Determining the Upgrades and Design Speeds That Two-Lane Highways Don't Require Climbing Lanes

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ABSTRACT

The relationship between the design speed and the value of two-lane highway upgrade has a significant importance in determining whether this part of highway requires a climbing lane or not. Climbing lanes are added to ensure not reducing the safety on the highway, because the reduced speed of trucks on the upgrade results in obstructing the traffic behind them.

Codes and references illustrated the cases when climbing lanes must be added in graphics, but these cases are limited by specific characteristics of trucks and specific design speeds. This leads to limitation of applicability of the graphics.

In this research, general relationships that relate the value of upgrade to the design speed and to the predominant truck characteristics are concluded. These relationships are applicable for design speeds between 40 km/h and 130 km/h and for different truck characteristics. This makes them have a wider range of usage than the graphics included in the current codes and references.

KEYWORDS: Two-lane highways, Climbing lane, Critical length, Maximum upgrade, Truck design.

INTRODUCTION

The longitudinal design (profile) of two-lane highways and the need of climbing lanes are affected by many factors, such as:

- the characteristics of truck design to determine trucks that will frequently travel on the upgrade portion of the highway.
- the value of upgrade of the highway.
- the service level required for the highway.
- the safety level required.
- the traffic volume on the highway.
- the ratio of heavy truck volume to the total volume on the highway.
- pavement type and pavement goodness.

These factors determine whether two-lane highways require adding climbing lanes or not. These additional lanes are necessary to reduce traffic obstruction resulting from existing trucks on the highway and to ensure the safety and service levels required on the highway.

Codes and references consider that the most important factor in determining the necessity of adding climbing lanes to road upgrades is the presence of heavy trucks travelling on these upgrades at low speeds (i.e., the speed is reduced by 15 km/h lower than the design speed).

Codes depend on graphics or tables for determining the design criteria related to climbing lanes. These codes

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depend on that a standard truck has a weight to horsepower ratio of ρ=W/P=120 kg-f/kW = 878 N/hp and has a weight to frontal area ratio of 1000 kg-f/m^2 = 9810 N/m^2. Also, the codes consider that the truck will enter the upgrade at a speed of 110 km/h (AASHTO, 2011; NCHRP, 2003).

As a result of the great development of truck manufacturing, truck characteristics have become different from those of typical trucks. The truck horsepower has become higher and the truck weight has become more reduced; therefore, the ratio ρ (weight to horsepower) will be significantly lower. In addition, some states may prevent some types of very heavy trucks (whose weights exceed a specific value) from travelling on the highway. This may make the road not in need of climbing lanes and make executing it become more economical. Therefore, it's necessary to perform studies showing the need to climbing lanes, finding the design criteria for these lanes and relating the upgrades with speed by considering different truck characteristics other than those mentioned in codes and references.

The aim of this research is to conclude one of the design criteria for climbing lanes. This criterion is determining the upgrades that don't need the execution of climbing lanes for different truck characteristics (i.e., for trucks with ρ ratios different from ρ ratios of typical trucks) and for different design speeds. Also, the research determines the design speeds that don't need climbing lanes at specific upgrades.

Dynamic Study on Trucks Travelling on Upgrades and Concluding Upgrades on Which the Highway Doesn't Need Climbing Lanes

The truck movement on upgrades of two-lane highways follows the general equations in dynamic science. On steep upgrades, the truck movement will be decelerated. After some distance, this decelerated movement will make trucks obstacles to the traffic, making the two-lane highway require adding climbing lanes for these decelerated trucks. The same truck can maintain its speed on smaller upgrades without any reduction in its speed.

Therefore, the dynamic condition for truck speed maintaining is: acceleration a=0 or the sum of all forces acting on the truck ΣF=0.

The forces acting on the truck while it travels on upgrades of two-lane highways are the tractive force F and resistance forces. Resistance forces are: air resistance F_a, rolling resistance F_r and grade resistance F_g (AASHTO, 2011; Hoel et al., 2011; Hoel and Garber, 2010; Manering et al., 2013) (Figure 1).

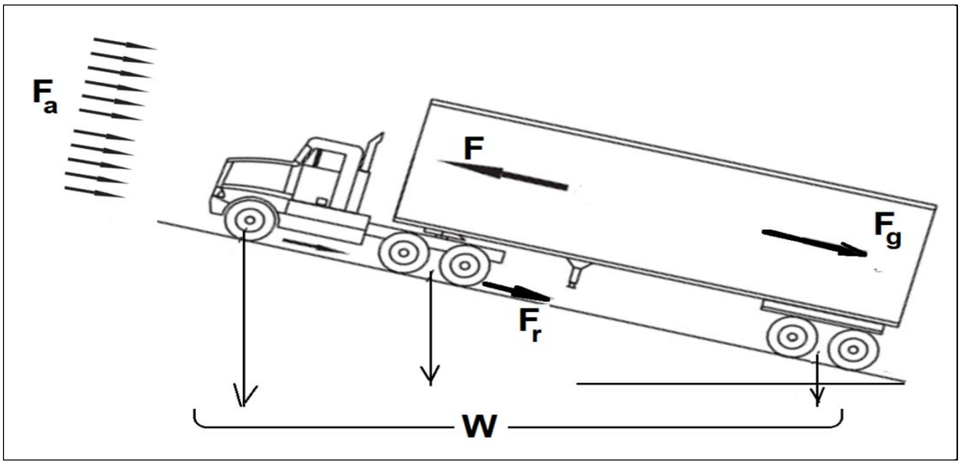

Figure (1): Forces acting on a truck travelling on an upgrade highway

- *Tractive force F:* It is given in relation with truck horsepower as hp, where:

$$hp = 0.00134.F.V \rightarrow$$
$$F = \frac{hp}{0.00134.V}$$
$$= \frac{746.27\ hp}{V} \ldots\ldots..(1)$$

where:
F = tractive force of truck engine in N.
hp = horsepower of truck engine.
V= speed in m/sec.

- *Air resistance F_a:* It's also called aerodynamic resistance. It's given as (Mannering et al., 2013):

$$F_a = \frac{\Psi.C_D.A}{2}.V^2 \quad \ldots..(2)$$

where:
F_a= air resistance in N.
Ψ= air density=1.227 kg/m^3 at sea level.
C_D= coefficient of drag. For heavy trucks, it is given approximately as 0.65 (Hoel et al., 2011).
A= frontal area of the truck in m^2.
V= speed in m/sec.

- *Rolling resistance F_r:* This force originates from the highway surface-tire interface. There are many empirical equations included in codes and references to calculate this force. The equation included in Rakha et al. 1999) and in Rakha et al. (2002) was chosen, because it gives rolling resistance values correspondent with the values obtained from AASHTO (2011) and because this equation is the most dependable by many researchers. This force is given as:

$$F_r = 1.25(0.0438V + 6.1).\frac{W}{1000} \ldots\ldots \quad (3)$$

where:
F_r = rolling resistance in N.
W= truck weight in N.
V= speed in m/sec.

- *Grade resistance F_g:* It is given as:

$$F_g = G.W \quad \ldots\ldots\ldots\ldots \quad (4)$$

where:
W= truck weight in N.
G= upgrade of the two-lane highway section.

Depending on Newton's second law (the basic law of movement) (Hibbler, 2007) and considering the deceleration equal to zero, the main equation (F=m × a) can be written as:
Sum of all forces affecting the truck= m × a=0; i.e., truck mass × acceleration=0

$$F - F_a - F_r - F_g = 0 \ldots\ldots\ldots \quad (5) \rightarrow$$

$$\frac{746.27\ hp}{V} - \frac{\Psi.C_D.A}{2}.V^2 - 1.25(0.0438V + 6.1).\frac{W}{1000} - G.W = 0 \ldots\ldots \quad (6)$$

By substituting Ψ and C_D with their values and by dividing by the weight W, Equation (6) can be written as:

$$\frac{746.27\ hp}{V.W} - \frac{1.227.0.65.A}{2.W}.V^2 - 1.25(0.0438V + 6.1).\frac{1}{1000} - G = 0$$

The symbol ρ is used as the value of the ratio of truck weight to horsepower ρ=W/hp and the symbol A' is used as the value of the ratio of truck weight to its frontal area A'=W/A. Because differences in A' (for common heavy trucks) have small effect on the results, the value of 33000 N/m^2 is dependable as mentioned in Rakha et al. (1999).

Therefore, the past equation can be written as:

$$\frac{746.27}{V.\rho} - \frac{0.4}{33000}.V^2 - (0.0548 * 10^{-3}V + 7.625 * 10^{-3}) - G = 0$$

Finally, the upgrade G on which the two-lane highway doesn't need climbing lanes can be given in relation with the speed V and the truck characteristics represented by ρ as:

$$G = \frac{746.27}{V.\rho} - 1.212 * 10^{-5}.V^2$$
$$-0.0548 * 10^{-3}V - 7.625 * 10^{-3} \dots\dots (7)$$

where:
V = design speed in m/sec.
ρ = truck weight to horsepower ratio in N/hp.
G= upgrade for the highway portion under study.

This equation can give the upgrade on which trucks with ρ ratio can travel with a speed of V without any reduction in their speeds. Therefore, at this upgrade, the highway doesn't need to add climbing lanes.

Depending on the existing trucks and possible near future trucks, ρ values will range from 300 to 1300 N/hp. On the other hand, practical speeds of trucks will range from 40 km/h to 130 km/h. By substituting these ranges of ρ and speed in Equation 7 (after converting the speed unit into m/sec), the grades that don't need climbing lanes are obtained. These grades are listed in Table (1). The symbol "*" in the table denotes that the truck with ρ can't maintain its speed even if the grade is zero (level). This means that this portion of the two-lane highway needs climbing lanes for these types of trucks. For example, if the trucks expected to travel on the two-lane highway have ρ=500N/hp and if the design speed of the highway V=60 km/h, then Table (1) shows that the upgrade of 7.8% or less doesn't need climbing lanes. But, if ρ is 900 N/hp and the design speed is 125 km/h, then Table (1) shows that this portion of highway needs climbing lanes even if the grade is zero (level).

Determining the Design Speed That Can Be Adopted for a Specific Upgrade of a Two-Lane Highway without Needing Climbing Lanes

The design speed that can be adopted for a specific upgrade of a two-lane highway without needing climbing lanes can be found from Equation (7) in terms of upgrade G and truck characteristics represented by ρ. But, using Equation (7) for determining speeds is not practical and need to use approximated mathematical methods utilizing special software. So, a relationship will be concluded here to find the speed directly in terms of the upgrade G and truck characteristics represented by ρ.

Table 1. Upgrades that don't need climbing lanes

V km/h	G ρ=300	G ρ=400	G ρ=500	G ρ=600	G ρ=700	G ρ=800	G ρ=900	G ρ=1000	G ρ=1100	G ρ=1200	G ρ=1300	G ρ=1400
40	0.21	0.16	0.13	0.1	0.09	0.07	0.07	0.057	0.051	0.046	0.042	0.038
45	0.19	0.14	0.11	0.09	0.08	0.06	0.06	0.049	0.044	0.04	0.036	0.032
50	0.17	0.12	0.1	0.08	0.07	0.06	0.05	0.043	0.038	0.034	0.031	0.028
55	0.15	0.11	0.09	0.07	0.06	0.05	0.04	0.038	0.033	0.029	0.026	0.024
60	0.14	0.1	0.08	0.06	0.05	0.04	0.04	0.033	0.029	0.025	0.023	0.02
65	0.13	0.09	0.07	0.06	0.05	0.04	0.03	0.029	0.025	0.022	0.019	0.017
70	0.12	0.08	0.06	0.05	0.04	0.04	0.03	0.025	0.022	0.019	0.016	0.014
75	0.11	0.08	0.06	0.05	0.04	0.03	0.03	0.022	0.019	0.016	0.014	0.012
80	0.1	0.07	0.05	0.04	0.03	0.03	0.02	0.019	0.016	0.013	0.011	0.009
85	0.09	0.06	0.05	0.04	0.03	0.02	0.02	0.016	0.013	0.011	0.009	0.007
90	0.08	0.06	0.04	0.03	0.03	0.02	0.02	0.013	0.011	0.008	0.006	0.005
95	0.08	0.05	0.04	0.03	0.02	0.02	0.01	0.011	0.008	0.006	0.004	0.003
100	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.008	0.006	0.004	0.002	0.001
105	0.07	0.04	0.03	0.02	0.02	0.01	0.01	0.006	0.004	0.002	0	*
110	0.06	0.04	0.03	0.02	0.01	0.01	0.01	0.004	0.002	0	*	*
115	0.06	0.04	0.03	0.02	0.01	0.01	0	0.002	0	*	*	*
120	0.05	0.03	0.02	0.01	0.01	0.01	0	*	*	*	*	*
125	0.05	0.03	0.02	0.01	0.01	0	*	*	*	*	*	*
130	0.04	0.03	0.02	0.01	0	0	*	*	*	*	*	*

*** Indicates that the truck can’t maintain speed even if the grade is zero.**

This methodology is adopted depending on the values listed in Table (1):

First, ρ=300 N/hp is considered and G values are calculated from Equation (7) (these are the same values listed in the second column in Table 1). Then, the graphic showing the relationship between G and V is drawn by using Excel program (i.e., by taking the values listed in columns 1 and 2 in Table 1).

Figure (2) shows this graphic.

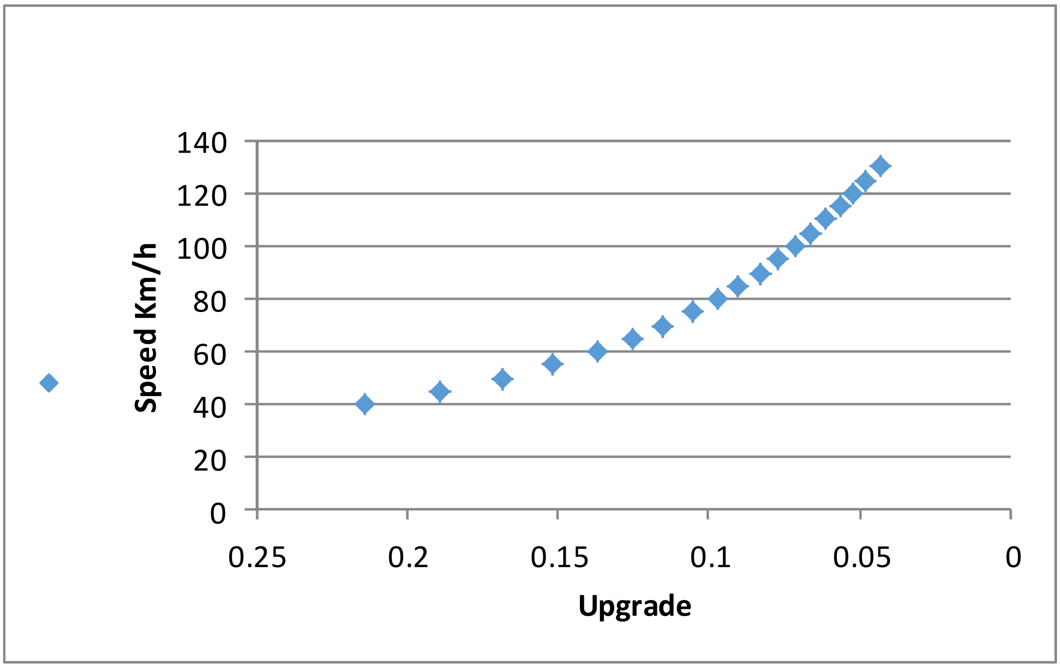

Figure (2): The relationship between speed V and upgrade G for trucks with ρ=300 N/hp

It's obvious that the shape of Figure (2) is similar to a logarithmic or polynomial relationship. Therefore, regression analysis is used to find a suitable and simple formula that represents the relation between V and G for ρ=300 N/hp. Regression analysis is a mathematical method that depends on minimizing the squares of the differences between the exact and the expected values of a dependent variable.

By comparing the logarithmic and the polynomial relationship, it is shown that the polynomial relationship gives more accurate results. The polynomial relationship is in the form of:

$$V=a.G^2+b.G+c \quad \ldots\ldots\ldots\ldots..(8)$$

By utilizing Excel program (using regression analysis), the constants a,b and c are determined. Therefore, Equation (8) can be written as:

$$V = 3118.1\ G^2-1298.9.G+178.05 \quad \text{for } \rho=300 \text{ N/hp} \quad ....(9)$$

with R^2=0.9968;

where:
V= speed in km/h.
G= the upgrade.

By repeating these steps for various values of ρ, it is found that:

For ρ=400 →
$V=4987G^2-1566.5G+165.56$ ………………………(10)
with R^2=0.9974.

For ρ=500 →
$V=7059\ G^2-1786.9G+155.2$ ....(11)
R^2=0.9983.

For $\rho=600 \rightarrow$
$V=9185.4\,G^2-1955G+145.7$ ……………………….(12)
$R^2=0.9988$.

For $\rho=700 \rightarrow$
$V=11602G^2-2118.9G+138$ …………………………(13)
$R^2=0.9991$.

For $\rho=800 \rightarrow$
$V=13229G^2-2183.5G+130.1$ ………………………… (14)
$R^2=0.9995$.

For $\rho=900 \rightarrow$
$V=15798G^2-2306.7G+124.2$ ………………………………………(15)
$R^2=0.9992$.

For $\rho=1000 \rightarrow$
$V=17463G^2-2362G+118.7$ ………………………………(16)
$R^2=0.9994$.

For $\rho=1100 \rightarrow$
$V=19571G^2-2441.5G+114.1$ ……………………………(17)
$R^2=0.9996$.

For $\rho=1200 \rightarrow$
$V=22064G^2-2512.1G+109.5$ ………………………… (18)
$R^2=0.9996$.

For $\rho=1300 \rightarrow$
$V=22638G^2-2482.1G+104.7$ ……………………………(19)
$R^2=0.9994$.

For $\rho=1400 \rightarrow$
$V=26466G^2-2636.6G+102.4$ ……………………………(20)
$R^2=0.9994$.

To determine the values of a, b and c mentioned in Equation (8) in terms of ρ, regression analysis is used too. By choosing the relation that gives the most accurate results, it's found that (by using regression analysis too):

$a=20.727\rho-3186.4$ ………………………………..(21)
$R^2=0.9967$.

$b = -839.4\ln(\rho) + 3441.5$ ………………………… (22)
$R^2=0.9903$.

$c=-50.49\ln(\rho)+467.76$ …………………………….(23)
$R^2=0.9988$.

By substituting the values of a, b and c in Equation (8), the final equation that gives the speed in terms of G and ρ is given as:

$$\mathbf{V} = (20.727\boldsymbol{\rho}-3186.4).\mathbf{G}^2 + (-839.4\ln(\boldsymbol{\rho}) + 3441.5).\boldsymbol{G} - 50.49\ln(\boldsymbol{\rho}) + 467.76 \quad \text{……….....(24)}$$

where:
V= design speed in km/h.
G= upgrade of the highway portion to be studied.
P= truck weight to horsepower ratio in N/hp.

Equation (24) is very important, because it gives directly the speed that can be adopted for a given upgrade part of a two-lane highway without needing climbing lanes for different truck characteristics.

Limitations of Using the Concluded Equation (24)

Using Equation (24) is limited by the ranges of the values of G and ρ used to conclude it. Using Equation (24) out of these ranges will give wrong results, because the shape of Equation (24) is a polynomial function. This means that out of the used ranges, the function may change from being increased to being decreased and *vice versa,* which results in inconsistent and wrong results. So, it is necessary to confirm the ranges of the values of G and ρ that give correct results when using Equation (24) as follows:

- Ratio of ρ is limited between 300 and 1400 N/hp.
- Speed is limited between 40 and 130 km/h.
- Upgrade G must not exceed the values corresponding to a speed of 40 km/h in accordance with ρ. By concluding the relationship between G_{max} and ρ (referring to Table 1), the upgrade must not exceed

the value in Equation 25.

$$G_{max} = 132.14 * \rho^{-1.122} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

R^2=0.9993.

Using Equation (24) for values of G which exceed G_{max} will give wrong results.

Assessment of the Concluded Equation (24)

For evaluating Equation (24), comparison among the results of applying this equation , the results of applying the graphic included in AASHTO (2011) and the results of research prepared by Yu (2005) is made for trucks with ρ=900 N/hp travelling on upgrades of 0%, 2%, 4% and 6%.

The comparison is performed for G equal to or less than:

$$G_{max}=132.14*900^{-1.122}=0.064\cong 6\%.$$

Table (2) shows this comparison.

The comparison in Table (2) indicates that applying Equation (24) gives conservative results than AASHTO (2011).

Figure (3) illustrates the comparison.

Table 2. Comparison for evaluating equation (24) for trucks with ρ=900 N/hp

Upgrade G %	Speed that the truck can maintain corresponding to AASHTO (2011) (km/h)	Speed that the truck can maintain corresponding to Y_u, (2005)	Speed that the truck can maintain corresponding to Equation (24)
0	110	132	124
1	97		103
2	78	82	85
3	61		70
4	50	54	58
5	44		49.5
6	37	39	43

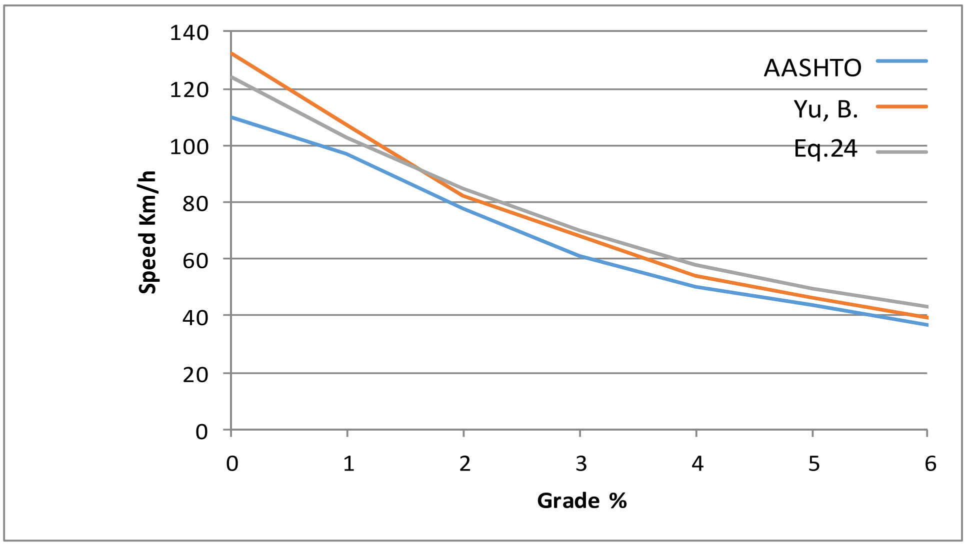

Figure (3): Comparison among the results of applying Eq. (24), AASHTO (2011) and Yu (2005)

CONCLUSIONS

- Equation (24) can be used to evaluate the need of adding a climbing lane to an upgrade two-lane highway. By knowing the upgrade G and defining the characteristic ρ of the truck which is expected to travel frequently on the upgrade, the speed for which the upgrade doesn't need a climbing lane can be determined by using Eq. (24). If the design speed of the two-lane highway is equal to or less than the calculated speed, the climbing lane will not be necessary.
- Climbing lanes are rarely added to multi-lane highways. But, some designers, sometimes, prefer to add these additional lanes to improve the level of service, if necessary. In this case, the equations included in the research can be applied to decide whether adding the climbing lanes is necessary or not.
- All of the concluded equations are valid only within the ranges mentioned in the research. If they are applied out of these ranges, the results may be incorrect.
- When the upgrade part of a two-lane highway is of short length, the truck speed will be reduced for a short distance and then the truck will accelerate to the design speed. The codes recommend that if the length of upgrade (i.e., the horizontal length of the upgrade) is equal to or less than a critical length, climbing lanes are not necessary. (The values of these critical lengths are given in codes by graphics).
- The same methodology included in the research can be applied for concluding similar equations applicable for wider ranges.

The equations that have been developed in this paper are approximate equations.

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