

An Empirical Approach in Determining the Effect of Road Grade on Fuel Consumption from Transit Buses

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ABSTRACT

Transit buses contribute a meager amount to the U.S. criteria pollutant and greenhouse gas (GHG) inventory, but they attract a lot of attention from the public and from local government, due to their nature of operation. Transit bus fleets are often employed for the introduction of advanced heavy-duty vehicle technology and the formulation of new performance models. Emissions and fuel consumption data, gained using a chassis dynamometer, are often used to evaluate performance of these buses. However, the effect of road grade on fuel consumption and emissions most often is not accounted for in chassis dynamometer characterization. Grade effect on transit buses' fuel consumption was investigated using the road-load equation. It was observed that two parameters, including the type of terrain that buses traverse and the percentage of grade for that terrain, needed to be determined for this investigation. It was assumed that all bus routes started and ended at the same point so that no average grade could be ascertained. The authors addressed this issue by assigning a sinusoidally varying road grade with a specified maximum positive or negative grade, and this was applied over the duration of the route, but was not aligned specifically with activity within the route. The grade effect depended on the ratio of the power demanded with grade to the power demanded without grade, provided the vehicle operated at a fixed weight and consumed auxiliary power at a uniform rate during its operation. This analysis was then extended to a number of conventional North American drive cycles to examine the effect of road grade on fuel consumption for varying grades on synthesized rolling and mountainous terrains. Results showed that the effect of road

grade on fuel consumption was also affected by bus operating speed. When a road grade analysis is performed and taken into consideration in conjunction with chassis data, it is likely to provide a better insight into the real-world emissions and fuel consumption from transit buses.

INTRODUCTION

Public transportation provides efficient transportation to urban population. Bus transport is the most desirable and sustainable system from a societal perspective because a well-designed bus system can provide a high level of mobility to large populations with the least cost [1]. Buses are also the dominant form of public transportation in cities and urban areas. They carried more than half of public transport riders and accounted for about 40% of the transit passenger miles in the U.S. in 2007 [2].

Diesel vehicles, including transit buses, are a known source of carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), oxides of nitrogen (NO_x), particulate matter (PM), and other unregulated species. NO_x, HC, and PM are precursors to ozone (O₃) and PM contributes to urban and regional smog [3]. CO and PM have been linked to toxic effects and PM is a possible carcinogen.

Emissions from heavy-duty on-road diesel engines in the U.S. are regulated by the Environmental Protection Agency (EPA) through a set of standards that limits the engine out emissions expressed in grams per brake horsepower-hour (g/bhp-hr) [4]. For this purpose, the engine is tested without its chassis and without considering freight or passenger weights, accessories, or real-world driving characteristics [5]. In order to test the

complete vehicle in a repeatable fashion, a chassis dynamometer is often employed. In chassis dynamometer testing, a complete vehicle is exercised through a speed-time schedule and emissions are characterized either on an instantaneous or cycle-averaged basis. However, chassis dynamometer results do not usually incorporate the effect of road grade and varying passenger weight on fuel consumption (FC) and emissions. Therefore, a correction factor for the zero grade chassis data is needed to accommodate the effect of varying road grade and terrain.

Limited research has been completed to determine the road grade for a particular route and show theoretically the effect of road grade on FC. Pelkmans et al. [6] compared emissions and FC from three bus technologies at different road grade while Conley and Clark [7] considered the contribution of road grade in evaluating power and energy requirements to find the optimal method of sizing hybrid-electric vehicle components. Kern et al. [8] modeled chassis data from a 1998 model year (MY) International Tractor Truck fitted with a Cummins N-14 435 hp engine at 46,000 lbs test weight and found that moderate road grade (less than 5%) had little bearing, while steep grade (more than 5%) had considerable effect on NOx emissions. Thompson et al. [9] made an effort to include the effect of uphill driving on a chassis dynamometer and observed that CO, HC, NOx, and FC increased at uphill driving, but PM did not change much. However, their research acknowledged drivers' discomfort in following an inclined trace during dynamometer testing. Samuel et al. [10] observed more than 100% increase in CO, HC, and NOx, and about 45% increase in CO₂ on a 1.4 liter, 100 hp gasoline vehicle with simulated road grade of +3%.

This paper analyzes the grade effect on FC using the road load equation and develops a grade correction factor (GCF) to account for the ratio of FC with and without road grade. This study was motivated by the findings of another study by these authors [11], in which they investigated the effect of passenger weight on emissions and FC from transit buses. In that study, the authors developed a theoretical weight correction factor (WCF) for three passenger loadings using the road-load equation which was validated with experimental data collected on three 40-foot diesel and natural gas buses.

THE ROAD-LOAD EQUATION

Total power needed at the wheels is expressed by the road-load equation [12,13,14,15,16] applied to a transit bus as:

$$P_t = mv(dv/dt) + 0.5 C_D \rho A v^3 + \mu mgv + mgvZ$$

[Equation 1]

where, m is mass of the bus (kg), v is speed of the bus (m/sec), A is frontal area of the bus (m²), g is acceleration due to gravity (9.81 m/sec²), C_D is aerodynamic drag coefficient, μ

is tire rolling resistance coefficient, ρ is air density, and Z is road gradient (%). P_t is the total power needed at the wheels and is expressed in kilowatts (kW) in SI unit. In this equation, the first term is referred to as the Inertia Load, the second term as the Wind Drag, the third term as the Rolling Resistance, and the last term is the Grade Load. Summation of these loads resulted in the "total load or total power." This was also termed as 'tractive force' needed to propel the vehicle at any prescribed velocity and acceleration [17].

The wind drag in Equation 1 is defined as the force required to overcome the resistance to vehicle motion. The value of drag coefficient, C_D for a standard bus used in the literature varies from 0.40 to 0.79 [18,19,20]. For a transit bus, the wind drag force is found to be small in comparison to its inertia load, from the order of 3% on the Paris Cycle [21] to 20% on the Commuter Cycle of Society of Automotive Engineers (SAE) J1376 [22].

The rolling resistance is defined as the force needed to roll a vehicle over a surface and is expressed as μmgv. The rolling resistance coefficient, μ, is influenced by tire size and pressure, axle geometry, and the amount of vertical load applied to tires. In reality, the tire loss may be affected by speed and by torque delivered, but these secondary effects are often neglected. The rolling resistance force is found to dominate the wind drag and inertia forces at low speed and steady operation, while at high speed operation, the wind drag dominates. However, most cycles are transient and the inertia demand is therefore high. The rolling resistance contributes to about 20% of the total load on the Orange County Transit Authority Cycle (OCTA) [23] for a transit bus. Previous research demonstrated that a 20% reduction in rolling resistance could yield as much as 2.5% reduction in FC [24]. The rolling resistance coefficient for a transit bus is found to vary from 0.005, when vehicle speed approached zero miles per hour (mph), to 0.011 when vehicle speed approached 56 mph [18].

The road gradient, Z, is referred to as the slope between two adjacent points and is expressed as a percentage [25, 26, and 27]. Note that the Z can be expressed as sine of angle 'theta,' θ, and is approximately equal to the percentage change in road grade. The gradient resistance in Equation 1 is defined as the force component in the direction of motion that is needed to overcome the force produced by the vehicle's weight, where vehicle weight is always directed to the downward direction.

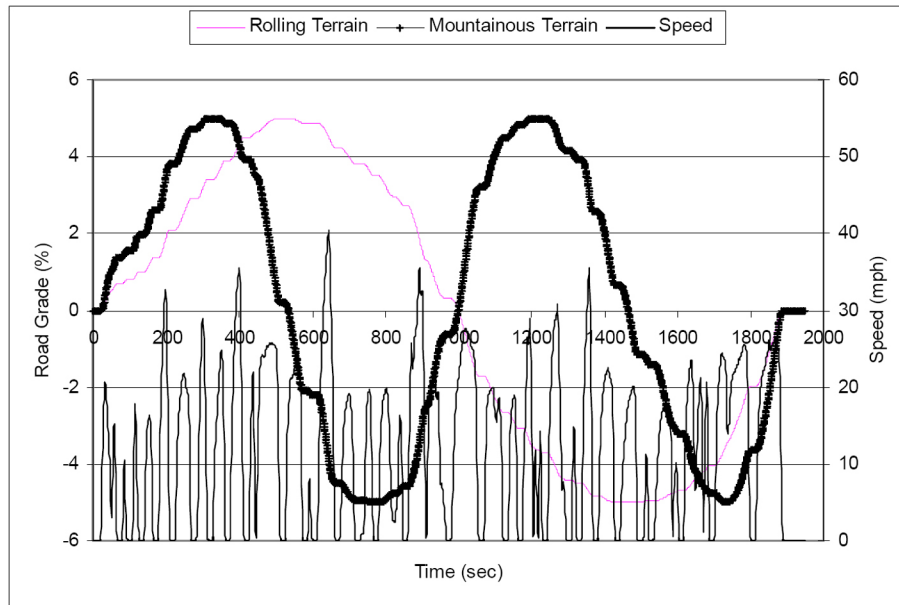


Figure 1. Representation of road grade on OCTA Cycle against cycle duration for different terrains

EFFECT OF ROAD GRADE AND TERRAIN ON FUEL CONSUMPTION

DEFINING ROAD GRADE AND TERRAIN

The American Association of State Highway and Transportation Officials (AASHTO) defines road grade as the rise or fall in vertical distance divided by the horizontal distance for that particular route. While discussing road grade, it is imperative to discuss terrains, as they are inter-related [26]. Terrains are classified into three types by AASHTO: flat or level terrain, rolling terrain, and mountainous terrain. Road elevations are occasional and smooth in flat terrain. In rolling terrain, natural slope consistently rises and falls below the average road grade. Elevations in mountainous terrain are abrupt and steep. A graphical representation of road grade with rolling and mountainous terrains on the OCTA Cycle is presented in [Figure 1](#). Note that the cycle both starts and finishes with a zero percentage grade.

By definition, rolling terrain with high grade could cause vehicles to reduce their speeds at constant power. Mountainous terrain, possessing steeper grades, could cause some trucks to significantly compromise their speed. It was observed that passenger cars could overcome 4-5% grade without compromising their speeds [26]. AASHTO recommended that road grade for commercial and business areas should be less than 5% [26]. A minimum road grade of 0.5% was also recommended by AASHTO for smooth drainage. AASHTO also pointed out the importance of the weight-power ratio of a vehicle in maintaining its driving

speed. A truck with a weight-power ratio of 200 lb/hp was expected to maintain 60 mph speed at 3% uphill grade [26]. Therefore, an under-powered bus would have to sacrifice its speed driving uphill, while an over-powered bus would have minimal problems driving uphill.

The basic definition of road grade is not adequate in determining road grade for a particular bus route. This is especially true in transit applications, because a bus route is considered to be a closed circuit of activity that starts and ends at the same altitude on a road. Hence, the average grade of a bus route will be zero. To avoid inconsistency, in this research, road grade was mimicked with a sine wave with respect to route distance and described in terms of the nature of terrain. A 5% road grade on synthesized rolling terrain implied ascending a rolling hill in a sinusoidal way reaching 5% maximum grade followed by descending to the 5% level in the same way and completing the cycle at the same elevations where it started. It was acknowledged that sinusoidal representation of grade was an approximation of road grade and might not truly represent the road elevation with respect to its distance.

The graphical representation of terrain in [Figure 1](#) was determined with respect to the distance traveled on that cycle, but plotted the time of the cycle on the X-axis in order to compare grade percentage with cycle speed. The same terrain, if plotted against distance traveled, would have been represented as shown in [Figure 2](#), where distance is shown on the X-axis. In [Figure 2](#), the grade increase or decrease is a continuous function with distance while, in [Figure 1](#), the small straight line on the grade represented idle time when no distance was traveled, and hence, no change in grade was

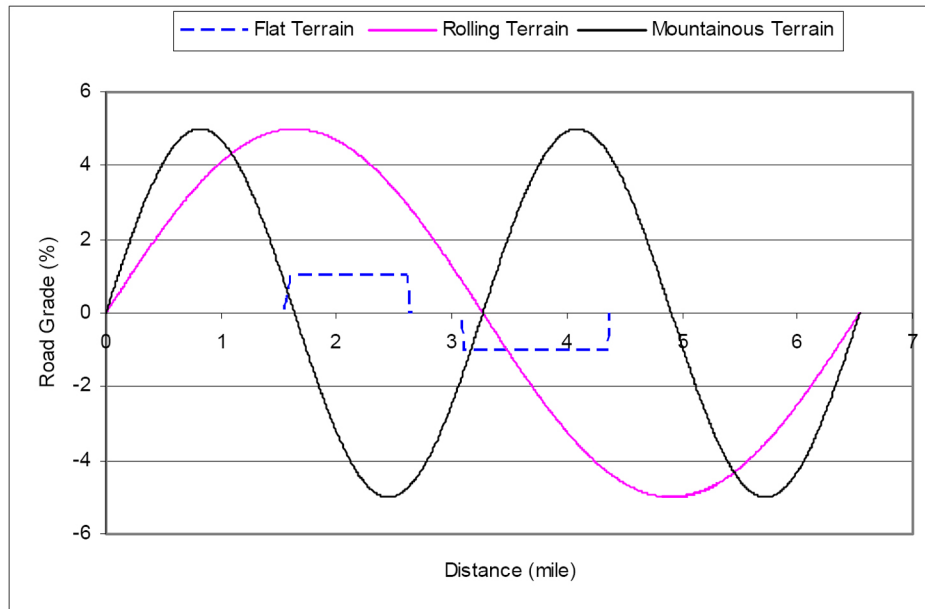


Figure 2. Representation of road grade on OCTA Cycle against distance traveled for different terrains

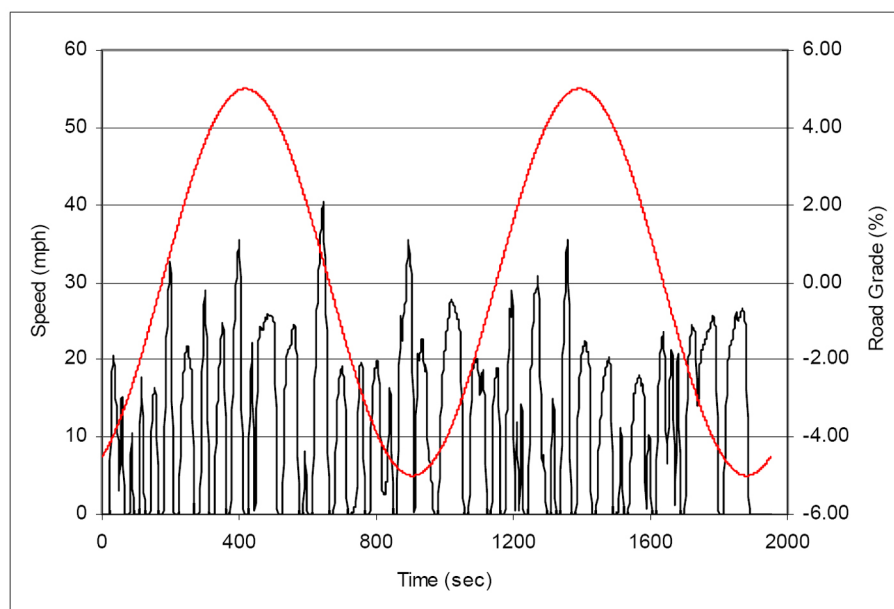


Figure 3. Representation of road grade on OCTA Cycle for mountainous terrain determined from cycle time

encountered. This is logical since during idle the bus did not move and no change of grade happened.

Alternately, road grade and terrain could be produced with respect to the time traveled on that cycle as shown in [Figure 3](#), where road grade was determined from the cycle duration. As a result, grade was represented as a continuous function of cycle time. In this instance, the cycle was started at a negative grade, followed by uphill and downhill driving and returning to the elevation from which it started. However, this method

failed to capture the fact that any change to road grade was not possible when the bus was idling. Therefore, grade representation in this paper was calculated as continuous function of distance, but presented with time to relate corresponding speed.

MODELING ROAD GRADE EFFECT ON FUEL CONSUMPTION

The effect of road grade on total load and FC was analyzed by assigning a road grade to a drive cycle. Here the drive cycle had no change in altitude. The grade effect was included in the road-load equation for a drive cycle and an empirical relationship was developed to account for the difference in FC with or without grade. Clark et al. [28] developed an empirical formula where FC from an engine was affected by its axle power, drivetrain efficiency, auxiliary power and fuel conversion efficiency, as shown in Equation 2. It was assumed, as a substantial approximation, that the automatic transmission had a constant value for efficiency over the whole operating range. It also was assumed that the auxiliary load on the engine was constant.

$$m_f = [1/\eta_d (P_{axle}) + P_{aux}]/(\eta_f * QHV) \quad [Equation 2]$$

Where, P_{axle} is axle power, P_{aux} is auxiliary power, m_f is the amount of fuel consumed per unit time, η_d is drivetrain efficiency, QHV is the heating value of fuel, and η_f is the fuel conversion efficiency.

The fuel consumed by the engine will not be in proportion to the power demand because the engine operates more efficiently at high load, and suffers proportionally higher losses to friction at low load. One may model the fuel consumed by the engine using an equation very similar to that used for instantaneous power. However, the constant value will have accounted not only for auxiliary loads, but also for frictional losses, which are most significant as a fraction of power at light loads. In the case of throttled engines used for natural gas buses, the constant value will also need to account for pumping losses across the throttle.

FC rate with no grade (ng) as shown in Equation 2 can be expressed as:

$$m_{f_{ng}} = [1/\eta_d (P_{axle}^{ng}) + P_{aux}]/(\eta_f * QHV) \quad [Equation 3]$$

Taking road grade into effect FC with road grade (wg) then becomes:

$$m_{f_{wg}} = [1/\eta_d (P_{axle}^{wg}) + P_{aux}]/(\eta_f * QHV) \quad [Equation 4]$$

Therefore, the ratio of FC with and without road grade is expressed as:

$$m_{f_{wg}} / m_{f_{ng}} = (1/\eta_d (P_{axle}^{wg}) + P_{aux}) / (1/\eta_d (P_{axle}^{ng}) + P_{aux}) \quad [Equation 5]$$

In this equation, the ratio of FC depends on only the ratio of power demanded with and without road grade, provided the vehicle operates at a fixed weight. Therefore, for any particular drive cycle, FC will be a function of cycle average speed and road grade. However, it is emphasized that engine efficiency is not constant. As such, a cycle that demands continuous high power will suggest more efficiency yet more fuel use than a cycle which demands only partial power output as the engine can operate on a high efficient area in the speed-torque map.

Equation 5 was applied to the speed-time traces of the Commuter Cycle, where a 5% maximum road grade was also assigned, as shown in Figure 4. While integrating the road-load equation over the Commuter Cycle with road grade, it was assumed that the driver would have pressed the brake when the negative road grade exceeded drag, rolling, and inertia load, combined. This would correspond to a negative power demand. A comparison of the difference in total load with and without road grade is presented in Figure 5. It was found that addition of road grade would result in about 28% additional FC considering the vehicle had 75% drivetrain efficiency and that the auxiliary power demand was about 7.5 kW (10 hp). The primary cause of the additional FC is that the energy lost to braking on downhills must be re-supplied on the uphill sections.

It is inconceivable that bus routes always start at zero grade. A bus route may have started at some uphill grade followed by downhill grade or vice versa. Effects of phase shift, therefore, were considered before computing the grade effect on FC. In this analysis, a bus is assumed to follow the OCTA Cycle and various combinations of road grades are imposed on its route. Two such combinations are presented in Figure 6 and Figure 7. It was found that change in phase shift for 5% mountainous grade on the OCTA Cycle caused a variation in its total load from about 15 kW-hr to 18 kW-hr. Therefore, an effort was made to create a representative number of combinations and the average total load was considered. In this way, for existing cycles, the grade effect can be decoupled from the vehicle speed activity.

However, caution must be exercised when analyzing grade effect on heavy-duty truck cycles, where the frequency of stops may be lower in revenue service than is typical for buses. Consider a 5% maximum synthesized grade effect on the UDDS cycle with no distance shift, as shown in Figure 8. In this case, the road grade resulted in an additional power demand of 4.7 kW-hr (42%). When this grade was imposed

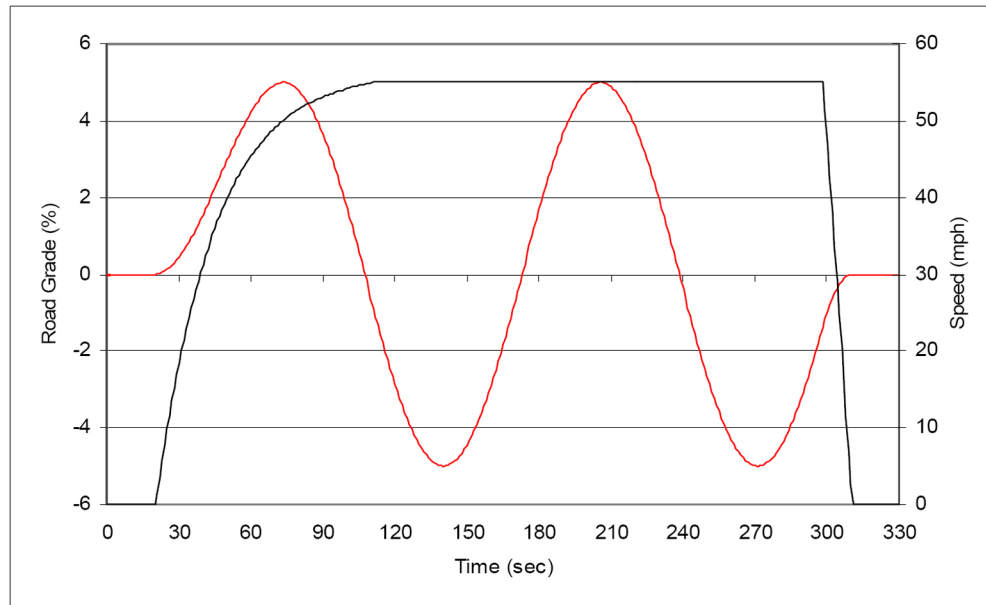


Figure 4. The Commuter Cycle with 5% maximum road grade on a mountainous terrain

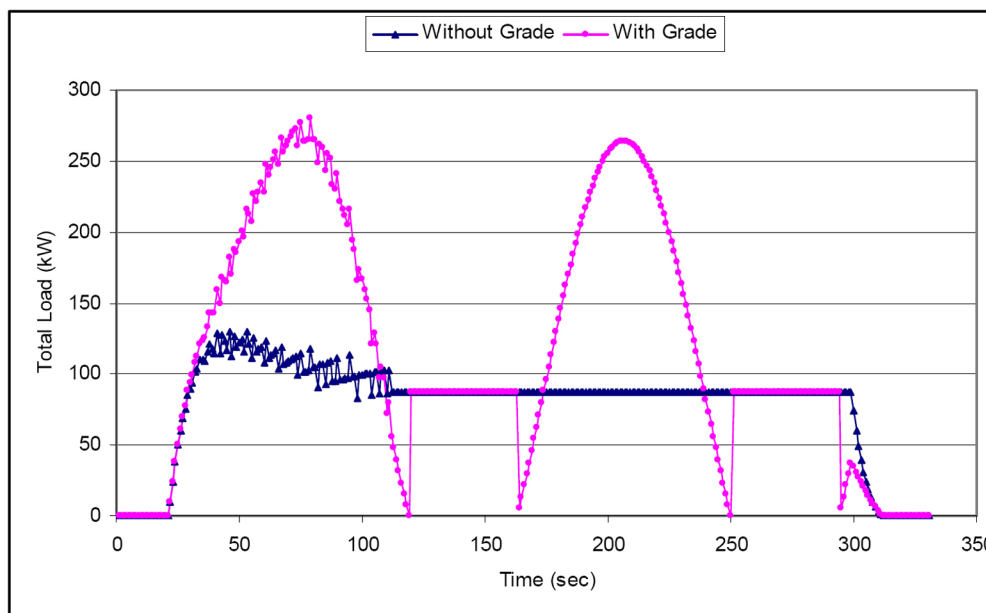


Figure 5. Comparison of the total load for a transit bus with and without road grade on the Commuter Cycle

with various distance shifts, additional power demands varied from 0.0 kW-hr (0%) to 10.7 kW-hr (96%). Therefore, a greater number of combinations for road grade will have to be considered for truck cycles. Note that the braking line on the negative grade load in Figure 8 resulted from the adjustment of grade load to zero, i.e. service braking, when negative grade load exceeded the load resulted from drag, rolling, and inertia loads.

Presence of road grade on a transit route can cause two scenarios for any vehicle. In the first scenario, the vehicle may be able to deliver the extra power demanded from the engine and follow the speed-time trace on uphill segments. This is more likely to happen for low and medium speed cycles with low road grade. In the second case, the vehicle may be unable to provide the additional power demanded from the engine, resulting in reduced speed at uphill grade. In this second scenario, completing the same route is more