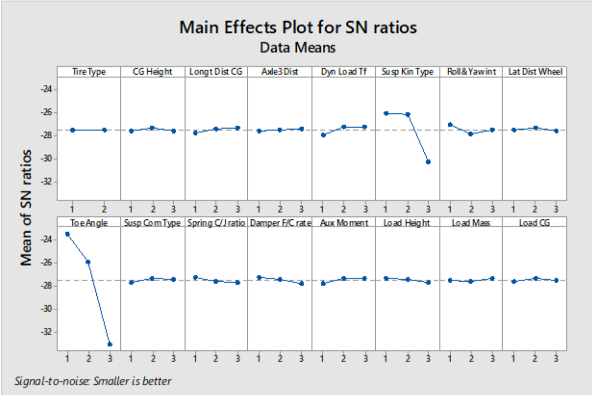

Figure29: Second Step Taguchi for Effective Factors of First Step

Table 29: Effective Factors of Second Step Taguchi for Trailer 2 Unit

	Class	Factor
1	Suspension Kinematics	Dynamic Load Transfer Coefficient
		Toe Angle
		Suspension Kinematic type

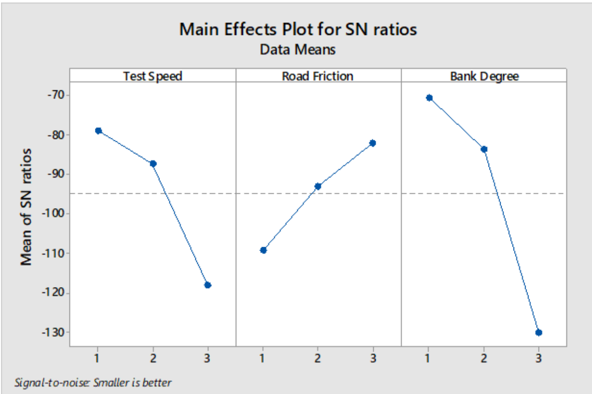

Figure30: Taguchi for Test Conditions

5. Discussion

The results of this study shows that Suspension parameters (Kinematics and compliance) are the most effective factors in rearward amplifications for each units and Geometric, Tire factors, and Load conditions stand in the second and third places respectively.

The Effects of Geometric, Load and Tire factors had been studied in details before [25],[11], but since studying suspension factors needs experimental or simulation tests it has not been covered properly since this study. As it was

[DOI: 10.22068/ijae.9.4.3108]

explained in section 3.1, the reason of limit founding in past studies was modeling MAVs based on linear and specific number of freedom degree that researcher applied for physical and geometrical parameters to reach state space matrix. Reviewing the latest researches a list of effective factors on RA value is given in Table 30. [25].

Table 30: Effective Factors studied in Latest papers

	Factors
1	CG Distance of Loads
2	neutral steer parameters
3	lengths of the units
4	Hitch Distance
5	Length between the axles
6	Height of the Load and Tractor
7	Speed of Vehicle
8	Road Friction

As it can be concluded mostly previous works didn't study the major effects of Suspension and other cited parameters, outcome in this study and that's the nobility of this research. In addition, the effects of test conditions are covered, and as can be derived bank degree of road has the first place and the two others in further have effective roles.

6. Conclusion

In this study in order to find the most effective factors of a specific and common MAV among tons of its statistical and dynamical parameters, multi-step Taguchi method applied as main process. Due to limitation of experimental test and its cost, TruckSim Simulator software which offered real time, non-linear and accurate studies were selected. After representing 6σ method for designing levels of factors variety in each step of Taguchi, a modified rearward amplification method was presented to compute deviation error of RA value for each unit from its criterion. After applying 2-step Taguchi for parameters of each unit, results concluded that factors like suspension's angle, tire type and bank degree of the road which had major effects, must be listed beside the geometric and load factors that had been study before.

Involving with these most effective factors instead of working tons of MAV's parameters in hard maneuvers driving conditions for body designing, controlling studies and optimization for further researches can be huge help [26].

7. Acknowledgment

The authors express their sincere thanks to Professor H. Moeenfard (Ferdowsi University of Mashhad, Iran) for allowing us to use the PCV Laboratory and Prof. H. Sadeghi Namaghi at Ferdowsi University of Mashhad, Iran for reading the draft and their support during this study.

8. References

[1] Kennedy, J. International comparison of roundabout design guidelines, 2007, Crowthorne, United Kingdom: Transportation Research Laboratory PPR 206.

[2] CETE, Inversion of the Heavy Lorries in Roundabouts, 1997 ,Centre d'Etudes Techniques de l'Equipement, Normandy Centre. Preliminary Study, Report of studies.

[3] Cerezo, V., & Gothiè, M., Heavy goods vehicle accidents on roundabouts: Parameters of influence., In Proceedings of the international symposium on heavy vehicle weights and dimension, 2006, University of Park, PA: Pennsylvania State University.

[4] K. Langwieder, J. Gwehenberger, T. Hummel, and J. Bende. Benefit potential of ESP in real accident situations involving cars and trucks, Technical report, GDV, Institute for vehicle safety Munich, 2003, 18*th* International Technical Conference on the Enhanced Safety of Vehicles.

[5] Chu, Z., Sun, Y., Wu, C., & Sepehri, N. Active disturbance rejection control applied to automated steering for lane keeping in autonomous vehicle, Control Engineering Practice, 2018, 74, 13–21

[6] ACEA. Official publication of the GSR (Regulation (EC) No 661/2009). Technical Regulations No 52, 2009. ACEA 20091118

[7] Rill, G. Road Vehicle Dynamics: Fundamentals and Modeling, 2011, CRC Press, ISBN 978-1-4398-3898-3.

[8] Moreno, G.; Manenti, V.; Nicolazzi, L.; Vieira, R.; Martins, D. Cap. Rollover of Long Combination Vehicles: Effect of Overweight. Book Multibody Mechatronic Systems,(2018),Mechanisms and Machine Science 54, DOI 10.1007/978-3-319-67567-1 47, Springer International Publishing Switzerland. ISBN: 978-3-319-67566-4.

[9] Sadeghi, J. Fathali, M. Deterioration Analysis of Flexible Pavements under Overweight Vehicles, 2007, J. Transp. Eng., 10.1061/(ASCE)0733-947X(2007)133:11(625), 625-633

[10] Moreno, G. Nicolazzi, L. Vieira, R S. Martins, D. Suspension and tyres: the stability of heavy vehicles, International Journal of Heavy vehicle Systems, 2017, ISSN online: 1741-5152. ISSN print: 1744-232X. 24 (4), 305-326, doi:10.1504/IJHVS.2017.10007635.

[11] Michihisa IIDA, Masashi FUKUTA, Hiroki TOMIYAMA, Measurement and Analysis of Side-Slip Angle for an Articulated Vehicle, 2010, Engineering in Agriculture, Environment and Food Vol. 3, No. 1.

[12] M. El-Gindy, B.T.Kulakowski, Xiaohua Tong, Nezih Mrad, Rearward Amplification Control of Truck/Full Trailer, 1998, Advances in Automotive Control, Mohican State Park, Loudonville, Ohio, USA.

[13]M.Sadeghi Kati, H.Koroglu, J.Fredriksson, Robust Lateral Control of an A-double combination via H and Generelized H_2 Static Output Feedback, 2016, IFAC-PapersOnLine 49-11(2016) 305-311.

[14 Kharrazi,S Steering Based Lateral Performance Control of Long Heavy Vehicle Combinations , 2012, Ph.D thesis, Department of Applied Mechanics Chalmers University OF Technology.

[15] Caizhen Cheng, Richard Roebuck, A.O.and Cebon,D, High- speed optimal steering of a tractor semi trailer, 2011, Vehicle System Dynamics, 49(4),561–593.

[16] Jujnovich,B.A.and Cebon.D,Path-following steering control for articulated vehicles, 2013, Journal of Dynamic Systems Measurement and Control Transactions of the ASME,135(3).

[17] Guidelines on Maximum Weights and Dimensions of Mechanically Propelled Vehicles and Trailers, Including Maneuverability Criteria, Vehicle Standards Section, Road Safety Authority, Moy Valley Business Park, Primrose Hill.

[18] H.C. Pflug. Innovative truck-trailer concepts as a means of efficiency improvement, 2008, Efficiency in Road Transport 62nd International Motor Show CV, Hanover.

[19] www.ecocombi.com, Sunday, October 27, 2019.

[20] M. Pinxteren. Brake and roll-over performance of longer heavier vehicle combinations, 2009, Master's thesis, Eindhoven University of Technology, Department Mechanical Engineering, Dynamics and Control Group, DCT 2009.063

[21] P. Fancher, C.Winkler, R. Ervin, and H. Zhang. Using braking to control the lateral motions of full trailers, 1998, In The dynamics of vehicles on roads and on tracks: Supplement to Vehicle System Dynamics Volume 29, pages 462–478.

[22] Antara Ghosh, Soma Barman, Application of Euclidean distance measurement and principal component analysis for gene identification,2016, Gene, Volume 583, Issue 2 Pages 112-120.

[23] The Technical Whitepaper series,2005, Series 6, Euclidean Distance raw, normalized, and double scaled coefficients.

[24] Lee, S. J. and Park, K., Development of Hardware-In-the-loop Simulation System as a Test bench for ESP Unit, 2007, International Journal of Automotive Technology, Vol. 8, No. 2, pp. 203-209.

[25] Md Manjurul Islam, Yuping He, Shenjin Zhu and QiushiWang, A comparative study of multi-trailer articulated heavy-vehicle models, 2014, Proc IMechE Part D: J Automobile Engineering, DOI: 10.1177/0954407014557053.

[26] Filipe Marques Barbosa, Lucas Barbosa

[DOI: 10.22068/ijae.9.4.3108]

Marcos, Maira Martins da Silva, Marco Henrique Terra, Valdir Grassi Junior, Robust path-following control for articulated heavy-duty vehicles,2019, Control Engineering Practice.

[DOI: 10.22068/ijae.9.4.3108]