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Modelling Effect of Weight-to-Power Ratio on Acceleration Profile of Trucks under Varying Gradient Conditions

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Abstract

The effect of grade is very significant on traffic flow characteristics. While negotiating a particular upward gradient, the vehicles will have to overcome the grade resistance additionally along with other resistances (air resistance, rolling resistance and resistance due to inertia). An important aspect of road geometry design is the provision of safe distances to allow vehicle to change speed from low or moderate speed flows to high speed flows, and vice versa. On level roads, vehicles may maintain their speeds uniformly. However, on upgrades, heavy vehicles such as trucks, will experience significant reduction in their speeds, whereas, passenger cars and other smaller vehicles such as motorized-two-wheelers may experience relatively lesser speed reduction. Similarly, the effect of gradient on truck performance on upgrade and downgrade are not same. One of the approaches, to estimate the acceleration rates of truck for different grades to develop the various traffic flow models. The main objective of this study is to study the effect of weight-to-power ratio on truck accelerating characteristics for varying magnitude of gradients. The outcome of the study is expected to explain the dynamics of trucks on grades.

*Keywords:*Acceleration, Gradient, Resistance, Vehicular Mechanics, Weight-to-power ratio and heavy vehicles (trucks)

1. INTRODUCTION

The effect of grade and its length is very significant on traffic flow characteristics. The variation in the effect of grades on different categories of vehicles may result in a different level of interaction between vehicles, when compared with their interactions while moving on level roads. For traffic engineers, vehicle performances are very much important. They form the basis for highway design guidelines and traffic analysis. The vehicle performance on grade is also necessary to study this aspect. Roadway grades have a diverse effect on vehicle speeds, depending on vehicle and roadway characteristics. On upgrade heavy vehicle class such as trucks, buses, etc. will

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experience significant reduction in their speeds, whereas passenger cars and other smaller vehicles such as motorized-two-wheelers may experience relatively lesser speed reduction. On downgrades trucks attain higher speed at higher grade, but acceleration rate reduces as weight of truck increases. But, this may not be true when braking action takes place on downgrades.

The present study does not consider the braking effect on downgrades. Under heterogeneous traffic conditions, this variation in speed reduction among different vehicle categories is due to their wide-ranging physical characteristics such as dimensions, weight, etc. as well as to their dynamic characteristics such as engine power, acceleration rate, etc. Therefore, due to the potential significant speed differential between cars and heavy trucks, these trucks can have a significant impact on the quality of flow and safety of a traffic stream. The acceleration is only possible when force is available in engine after overcoming the resistances acting on the vehicle. The acceleration rates of the trucks with different weights, grades and speeds are calculated using force balance equation (HDM-IV) given by Bennett and Greenwood (2001). The truck weight data for this study was collected on hilly road in South region of Gujarat state for a week. The data shows almost same distribution for all seven days. For the purpose of this study, first quartile (25^{th} percentile), average (50^{th} percentile) and third quartile (75^{th} percentile) of the gross weight data is considered for analysis. It is found that acceleration rates are high for low gradient but decrease drastically, when magnitude of upgrade increases, while on downgrades acceleration rate increases as gradient magnitude increases. It was found that up to 20 km/h of speed, acceleration rate increase for various upgrades, while in the case of downgrades up to 30 km/h of speed acceleration rate increases and after that it decreases significantly. Also for higher magnitude of upgrades, acceleration rate is zero; this is because when encountering a grade of higher magnitude of upgrade, amount of resistances is higher than the drive force generated by the engine of the vehicle. The research work reported here is related to the study of effect of magnitude of grades on acceleration characteristics of trucks pertaining to the different weight-to-power ratios. The procedure adopted for estimation of acceleration profiles for trucks having different weight-to-power ratios on grades of different magnitudes, along with the details of the analysis and the relevant results are presented in the following sections of this paper.

2. LITERATURE REVIEW

In the past, researchers used a force balance equation and vehicle mechanics for developing models predicting truck speeds on upgrades of any percentage and length. The impact of road gradient on speed was analyzed by Yagar and Aerde (1983)who found that the operating speed at a location is expected to decrease by approximately 1.8 km/h for each 1% of grade when going uphill. Gillespie (1985) developed a simplified means of predicting truck hill-climbing performance based on the characterization of the available power for accelerating and overcoming grade. The author also found that the ratio of the available power to weight is speed dependent but provides an easy means for calculating truck speed profiles on arbitrary grades. Archilla and Fernandez De Cieza (1996) developed truck speed profiles on different grades. The simple force balance equation was fitted to the field data. The model explained about 80% of the observed variation. For developing speed profiles on grades, the weight-to-power ratio of 190 kg/kW was considered. Bester (2000) developed a procedure for calculating speed profiles of trucks by using the assumption that the acceleration of a truck was a linear function of speed. A Policy on Geometric Design (2004)provides a single set of speed profiles over distance to characterize the deceleration and acceleration of typical heavy trucks based on the weight-to-power ratio of 120 kg/kw on different grades. Bennett and Greenwood (2001) as a part of Highway Development and Management series, popularly known as HDM-IV manual, has given the governing equation for the forward movement of a road vehicle, when the latter encounters a grade. The manual has also given the values of different parameters that can be used for estimating the magnitude of resistance (air resistance, rolling resistance, grade resistance, etc.) involved in the forward movement of vehicle on grades. Lucic (2001) extended the vehicle-dynamics model by introducing the concept of variable power in order to capture the buildup of power as the vehicle engages in gearshifts. The proposed extension has resulted in the significant enhancement of the state-of-the-art vehicle dynamics model. The author finally concluded that the use of constant transmission efficiency results in an overestimation of vehicle speeds at low speeds and an underestimation at high speeds. Lan and Menendez (2003) developed a well-defined speed profile for trucks based on dynamic, kinematic and operating characteristics of moving trucks on grades. For developing speed profiles on grades, the weight-to-power ratios of 121.7 kg/kW and 182.5 kg/kw were considered. All these studies, however, are mainly related to the characterization of truck performance on upgrades under homogeneous traffic conditions and hence, the results of these studies are not applicable for Indian conditions. A review of Indian studies related to the traffic flow characteristics of grades proposed that there had been only one study on the subject matter. Chandra and Goyal (2001) measured a free speed of different types of vehicles on two-lane intercity roads having grades with different magnitudes. The authors concluded that the free speed of a vehicle decreases uniformly with an increase in a gradient. The actual amount of reduction depends upon the type of a vehicle and the magnitude of the gradient. Arasan and Arkatkar (2010) found that the rate of speed reduction in the vehicles, on upgrades, will vary based on the type of a vehicle and it is a function of a magnitude of an upgrade and the power-to-weight ratio of the vehicle. Also it was found that the effect of an upgrade on vehicle performance (speed) may not be significant beyond a length of 1600 m. All these studies show the effect of gradient on the speed with different types of vehicle but do not reflect effect of different weight–to-power ratio on acceleration of same category of vehicle, for example, heavy truck. Also in Highway Capacity Manual-2010 acceleration curves for various speed and grade length only cover a single truck weight-to-power (W/P) ratio. The literature survey clearly shows that, at present, there is no ready-to-use reference material available regarding developing acceleration profiles for different vehicles on grades of varying magnitudes under heterogeneous traffic conditions in India. Hence, there is a need to model acceleration profiles for different vehicles, particularly for heavy vehicles i.e. trucks having different weight-to-power ratios on grades. This may enable researchers to study traffic flow characteristics with variation in the magnitude of a grade over a wider range.

3. SCOPE AND OBJECTIVES

The main objective of this study is to study the effect of weight-to-power ratio on truck accelerating characteristics for varying magnitude of gradients. This study investigates the impact of different truck gross weight, and power characteristics on its acceleration behavior. It is hypothesized that the truck characteristics will significantly affect truck acceleration behavior along grade sections because of variation in the truck weight-to-power ratio, rolling resistance, aerodynamic resistance, etc. Field data collected on truck gross weights and engine power are used in the present study for the purpose of developing acceleration profiles for trucks with different weight-to-power ratios on grades having different magnitudes. The acceleration rates are estimated using the equations given in Manual of Highway Development and Management-HDM-IV (2001).

4. METHODOLOGY

The thrust required for the forward movement of a road vehicle is determined by the summation of forces acting on the vehicle in the longitudinal direction. The forces acting on the vehicle while negotiating an upgrade of magnitude i % is given as follows:
1) Rolling resistance;
2) Air resistance;
3) Grade resistance;
4) Inertial forces, during acceleration and deceleration, as shown in Fig. 1.

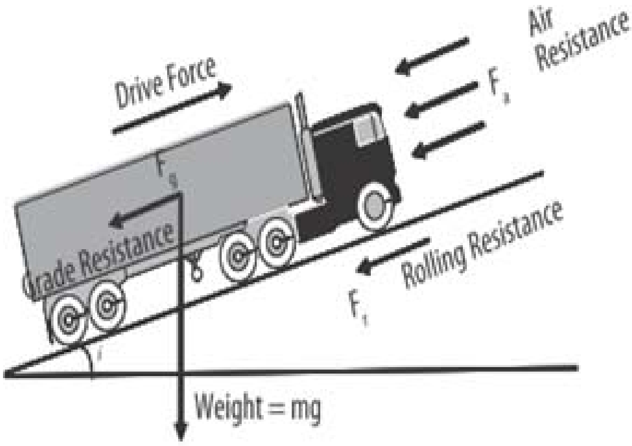


Figure1. Forces acting on a moving vehicle on upgrades

4.1.Estimation of Acceleration Rates

The propulsive effort (drive force) is derived from the engine to overcome these forces. Any reserve in drive force, if available, maybe used either to accelerate the vehicle or toovercome the drag arising from upgrades. When encountering a grade requiring thrust greater than the available drive force, deficiency is made up by the deceleration of the vehicle. The speed at which the available drive force is zero represents the steady state orterminal or 'crawl' speed of the vehicle. The steady-state speed that a vehicle can maintain on an upgrade occurs when forces are in balance. The following (Equation 1) is the fundamental equation of motion for a road vehicle (Bennett and Greenwood 2001) [6]

$$a = \frac{1000 P_d}{M * EMRAT} \frac{1}{v} - \frac{1}{M * EMRAT}[F_a + F_r + F_g] \quad (1)$$

Where,

a – acceleration, m/s^2;
P_d – driving power delivered to wheels, kW; M – vehicle mass;
EMRAT – effective mass ratio; F_a – aerodynamic drag resistance, N;
Fr – rolling resistance, N; F_g – gradient resistance, N; v – vehicle speed, m/s.

For downgrade extra power i.e. gradient resistance is added to the vehicle because of down gradient and equation (1) is modified as equitation (2)

$$a = \frac{1000 P_d}{M * EMRAT} \frac{1}{v} + \frac{F_g}{M * EMRAT} - \frac{1}{M * EMRAT}[F_a + F_r] \quad (2)$$

4.2.Air resistance

When a vehicle is in motion, air resists it in the following ways:

(i) Since air has density, it exerts a reaction pressure against the front of the vehicle when it moves at a certain speed.
(ii) The friction of air against the sides of the vehicle body causes resistance.
*(iii)*The eddying of the air stream behind the vehicle, under the body and around the wheels causes power loss.
*(iv)*The flow of air through the vehicle for ventilating and cooling causes resistance to motion.

The equation used for calculating aerodynamic drag resistance Bennett and Greenwood (2001) is as follows:

$$F_a = 0.5 * \rho * CD * CDmult * AF * v^2 \quad (3)$$

Where,

F_{a-} aerodynamic force opposing the motion of vehicle in N,
ρMass density of air in kg/m^3 (1.2 kg/m^3);
CD-aerodynamic drag coefficient;
CD_{mult}- aerodynamic drag coefficient multiplier; AF-projected frontal area of the vehicle in m^2; v-speed of the vehicle in m/s

4.3.Rolling Resistance

When the vehicle wheels roll over the road surface, the irregularities and the roughness of the surface cause deformation of the tyres. The road surface itself may undergo deformations. Shocks and impacts are caused by such a motion and these hinder rolling motion of the wheels. The rolling resistance varies with the type of surfacing. The equation used for calculating rolling resistance is given as follows:

$$F_r = Mfg \quad (4)$$

Where:
F_r- rolling resistance in N,

M-Mass of vehicle in kg, andf - coefficient of rolling resistance.

The value of the coefficient of rolling resistance (f) is approximately constant up to a speed of 50 km/h (Kadiyali *et al*., 1982). At higher speeds (more than 50 km/h); the values can be approximately calculated given as follows:

$$f = f_o[1 + 0.01(v - 50)] \quad (5)$$

Where,
f: coefficient of rolling resistance at speed v, v- speed in km/h,
f_o: coefficient of rolling resistance assumed constant up to a speed of 50 km/h

4.4.Grade Resistance

When a vehicle which was moving on a level stretch at a particular speed has to move up an incline on upgrade of certain magnitude, additional work has to be done in keeping the vehicle at the same speed as in the level road. The additional work is equal to the work that will be needed to lift the vehicle through a height represented by the inclination. If the horizontal distance is unity (i.e. 1 meter), and the slope is i percent, the rise will be i/100 m. If the mass of the vehicle is m kg, the additional force (grade resistance) to move the vehicle up the incline, F_g, can be calculated using the equation given as follows:

$$F_g = \frac{Mig}{100} \quad (6)$$

Where,
F_g-gradient resistance in N,M - mass of vehicle in kg, g - acceleration due to gravity, 9.81 m/s^2 and *i*- the Magnitude of gradient in percentage.

4.5.Inertia Forces during Acceleration and Deceleration

When a vehicle accelerates it needs to overcome inertial resistance. The inertial effects of the various rotating parts (engine, wheels and drive-train), serves to increase the vehicles dynamic mass over its static mass. This increased mass is termed the effective mass. Thus, inertial resistance is given by the equation as follows:

$$F_i = M * EMRAT * a \quad (7)$$

Where,
F_i is the inertial resistance; M is mass of vehicle in kg,
EMRAT is the effective mass ratio and,
a is the acceleration in m/s^2.

4.6.Transmission Losses

Losses in power occur to the mode of power transmission (clutch or automatic fluid coupling) from the engine to the gear system and in the gear system itself. The vehicle has a system of gears such that the speed of the vehicle can be altered relative to the engine speed. A high engine power is needed while climbing an upgrade, which is accomplished at a lower road speed than when driving at a level road. These manoeuvres are made at the lowest gears. For movement along a good road where the resistance to motion will be small, a high gear will tend to be used. The highest forward gear will generally be 1:1, representing direct drive. But while negotiating a grade, it may not be possible to drive a vehicle with highest forward gear. Hence, gear reduction is made at the rear axle. The total effect of all the above is to consume about 15-25 percent of the engine power (Kadiyali*et al.*, 1982).

Equation (1) indicates that the ability of a vehicle to accelerate on an upgrade is dependent on the used power-to-weight ratio, the mass and various forces opposing motion. Vehicles with low power-to-weight ratios such as trucks, while negotiating up grades, may decelerate to a crawl or terminal speed where forces are in balance and acceleration is equal to zero. The steady-state terminal speed can, thus, be obtained by solving Equation (1) for the velocity term. Hence, the data pertaining to maximum power (KW) and gross weight (kg)for various trucks was collected from the manufacturers' websites, brochures, and also from the field. Finally, the average representative values of power and three different values of gross weight of trucks obtained using the field data are selected in such a way that it represents 25^{th} percentile, average and 75^{th} percentile values of the data. These values were used for calculating acceleration rates at various speed ranges.

For determining air resistance at a particular speed of trucks, the values pertaining to the coefficient of drag (CD), CD multiplier (CD_{mult}), and the projected frontal area in m^2 (AF), are required. The CD is a function of the direction of movement of vehicle relative to the wind direction. The apparent direction of the wind, which is the vector resultant of the vehicle-movement direction and the wind direction, is termed the yaw angle (Ψ). The values of CD, reported in the literature, are usually from wind tunnel tests conducted with a zero degree yaw (*i.e.* front on to the wind) and accordingly, are the minimum for the vehicle. Hence, to obtain typical values of CD, which would be found on roads, it is necessary to adjust for the variation in wind direction. This can be done using a "typical" wind angle which increases the zero degree-yaw CD, leading to wind averaged CD, or CD (Ψ). The ratio of CD (Ψ) divided by CD is termed the CD multiplier (CD_{mult}). The values pertaining to the coefficient of drag (CD), CD multiplier (CD_{mult}), and the projected frontal area (AF), were taken from the manual of Highway Development and Management (HDM-4) (Bennett and Greenwood 2001) [6]. For determining rolling resistance, the coefficient of rolling resistance (f) is taken as 0.01 (Kadilyali et al., 1982) as the pavement surface of the study stretch is made of asphaltic concrete. At higher speeds (more than 50 km/h), the values can be approximately calculated using equation 5. The grade resistance based on the magnitude of a particular grade can be determined using equation 6. The magnitude of different resistances (air, rolling and grade resistances) for the different upgrades varying from 2% to 6%, and 0% pertaining to each of the truck gross weights are determined over a wide range of speeds. As given in the HDM-IV manual (Bennett and Greenwood, 2001), a more convenient method of representing the effective mass is through the ratio of effective mass to mass. Since the effective mass is dependent on the gears in use, and gear selection is a function of road speed, it is necessary to take both of these considerations into account as well as other physical attributes of the vehicle to calculate the effective mass and Effective Mass Ratio (EMRAT).

The Effective Mass Ratio (EMRAT) for each of the gross weights is also calculated at various speeds as per the guidelines of HDM-4 manual (Bennett and Greenwood 2001). Lucic (2001) extended the vehicle-dynamics model by introducing the concept of variable power in order to capture the buildup of power as the vehicle engages in gearshifts. The proposed extension has resulted in a significant enhancement to the state-of-the-art vehicle-dynamics model. The author finally, concluded that the use of a constant transmission efficiency results in an over-estimation of vehicle speeds at low speeds and an under-estimation at high speeds. For calculating used driving power delivered to the wheels (Pd), the variable 'power factor' is used. The calculation of the variable 'power factor' involves finding speed at which vehicle power reaches its maximum. For this purpose, a steady state or terminal speed for each weight category, at which the vehicle power reaches its maximum, is calculated considering acceleration, a = 0 in Equation (1). The values of the driving power delivered to the wheels of the vehicle were taken as 85% of the value of maximum power (due to transmission loss). The terminal speeds of truck for different weight-to-power ratio, hence determined, pertaining to different upgrades of magnitude, namely,0%, 2%, 3%, 4%, 5% and 6% are given in Table-1. From Table 1, it can be noted that terminal speed of a truck, is a function of its power-to-weight ratio.

Table 1.Terminal Speeds of different weight of truck on different upgrade

Magnitude of Gradient (%)	Terminal speeds (Speed which needs maximum power) for different trucks with average gross truck weight (Km/h)		
	13000 kg	**17000 kg**	**25000 kg**
0	100	92	86
2	66	55	42
3	54.5	43.5	32
4	47	35.5	26
5	41	30.5	21.5
6	35	26.5	18.5

The ratio of vehicle speed under consideration and maximum speed at which vehicle-power attains its maximum is considered as the variable 'power factor'. The used driving power (Pd), then, can be estimated by multiplying the maximum power value by the variable power factor. Thus using all these parameters acceleration rates at various speed ranges with respect to each upgrade considered for the study, are calculated for three different gross weights of trucks.

5. DATA COLLECTION

The trucks data along with weight was collected from the nearestweigh-in-bridgefacility, which is situated on the upstream side of the Saputara ranges in Gujarat. The data regarding gross weight and net weight was collected for seven days, comprising of total 1400 trucks. The detailed analysis of the gross weightof 1400 trucks showed that there is a significant variation in the weights of trucks on a particular given day, but there is no much variation in the weight of trucks over seven days as shown in figure 2. Also, it is found that with increase in weight of the truck, there is a marginal variation in the power of engine for most of the trucks.Hence, based on the collected field data, for the purpose of this study (analysis regarding estimating of acceleration rates), three different weights, i.e. 25th percentile, 50th percentile and 75th percentile values of gross-weight of seven days are consideredas shown in box plot below (Fig. 2).

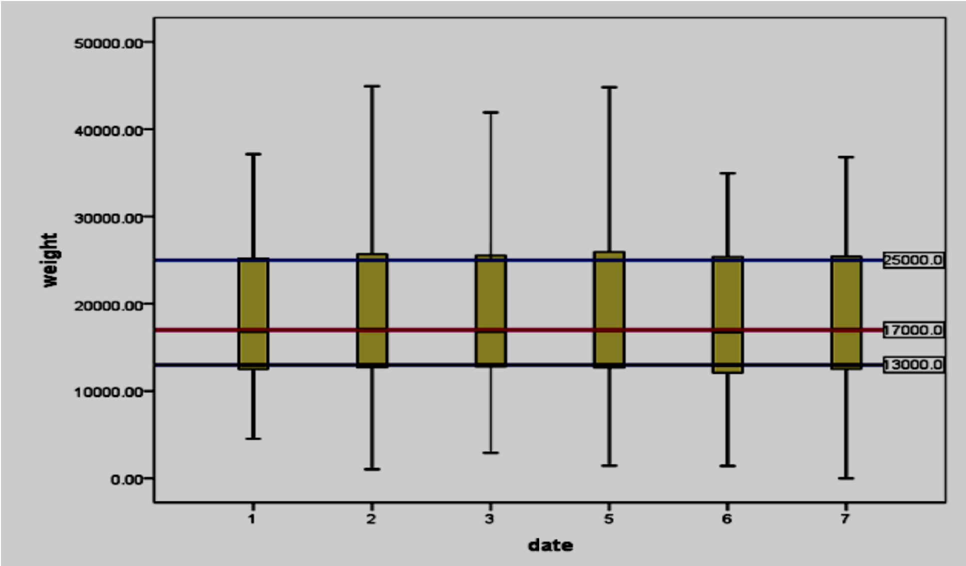


Figure 2. Box plot of weight of trucks

6. DATA ANALYSIS

Considering the average representative value of truck power as 104 KW and frontal area as 5.0 m^2 (Arasan and Arkatkar, 2010), the various resistances are estimated using equations 3 through 6. Further, the acceleration rates are calculated for each of the gross weights of trucks: (i) 25th percentile gross weight having value 13000 kg, (ii) 50th percentile gross weight having value 17000 kg, and (iii) 75th percentile gross weight having value 25000 kg. While estimating acceleration rates, the same average representative value of engine power (104 KW) is used for all the three gross weights. The acceleration rates are calculated for trucks on various upgrades and downgrade having different magnitudes; varying from 0 % gradient and 2% gradient (level terrain)to 6% gradient(hilly terrain).

The magnitude of calculated air resistance, rolling resistance for a speed of 40 km/h and grade resistance pertaining to each of the truck gross weight considered in this study, for2% to 6% gradient, are given in Table 2. It can be seen that air resistance is constant for each category because it is independent of mass of the vehicle and rolling resistant is constant for each gradient for a given mass of the vehicle. However, gradient resistance is found to increase with increase in weight of the truck and gradient.

Table 2. Resistance to truck at speed 40 km/h and at various upward gradients

Weight of truck Kg	Resistance to truck movement (N)						
	Air resistance	Rolling resistance	Gradient resistance				
			2%	3%	4%	5%	6%
13000	264	1275	2550	3826	5101	6376	7652

17000	264	1668	3335	5003	6671	8339	10006
25000	264	2453	4905	7357	9810	12262	14715

Table 3.Estimated Acceleration Rates for the Gross Weight of Trucks (17000 kg)

Speed of Truck Km/h	**0% Grade**	**Accelerate Rate m/sec^2 For Upgrade**					**Accelerate Rate m/sec^2 For Downgrade**				
		2%	**3%**	**4%**	**5%**	**6%**	**2%**	**3%**	**4%**	**5%**	**6%**
10	0.10	0.07	0.07	0.07	0.08	0.06	0.18	0.23	0.29	0.34	0.40
20	0.12	0.09	0.08	0.09	0.11	0.07	0.24	0.31	0.38	0.46	0.54
30	0.13	0.09	0.08	0.09	0.11	0.04	0.24	0.32	0.39	0.47	0.56
40	0.12	0.08	0.08	0.04	-0.05	-0.14	0.24	0.31	0.39	0.47	0.55
50	0.11	0.07	0.02	-0.07	-0.17	-0.26	0.23	0.31	0.38	0.46	0.55
60	0.09	0.03	-0.07	-0.16	-0.26	-0.35	0.21	0.29	0.36	0.44	0.53
70	0.07	-0.05	-0.14	-0.23	-0.33	-0.42	0.19	0.26	0.34	0.42	0.51

Table 3 presents acceleration rates estimated using force balance equation (equation no. 1 and 2) for a gross truck weight of 17000 kg over wider ranges of speeds (starting from 10 km/h to 70 km/h) and grades of magnitudes 0%, 2% and 6% as examples. From Table 3, it may be noted that for the upward gradient of magnitude of 6%, negative rate of acceleration i.e. deceleration takes place at and above the speed of 40 km/h, as example. The reason behind these negative values can be explained as follows. The force balance equation (1) consists of two components, namely, drive force derived based on the engine power of the vehicle type and resistances (air, rolling and grade) arising from the grade of certain magnitude. The propulsive effort (drive force) is derived from the engine (based on the power of the vehicle) to overcome these forces. Any reserve in drive force, if available, may be used to accelerate the vehicle. When encountering a grade of certain magnitude, requiring thrust that is greater than the available drive force (magnitude of resistances is higher than the drive force generated by the engine of the vehicle), the deficiency is made up by a deceleration of the vehicle. On downgrades, the estimated acceleration rates are shown in table 3, which indicates that it increases upto 30 km/h speed and then, thereafter it decreases.

7. ACCELERATION PROFILES OF TRUCKS

After estimating acceleration rates over a wider range of speeds, namely, 10 km/h, 20km/h, 30km/h, 40km/h, 50 km/h, 60 km/h and 70 km/h for grades having magnitude of 0%, 2%, 3%, 4%, 5% and 6%,the plots are made between the same set of axes for studying variation of (i) acceleration rates over speeds for different gross truck weights on a particular given upgrade and downgrade and , (ii) acceleration rates over speeds for different magnitudes of upgrades and downgrade for a particular given gross truck weight as shown in figures 3through11.Figures 3, 4, 5, 6, 7 and 8showthe variation of acceleration rates over related speeds for different gross weights of trucks for gradients having magnitudes 0%, 2%, 3%, 4%, 5% and 6%, respectively. From the plots, it may be noted that as the weight-to-power ratio increases(i.e. weight of truck increases for this study); acceleration rates are found to be decreased on a particular upgrade. On the other hand, figures9, 10 and 11show the plots indicating the comparison and variation of acceleration rates over speeds on various grades for truck having gross weights of 13000 kg, 17000kg and 25000 kg, respectively. From the plots, it may be noted that even though the weight-to-power ratio remains constant as the magnitude of upgrade increases acceleration rate is found to be decreased. But, for downgrade initially acceleration rate increase with the speed and then it starts decreasing with increase in the speed. It may also be noted that the acceleration rate decreases with increase in the magnitude of upgrade and speed but for downgrade acceleration rate increases as the magnitude of downgrade increases ignoring the effect of braking. The acceleration rate is found to be increased for initial speed for lower upgrades as because vehicle change from stationary position to a running position.

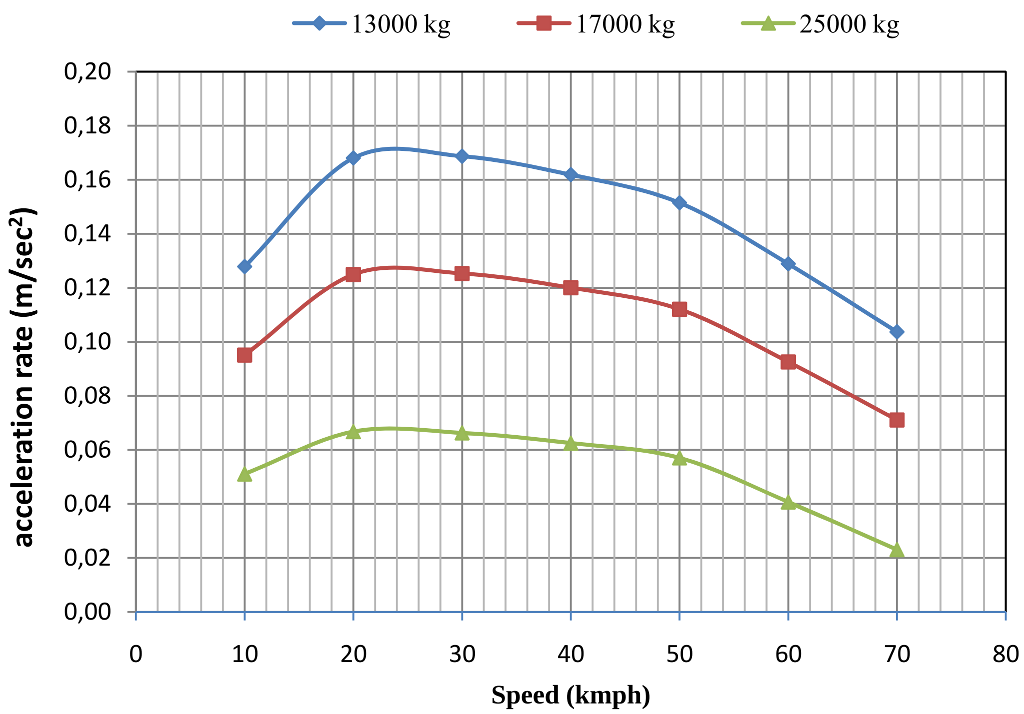
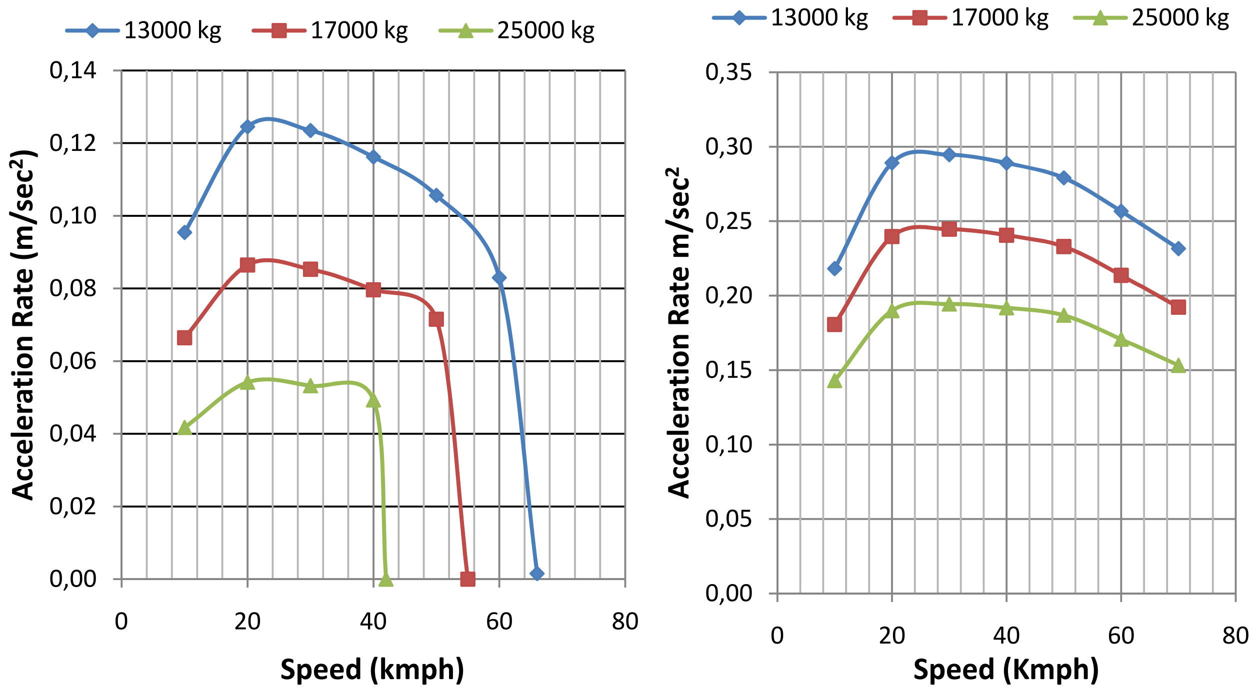
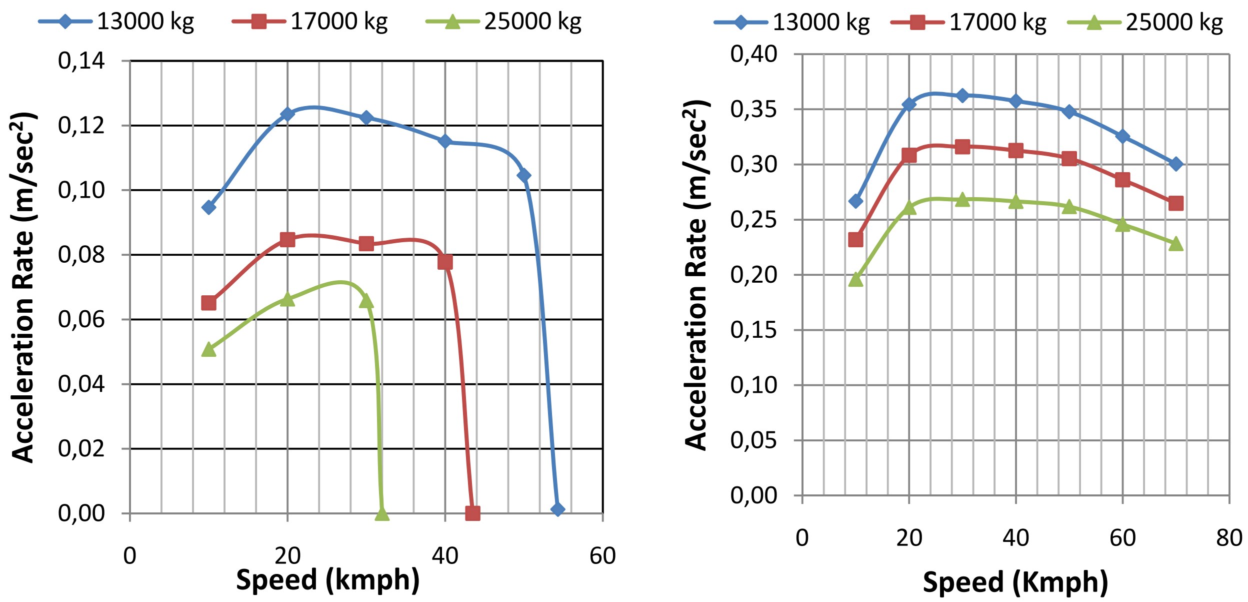


Figure 3. Estimation of acceleration rates over wider speed range for 0% gradient



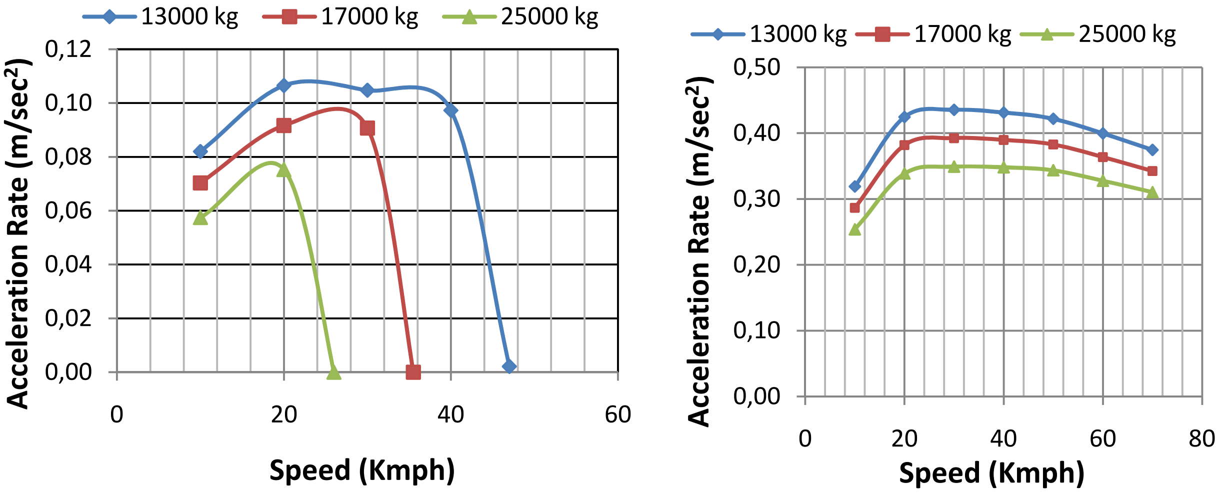
Upgrade **Downgrade**

Figure 4. Estimation of acceleration rates over wider speed range for 2% gradient



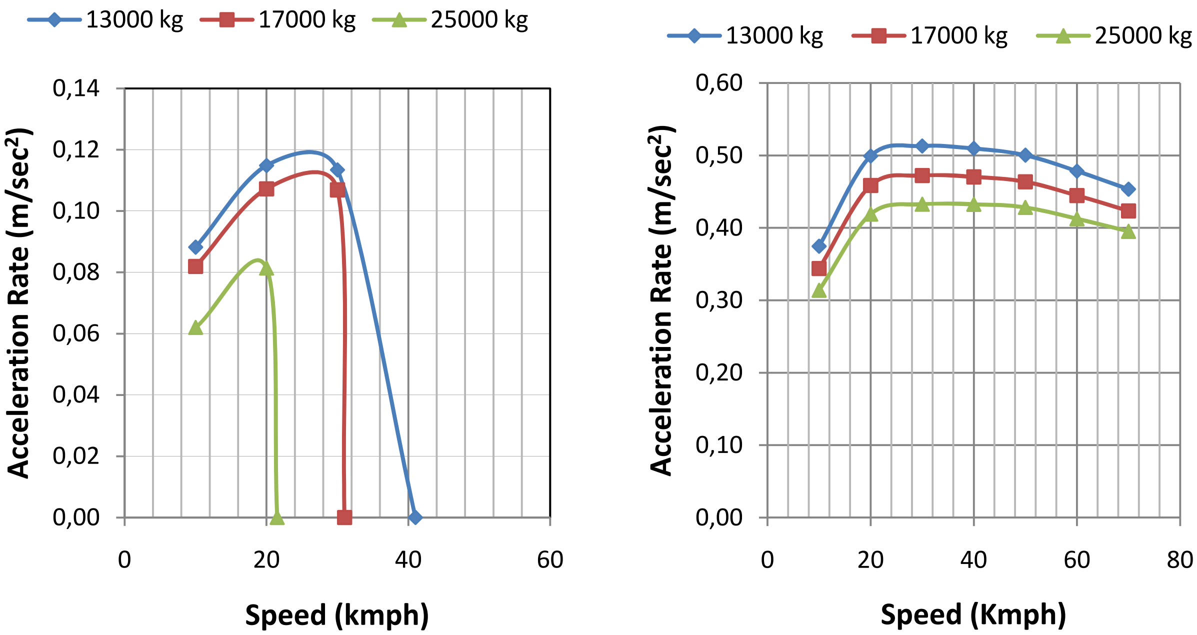
Upgrade **Downgrade**

Figure 5.Estimation of acceleration rates over wider speed range for 3% gradient



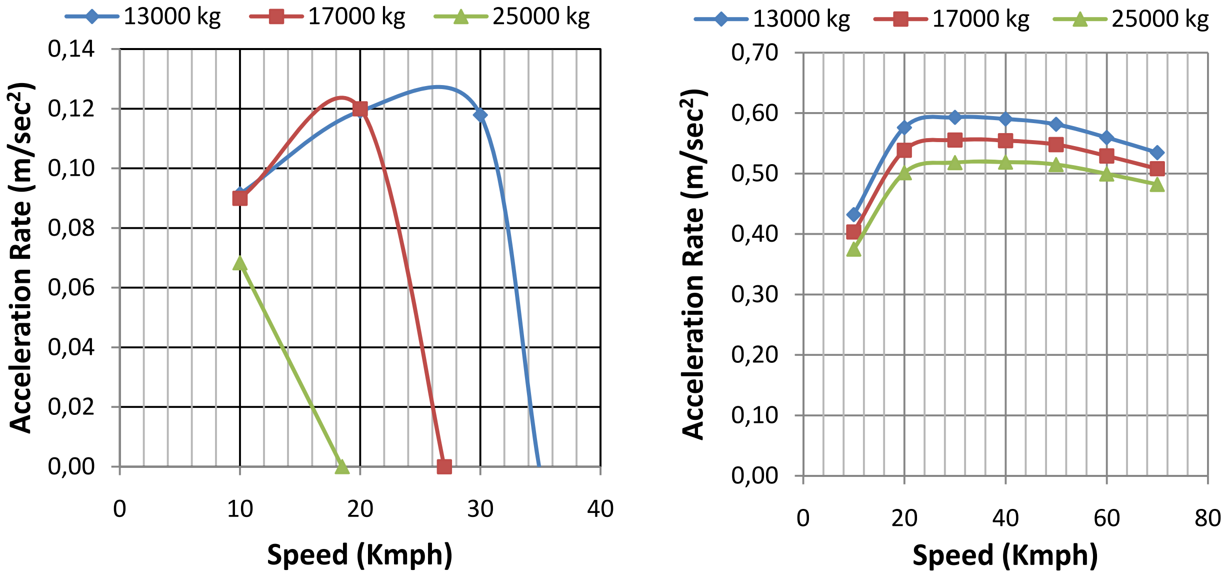
Upgrade **Downgrade**

Figure 6. Estimation of acceleration rates over wider speed range for 4% gradient



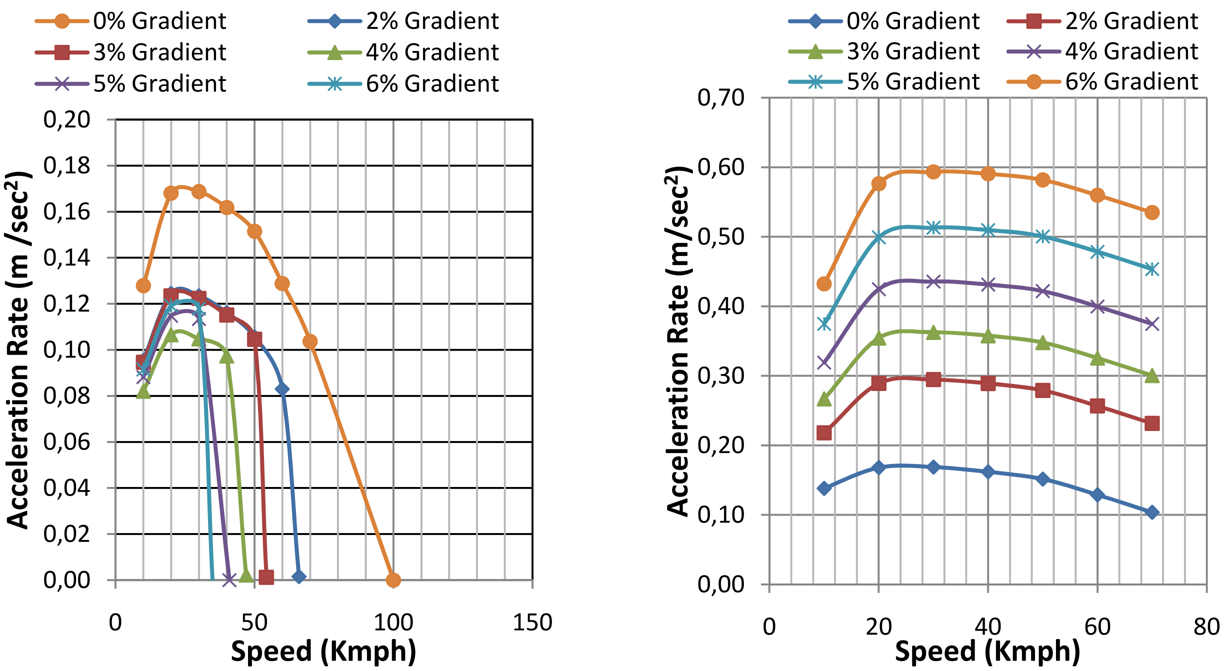
Upgrade **Downgrade**

Figure 7. Estimation of acceleration rates over wider speed range for 5% gradient



Upgrade **Downgrade**

Figure 8. Estimation of acceleration rates over wider speed range for 6% gradient



Upgrade **Downgrade**

Figure 9. Comparison of acceleration rates for a truck with gross weight 13000 kg over magnitude of different gradients

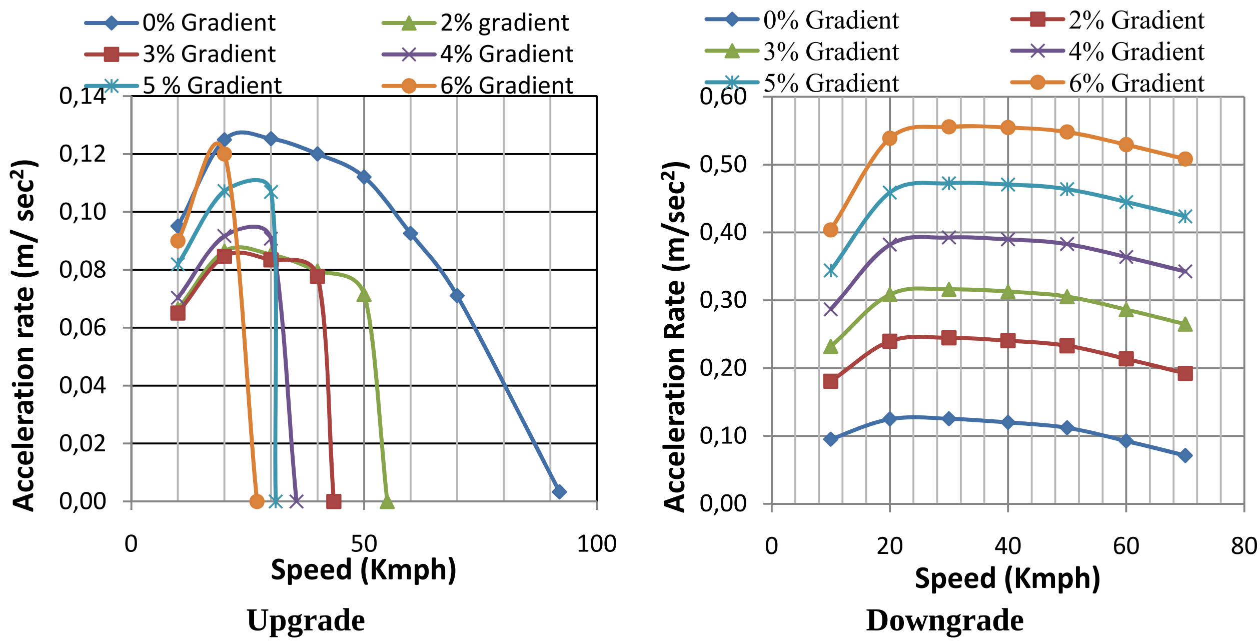


Figure 10. Comparison of acceleration rates for a truck with gross weight 17000 kg over magnitude of different up gradients

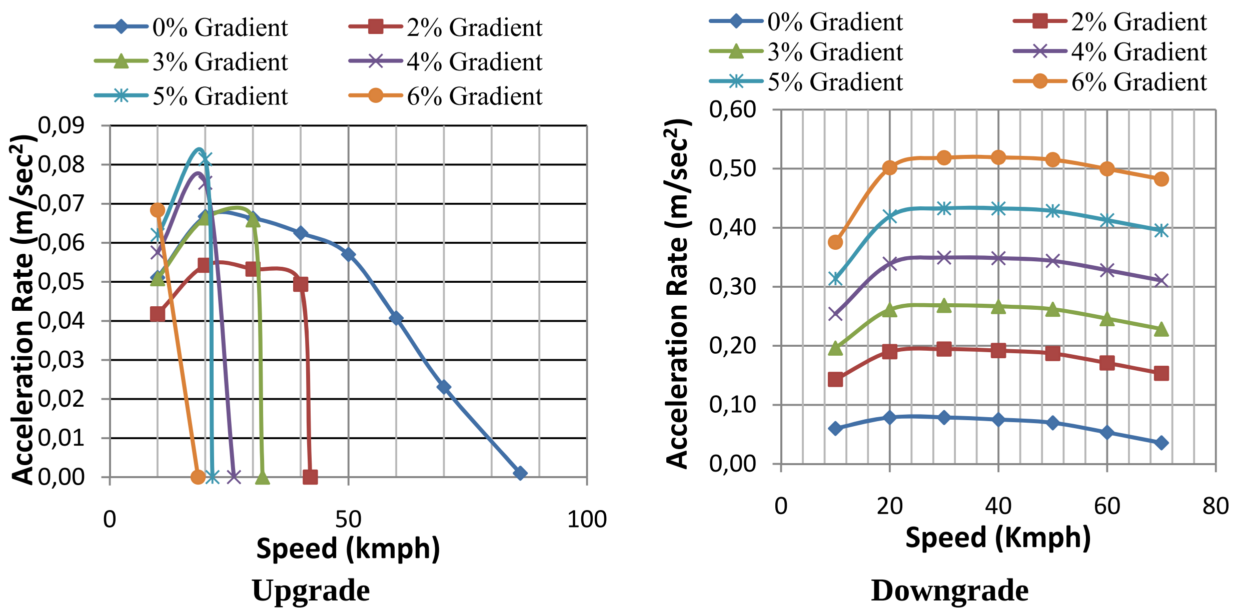


Figure 11.Comparison of acceleration rates for a truck with gross weight 25000 kg over magnitude of different gradients

8. RESULTS AND DISCUSSIONS

The present research study presents theoretical estimated results pertaining to the variation of (i) acceleration rates over speeds for different gross truck weights on a particular given gradient and, (ii) acceleration rates over speeds for different magnitudes of grades for a particular given gross truck weight. From the plots, it may be noted that as the weight-to-power ratio increases (i.e. weight of truck increases for this study); acceleration rates are found to be decreased for upgrade indicating trucks' inferior performance. It is also observed that, for all the grades, the acceleration rate increases initially up to a certain speed (20 km/h for upgrade and 30 km/h for downgrade, in this study), beyond which the acceleration rate decreases significantly till it becomes zero. Moreover, for relatively lesser upgrades, having magnitude 0% and 2% and even for 3% upgrade, the variation of acceleration rates of trucks having different power-to-weight ratios, over speeds, is relatively flat. On the other hand, for steeper upgrades (4% and more), the variation of acceleration rates, over speeds, is relatively higher. From the plots, it is also noted that even though the weight-to-power ratio remains constant as the magnitude of gradient increases acceleration rate is found to be decreased for upgrade. The reason behind all these aspects may be attributed to the fact that as the weight-to-power ratio and speed of trucks increases, the total magnitude of resistances to be overcome by truck increases. On the contrary, there is no increase possible in the magnitude of drive force to be derived from the engine with increase in the magnitude of upgrades. This results in deceleration with increase in magnitude of upgrade and speeds. On other hand, on downgrades the acceleration rate increase as magnitude of gradient increase, as the force due to gradient gets added in the force-balance equation. Also, from the plots, it is noted that even though the magnitude of gradient is constant and weight-to-power ratio increases acceleration rate is found to be decreased for downgrade. Also, it was checked that there is no significant effect of variation in transmission loss on acceleration rates.

Further, the acceleration rate is found to be increased up to certain initial speed for all magnitude of grades. This increase in found to be more prominent with increase in the weight-to-power ratio of trucks for steeper upgrades (4% and more). The reason behind this aspect may be attributed to the fact that with increase in weight-to-power ratio, the maximum magnitude of drive force or driving power is consumed at lower speeds. In other words, for steeper upgrades, for heavy trucks, there is maximum requirement of acceleration rates even at lower speeds. Moreover, for steeper upgrades, after initial increase in the acceleration rate, there is quick drop in the acceleration rates, because of lack of drive force at higher speeds. On level roads, having magnitude of upgrade 0%, the rate of acceleration may be increased initially till truck achieves higher speed from the rest position.

9. CONCLUSIONS

The present research study presents results pertaining to the variation of acceleration rates with variation in magnitude of upgrades, speeds and weight-to-power ratios in India. It has been demonstrated that as the weight-to-power ratio increases (i.e. weight of truck increases for this study); acceleration rates are found to be decreased for upgrade. It is also observed that, for all the grades, the acceleration rate increases initially up to a certain speed (20 km/h for upgrades and 30 km/h for downgrades, in this study), beyond which the acceleration rate decreases significantly till it becomes zero in the case of downgrade, as the truck speed increases initially and then attends the crawling speed. However, the present approach does not consider the effect of instantaneous braking on downgrades. It is also observed that for the 6% upgrade, acceleration rates at and above 20 km/h speed is found to be zero, which means that on hilly road heavy truck moves at very low speed, which may be designated as a crawling speed. Therefore, the effect of upgrade on vehicle performance is always significant. The terminal speed of trucks (the speed at which whole engine power is consumed) on a particular upgrade may be estimated using this approach. From the acceleration rates estimated for different gross-weight of trucks over a wider range of speeds, it is observed that weight-to-power ratio is an important parameter for estimation of acceleration values. It is also observed that for a heavy vehicle category such as trucks having same magnitude of engine power but different gross-weights, there may be a huge variation in the values of acceleration and hence performance. Hence, single average weight-to-power ratio of a given vehicle category may not represent the total variation of acceleration rates. Therefore, it is suggested to consider different percentiles of the gross weight of trucks (25^{th}, 50^{th} and 75^{th}percentiles as suggested in this study) to investigate the possible impact of weight-to-power ratio on performance of vehicles more accurately.

10. FUTURE SCOPE OF THE STUDY

In the present study, the effect of variation in weight-power ratio on sensitivity of acceleration rates is considered. The approach used in the present study is partially mechanistic, as some of the parameters used in the force-balance equation for estimating resistances to be overcome by trucks are based on the vehicular characteristics such as weight, engine power, transmission losses, etc. The contribution of the present approach is to develop and demonstrate the theoretical framework for modeling the performance of trucks with varying weights on grades. However, in future the authors would validate the estimated truck profiles and their acceleration rates based on the field studies.

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