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Title: Acceleration Characteristics of Starting Vehicles

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ABSTRACT

Acceleration characteristics of starting vehicles are needed for many transportation analysis and design purposes involving driveways, turning bays, intersecting streets, traffic signals, railroad crossings, simulation software, etc. Constant acceleration is sometimes assumed or AASHTO Green Book values based on piecewise-constant accelerations are sometimes adopted. Yet, continuing research has shown linearly-decreasing acceleration rates better represent both maximum vehicle acceleration capabilities as well as actual motorist behavior. It is not acceleration that is usually constant during speed changes, but the rate of change in acceleration.

The evolution of AASHTO acceleration values for design is traced, and the literature is reviewed for pertinent field observations. Linearly-decreasing acceleration (and some deceleration) model parameters are calibrated for various sets of observational and design data. Despite published results from thousands of field measurements, the values selected for design were found to be based mostly on vehicle performance capabilities with conjecture about how much of these capabilities are normally used by drivers. Design accelerations were found to deviate substantially from observed accelerations. At the start of motion, observed accelerations were about 15% faster for passenger cars and 45% faster for SU trucks than design accelerations. As speed increased, observed accelerations dropped 3 to 4 times faster than design accelerations for these vehicles. Observed accelerations for WB-15 trucks began 40% to 75% slower than design accelerations, and were considerably slower than the values in the Green Book for trucks at railroad crossings.

Voids in the available information base are identified. Linearly-decreasing design acceleration rates for motorists operating different classes of vehicles in different design situations are recommended, and revisions for Green Book parameters and charts are suggested. The recommended acceleration model greatly simplifies acceleration parameters, but implies using different acceleration relationships for different design speeds instead of one for all.

Keywords: starting acceleration, design acceleration, motorist acceleration, deceleration

Acceleration Characteristics of Starting Vehicles

Acceleration characteristics of vehicles starting from rest are needed for many transportation analysis and design purposes involving driveways, turning bays, intersecting streets, traffic signals, railroad crossings, simulation software, etc. Constant acceleration is often assumed or piecewise-constant values derived from the AASHTO Green Book *(1)* are frequently adopted. This paper examines whether the acceleration of vehicles starting from rest is constant, or nearly constant, for various classes of vehicles, and suggests improvements for modeling vehicular acceleration.

Several issues are involved. Vehicle acceleration depends upon the type of vehicle, insofar as its size and weight and the engine power available to propel it. This determines the maximum acceleration of which a vehicle is capable. Maximum acceleration is useful only when utilized. Heavy trucks that are fully loaded sometimes accelerate at the maximum rate permitted by their diesel engines. Most passenger car motorists, however, routinely utilize only a portion of the maximum acceleration of which their vehicles are capable. The acceleration rates actually applied by motorists are usually more important in design than vehicle maxima. For some situations, average acceleration rates may be applicable. Often, 'worst-case' or lesser rates are pertinent in order to accommodate more than just the half of motorists who exercise average or above-average rates of acceleration.

ACCELERATION RATES FOR DESIGN

The most widely-accepted source for design information about the acceleration characteristics of vehicles starting from rest in the U.S. is surely the AASHTO Green Book. Acceleration information is presented in several places in the 1994 Green Book (i.e., Figure II-

16, Figure IX-33, Figure IX-34, Figure IX-35, Table IX-8, and Table IX-9, as illustrated in Table

1 of this paper), but none of the presentations actually specify acceleration rates or underlying

acceleration models or assumptions. The Green Book states that values for acceleration rates for

passenger cars starting from rest are shown in Table IX-8, but really only speed, distance and

time are actually specified, not accelerations. It is hinted that the data in Table IX-8 are derived

from Figure IX-33, but only the first two of the nine lines of data in Table IX-8 fall within the

domain of Figure IX-33, and the rounding of speed and distance in Table IX-8 create some minor

disparities. However, the speeds and distances in Table IX-8 appear to match the data in Figure

II-16 very closely, which are reported as being based on the same data for passenger cars as used

in Figure IX-33. These inconsistencies can be bewildering for some design uses.

Some of the Green Book information is confusing. The top portion of Figure IX-34

appears to be a redundant re-plot of the same information in Figure II-16. The reference sources

for these figures appear be the same report, although the report is cited quite differently in the

reference lists at the ends of the two chapters. The data in the plots seem to present conflicts.

The 30 km/hr initial speed curve in Figure II-16 does not intersect the curve for initial speed of 0

km/hr, but the two curves merge at 300 m in Figure IX-34. The 30 km/hr line in Figure IX-33

seems to be mis-plotted at long acceleration distances which actually take less time than shown.

The reference source for truck data in Figure IX-34 seems faulty.

The Green Book provides a starting point, but the information is inadequate for many

design purposes. It is unclear whether some of the figures and tables represent average

accelerations or accelerations for design which will accommodate more than just half of all

motorists. It is unclear if the data pertain only to full-size passenger cars (P vehicles) or if low-

power compact cars and other passenger cars are also represented. Several figures and tables

pertain only to passenger cars, yet loaded trucks may be the critical vehicles for design. Higher

than normal accelerations are adopted for unsignalized at-grade intersections based on the

concept that motorists may accelerate faster when maneuvering at these intersections, but the

same acceleration rates may not be applicable for clearing a queue that backs up onto a railroad

track where queue clearance is constrained by leading motorists who may have no particular

incentive for faster than normal acceleration. Yet, below-average accelerations are not addressed

for design. More detailed information is needed to be disclosed in the Green Book regarding

acceleration rates and the underlying models and assumptions. Although surprising, much of the

acceleration information reflected in the Green Book seems related to data from more than a half-

century ago rather than recent observations.

VEHICLE ACCELERATION CAPABILITIES

Maximum vehicle acceleration rates have long been recognized as decreasing with

increasing speed. Most motorists have observed that when accelerating from rest, such as at a

traffic signal, it is possible to accelerate faster, possibly to the extent of spinning the drive

wheels, than it is when accelerating from a high rate of speed, such as when passing a slower

vehicle on a two-lane roadway, where pushing the accelerator to the floor sometimes does not

deliver the boost desired. This is clear evidence that it is unreasonable to simply assume that

acceleration rates are constant over all vehicle speeds.

Loutzenheiser *(2)* reported in 1937 that the Bureau of Public Roads found little

acceleration information available, especially for speeds above 48.3 kph (30 mph), so they

conducted a series of tests on six "modern" 1935 to 1937 6- and 8-cylinder passenger cars, all

equipped with 3-speed manual transmissions. The acceleration results from repeated trials at full

acceleration with all six vehicles and different drivers were averaged together in successive 8.05

kph (5 mph) speed increments. The maximum acceleration was 1.74 mps^2 (5.72 fps^2) at speeds

of 0-8.05 kph (0-5 mph), and the rates dropped linearly to 0.45 mps^2 (1.47 fps^2) at speeds of

104.7-112.7 kph (65-70 mph). The findings are displayed graphically in Figure 1, where the

strong linearly-decreasing relationship of acceleration related to speed is quite evident.

At about the same time as the tests by the Bureau of Public Roads, the Oregon State

Highway Department conducted similar tests. As reported by Beakey *(3)*, the vehicles selected in

the Oregon tests of maximum vehicle accelerations involved one 1931 and five 1935 to 1937

passenger cars. Although the results were reported for each vehicle separately for 16.1 kph (10

mph) speed increments, Oregon researchers measured only full-throttle accelerations in second

gear, and separate full-throttle accelerations in high gear, rather than continuous accelerations

from stop. The optimum speed for shifting from second gear to high gear to maximize overall

vehicle acceleration was about 48.3-64.4 kph (30-40 mph) for all vehicles. From the speed data

in high gear, Beakey found the maximum accelerations followed "an approximate straight-line

decrease to zero at maximum speed" for each vehicle. Accelerations of three of the 1935-37 cars

were very close at each speed to the 6-vehicle average reported by Loutzenheiser. Accelerations

of the 1931 car were about 0.4 mps^2 (1.3 fps^2) below the 6-vehicle average at each speed,

probably due to a less powerful engine from the 5-year earlier era of development and

manufacturing. It had a top speed of only about 98 kph (61 mph), where all other vehicles

exceeded 113 kph (70 mph). One 1937 car had accelerations about 0.4 mps^2 (1.3 fps^2) above the

6-vehicle average at each speed. Engine and chassis sizes were not disclosed so it is not known

if it might have had more cylinders or a lighter chassis than the others. The average of the

accelerations of these five vehicles would be about the same as the 6-vehicle average reported by

Loutzenheiser. One car departed from the trend. The accelerations of a 1935 Chevrolet, while

nearly linear, were higher at speeds near 64 kph (40 mph) and lower at 113 kph (70 mph) than

the 6-vehicle average, possibly due to a lower gear ratio in high gear than the other vehicles.

While this evidence from over 60 years ago indicated a strong linearly-decreasing

relationship between maximum accelerations and vehicle speeds, for both individual vehicles and

averages, vehicles have certainly evolved during the interim. Engines are more powerful and

compact, vehicles are smaller and lighter in weight thereby reducing weight-to-horsepower

ratios, and automatic transmissions have mostly replaced 3-speed manual transmissions in

automobiles. Thus, information on recent vehicles is of interest.

The *Traffic Engineering Handbook (4)* provides information on typical maximum

acceleration rates on level surfaces related to speed ranges for recent passenger cars and tractor-

semitrailer trucks. These are also plotted in Figure 1. As can be seen, recent automobiles do

indeed display higher acceleration capabilities than those of 60 years ago, but the rate of

reduction in acceleration capability with increasing speed is still almost the same as before.

While the performance of heavily-laden tractor-semitrailer trucks is considerably less than

automobiles, the reduction in acceleration capability with increasing speeds is less, likely due to

having many more incremental gears to use for acceleration. The linearly-decreasing

accelerations with increasing speed are clearly evident in each class of vehicles, but the strong

compliance is due to the accelerations being estimated from a model rather than empirical tests.

However, the underlying model was based on experimental test results from research reported in

NCHRP Report 185 *(5),* and these findings have also been confirmed in other research studies.

As the engine power of a vehicle is increased, not only can the vehicle accelerate faster, but usually it can also attain higher speeds. If the maximum acceleration and the maximum speed increase together, then the ratio of maximum acceleration to maximum speed can be nearly constant, which means that the slope of the acceleration-speed lines would be nearly constant, as suggested by the information in Figure 1.

The linearly-decreasing relationship is a consequence of the physics of motion. Consequently, these empirical observations are associated with theoretical concepts. While the relationships have long been known, they are not widely found in textbooks, but are presented in the *Traffic Engineering Handbook* and various research reports such as NCHRP Report 185.

Traffic Observations

The vehicular behavior described by a linear model has been widely observed by motorists. Trucks traveling on freeways at high rates of speed tend to slow when going up hills and speed up when descending because they lack sufficient extra engine power to maintain a constant speed while climbing at high speeds. Observations of vehicles in motion support the concepts that the maximum vehicle acceleration likely occurs when starting from rest, the ability to accelerate attenuates with higher vehicle speeds, and there is some maximum speed beyond which a vehicle cannot accelerate further, as implied by the linear conceptualization of acceleration.

It is also well recognized that it is often possible to spin the drive-wheel tires of passenger cars when accelerating rapidly from rest. This is not generally possible when a vehicle is moving at moderate or high speeds. It is due to the maximum accelerating force being available from

rest, and that force can exceed the tractive force provided by friction between the tires of the

drive wheels and the pavement. When the drive-wheels spin, the tractive force delivered to the

wheels is not applied entirely to the propulsion of the vehicle, so the maximum vehicle

acceleration rate can be limited by friction, from rest up to some speed, and then limited by

engine power beyond it.

While the acceleration model could be extended easily to include acceleration limitations

imposed by friction, there is no need for this. Most heavy trucks lack sufficient power to spin

their wheels under normal loaded conditions, and passenger cars rarely exercise wheel-spinning

acceleration. Consequently, a sufficient model for the maximum acceleration of both passenger

cars and trucks is given by $a = \alpha - \beta v$. The parameter α represents the maximum acceleration,

which occurs when the vehicle speed is zero, just as it starts. The parameter β represents the

slope of the line or the rate of decrease in acceleration as speed, v, increases. To account for

grades, G, the model can be expanded to $a = \alpha - \beta v \pm Gg$, where g represents the acceleration of

gravity.

Equations for Linearly-Decreasing Acceleration

The linearly-decreasing acceleration model can be rewritten as a differential equation and

integrated to derive the following relationships (treating a grade as being constant), as partially

shown in pertinent textbooks *(6)*:

$$\partial v / \partial t = \alpha - \beta v \pm Gg \tag{1}$$

$$v = (\alpha \pm Gg) / \beta - ((\alpha \pm Gg) / \beta - v_0) \, e^{-\beta t} \tag{2}$$

$$d = ((\alpha \pm Gg) / \beta) \, t - ((\alpha \pm Gg) / \beta - v_0)(1 - e^{-\beta t}) / \beta \tag{3}$$

$$t = (\beta \, d + v - v_0) / (\alpha \pm Gg) \qquad \text{(from equations 2 and 3)} \tag{4}$$

$$v_{max} = (\alpha \pm Gg) / \beta @ a = 0 \quad (\text{since } a = \alpha - \beta v \pm Gg) \tag{5}$$

$$v = v_{max} - (v_{max} - v_0) e^{-\beta t} \quad (\text{where } \beta = (\alpha \pm Gg) / v_{max}) \tag{6}$$

$$d = v_{max} t - (v_{max} - v_0)(1 - e^{-\beta t}) / \beta \tag{7}$$

$$t = d / v_{max} + (v - v_0) / (\alpha \pm Gg) \tag{8}$$

The equations presented above arising from the linearly-decreasing acceleration model are not quite as simple or as easy to apply as their counterparts based on constant acceleration rates, but they are processed readily by a computer.

Maximum Vehicle Acceleration Parameter Values

The parameter values for α and β were determined for each class of vehicle in Figure 1 as presented in the vehicle performance section of Table 2. The values for β are rather similar for each vehicle type, and the values for α increase with decreasing weight-to-horsepower ratios.

MOTORIST ACCELERATION PREFERENCES

Since motorists rarely exercise the maximum acceleration capabilities of their vehicles, except in emergencies, the maximum acceleration characteristics are not useful in design except as bounding values. When considering the accelerations chosen by motorists, the linearly-decreasing relationship with increasing speed no longer has a strong theoretical foundation. Motorists usually apply a high level of power initially to overcome inertia while at rest to begin to move, and then they tend to reduce acceleration gradually so that they make a smooth transition to zero acceleration when they reach the speed limit or their desired speed of travel, for continuing at a constant speed. This could be achieved in a variety of nonlinear patterns. However, observations of travel behavior indicate that the linearly-decreasing model of acceleration usually describes motorist behavior effectively.

Early Observations

In 1937, Beakey (3) reported that the Oregon State Highway Department conducted

measurements of accelerations of the lead automobiles starting from rest at a traffic signal as they

traveled straight forward through a series of traps spanning a total of 290 meters (950 feet). The

roadway had no major street intersections, few minor intersections, and rural highway speeds

were permissible and immediately attainable after clearing the intersection traffic signal control

area towards the middle of the 290-meter observation zone. Most vehicles reached speeds of 48-

64 kph (30-40 mph) at the end of the 290-meter zone, and were still accelerating. These

observations were grouped together as average motorists. A few vehicles reached speeds of 64-

81 kph (40-50 mph) and were still accelerating at the end of the 290-meter zone. These were

grouped together as faster-than-average motorists. A few other vehicles only reached speeds of

32-48 kph (20-30 mph) and were no longer accelerating at the end of the 290-meter zone. These

were grouped together as slower-than-average motorists. The proportions of motorists in each

group were not reported. From the figures reported by Beakey, observed accelerations related to

automobile speeds were calculated and are presented in Figure 2 for each of the three groups of

motorists. Also shown in Figure 2 are the automobile maximum accelerations reported by

Loutzenheiser from Figure 1.

Each of the relationships displayed in Figure 2 exhibits linearly-decreasing accelerations

associated with increasing automobile speeds. Each of the three groups of motorists appears to

start from rest at an acceleration which is about the maximum of the vehicle, probably due to

revving up the engine either before or while disengaging the clutch to deliver sufficient power to

avoid the engine dying as the clutch is disengaged, and releasing the clutch as quickly as possible

to avoid unnecessary friction-heat or wear. The parameter values for α and β were determined

for each group of motorists in Figure 2 and are presented in the motorist observations section of

Table 2.

The Bureau of Public Roads also addressed the issue of "normal" accelerations by

motorists in the studies reported in 1937 by Loutzenheiser *(2)*. Rather than observing motorist

behavior in actual traffic conditions, the test drivers used in measuring maximum automobile

accelerations were instructed to drive the same test vehicles again in a series of trials, but to

emulate what they perceived to be their normal driving behavior. Loutzenheiser compared the

results with the findings of Beakey and observed that accelerations of the test drivers were

similar but slightly slower than the faster-than-average drivers reported by Beakey. He noted that

this somewhat faster than average result was not surprising since the advance-alerted test drivers

were probably concentrating more on their driving and likely were going faster than the unalerted

public motorists. He also noted some disparities in the test drivers replicating their "normal"

driving performances in repeated tests involving the same acceleration ranges.

Although the relationship between acceleration and speed for normal driving found by the

Bureau of Public Roads appeared to be somewhat curved rather than straight, Loutzenheiser

deduced that the normal acceleration rate was about two-thirds of the maximum automobile

acceleration rate. Loutzenheiser concluded that the Bureau of Public Roads' tests seemed to

support the Oregon State Highway Department's findings about normal driving behavior.

Other Parameter Sources

The decreasing linear relationship between acceleration and vehicle speed has been

reported in a number of studies. In a detailed investigation in NCHRP Report 185 of the effect of

grades on traffic movements, St. John and Kobett *(5)* examined test results reported in the

literature along with underlying theoretical considerations and determined that the acceleration

capability of passenger cars, pickup trucks and recreational vehicles was a linearly-decreasing

function of speed. This was verified by their own tests in which they found a linear relationship

with $\alpha = 3.36$ (11.0) and $\beta = 0.0803$ for a 1970 Chevrolet sedan on level terrain, and $\alpha = 5.19$

(17.0) and $\beta = 0.1478$ for a 1971 Chevrolet 3/4-ton pickup truck on level terrain, under maximum

acceleration. They provide similar results for other vehicles.

Glauz et al. *(7)* established a linear relationship with $\alpha = 2.5$ (8.2) and $\beta = 0.104$ for the

acceleration characteristics of the lowest 10% in performance capabilities of 1975-1995

recreational vehicles, and $\alpha = 2.85$ (9.36) and $\beta = 0.0853$ for passenger cars. These were

forecasts, but they reflect a departure from the typical approach of trying to identify the average

acceleration characteristics of a class of vehicles in favor of an approach more suitable for design

purposes where more than just half of a class are intended to be accommodated. Vehicle

acceleration capabilities, of course, may not be as important in design as the acceleration rates

chosen by the slowest 10% of motorists.

In 1958, Bellis *(8)* collected data at three signalized intersections in New Jersey using a 5-

man field crew pressing telegraph keys wired to a 20-pen chart recorder. Only a couple of traps

were configured at most locations, which are not useful for determining acceleration profiles, but

average travel times were reported for one location at six positions. Data for passenger cars were

too incomplete to be useful, but the truck data had fewer gaps and exhibited a linearly decreasing

relationship with $\alpha = 1.67$ (5.47) and $\beta = 0.1229$. Bellis identified heavy trucks as having an

average length of 12.8 meters (42 feet), which suggests that today's heavy trucks may be bigger

and heavier, and the trucks in Bellis' study may be closer to SU vehicles.

In 1966, Dockerty *(9)* used motion picture photography to study the acceleration characteristics of leading vehicles queued at two traffic signals in England to capture actual motorist behavior in traffic streams instead of using observations made on test tracks under controlled conditions. He measured the distances of movement during 1-second intervals commencing at the beginning of vehicle motion. Observations were separated for passenger cars, small vans and medium vans from heavy vehicles, which included all others. While his report did not present it, a linearly-decreasing model with $\alpha = 2.27$ (7.45) and $\beta = 0.1487$ fits the data from his observations of cars starting in the median lane. His data reflect that leading vehicles tend to accelerate in the outside travel lane a little slower, with $\alpha = 1.88$ (6.17) and $\beta = 0.1201$. These two sets of findings are similar to Beakey's findings from 1935. Dockerty's data indicate leading trucks in both lanes accelerated slower yet, with $\alpha = 1.49$ (4.87) and $\beta = 0.1455$, which is similar to Bellis' data. The site had no pedestrian interference, but where this interference existed in his site in London, a linearly-decreasing model does not fit his leading car accelerations, which instead seem to begin accelerating very slowly, and then gradually increase to a maximum before gradually reducing acceleration.

In 1972, Evans and Rothery *(10)* collected speed and acceleration data on the characteristics of 15,138 queued motorists crossing a trap after stopping for a red traffic signal at a suburban location near Detroit. From their data, Bonneson *(11)* calculated a strong linearly-decreasing relationship between acceleration and speed. The first sensor in their trap, however, was so far beyond the stop-line that speed measurements reached 35 to 55 kph (22 to 34 mph), which requires excessive extrapolation, with no intervening data points, back to a speed of zero

to determine the maximum acceleration at startup. Their data showed slightly higher rates of

acceleration of about 0.1 mps^2 (0.33 fps^2) in the left travel lane than in the right lane at all

positions in the queues. Of course, motorists in a queue cannot go faster than the motorists in

front of them, but they can always choose to go slower. Consequently, queue accelerations can

be slightly slower than the accelerations of queue leaders, but they represent the majority of

"normal" accelerations for use in design.

In 1989, Bonneson (11) applied the technique of Evans and Rothery (but with the first

sensor located close to the stop-line) and collected acceleration and speed data for a large sample

of 4,820 passenger cars accelerating straight ahead at five different signalized sites in two States.

His data, which consisted of averages over different distances of acceleration, showed very

strong linear relationships between acceleration and speed, with $\alpha = 2.02$ (6.63) for each traffic

stream. The five through-traffic streams had very similar accelerations ranging from $\beta = 0.1184$

to $\beta = 0.1326$. This is very close to the data of both Beakey and Dockerty. In another treatise,

Bonneson (12) reported on eight left-turning movements with a total sample of 13,881 observed

passenger cars also having $\alpha = 2.02$ (6.63) that were studied at this same set of sites. All left-

turning movements showed slower accelerations at higher speeds than through movements,

ranging from $\beta = 0.1339$ to $\beta = 0.3157$, probably due to centrifugal forces affecting occupant

comfort while turning through different radii under "normal" conditions.

Acceleration data for a sample of 98 left-turning and 342 right-turning vehicles moving

from minor streets into cross-street gaps of 10 seconds or less were reported in 1996 by Harwood

et al. in NCHRP Report 383 (13). This limitation on gap time was imposed to select samples

where drivers had some incentive to use relatively high accelerations. Speeds were measured

across a series of four 61-meter to 122-meter (200-foot to 400-foot) traps on the cross streets, so

the observations did not provide much detail, did not provide startup accelerations, and were only

summarized in NCHRP Report 383. All of their computations assumed that each vehicle had a

constant acceleration over each long trap. Rather than rely on these data for design accelerations,

AASHTO 1994 Green Book values were stated as being similar and were used by the authors.

Akcelik and Biggs (14) used measurements of the second-by-second speeds of 1,037

samples of vehicles accelerating from a stop in three types of locations (CBD, urban and

nonurban) in Australia, collected with an instrumented chase-car, to calibrate a polynomial

model for acceleration. The polynomial model was formulated to satisfy conceptual constraints

of zero jerk at the start and end of acceleration by starting and ending acceleration with an

acceleration rate of zero and requiring smooth changes in acceleration in between. While the

polynomial model was reported to provide the best fit to the data, detailed evidence of its

effectiveness was not provided. Instead of being linear, the relationship appears nearly as a

semicircle on an acceleration versus speed plot. However, except for two data points, the model

seems to conform relatively well to Dockerty's results from a location having pedestrian

interference. Furthermore, unlike other data collection techniques which obtain only one or two

or maybe three speed measurements for each vehicle, and few, if any, measurements within the

first few seconds of movement, the second-by-second data stream captures an average of about

19 measurements for each starting vehicle, and all of the measurements are evenly-spaced in

time. With 19 measurements pertaining to the accelerations of each of a thousand different

vehicles having different drivers at multitudes of different locations (956 km of urban roads and

1361 km of nonurban roads), this data set would be expected to be superior to most data for

deriving and calibrating a model for accelerations at slow speeds. However, to be reliable, the

chase-car spacing must be very accurately known or somehow maintained at a rigorously

constant distance. This is difficult to achieve, and how it was accomplished was not reported.

ACCELERATION DESIGN VALUES

For design purposes, AASHTO (and formerly AASHO) has prepared and released a

series of design policies recommending what a consensus of State and Federal transportation

officials, and other professionals, have deemed to be the best practices for use throughout the

U.S. This started with 7 separate design policies released between 1938 and 1944, which were

integrated into the Blue Book *(15)* of 1954 and its second edition in 1965. Subsequent works

include a reorientation and refinement of these policies in the Green Book *(1)* of 1984 with its

succeeding editions in 1990 and 1994. Promoting consistency in design across the U.S., these

and some companion documents have been widely adopted as the standards for most design

activities.

Early Design Values for Acceleration

For two design issues, the design of the lengths of acceleration lanes needed for merging

traffic and the design of intersections with stop control on a minor road crossing a major

highway, acceleration rates are needed. In the 1954 Blue Book, a plot of acceleration rates

versus speed, similar to the graph reported by Loutzenheiser *(2)*, was provided as Figure VII-17

(see Table 1). It included Loutzenheiser's and some of Beakey's *(3)* findings, and was

augmented with some later findings. The text stated that limited available data showed that the

average or normal accelerations of more recent vehicles having semi-automatic and fully

automatic gear shifts and torque converters were in the same range as vehicles with manual gear

shifts as in Loutzenheiser's and Beakey's studies. It was declared that the acceleration rate of the

normal or average driver was about 60% of the automobile maximum rate that was reported in

Loutzenheiser's tests, which was slightly less than the two-thirds proportion concluded by

Loutzenheiser. This relationship was used in preparing curves describing acceleration times in

Figure VIII-4 for use in the design of two-way stop-controlled intersections. The specific

acceleration values that were applied were not disclosed, but Loutzenheiser's nonlinear test-

driver accelerations evidently were intentionally replaced with 60% of his automobile maximum-

acceleration test results, which resulted in a linearly-decreasing relationship being adopted for

normal motorist accelerations.

   A line corresponding to 60% of the automobile maximum acceleration rate is shown in

Figure 2. It is easily seen that this relationship is grossly inconsistent with the behavior of actual

traffic as observed by Beakey. Its slope is flatter than the maximum vehicle acceleration line

whereas the slope from observed traffic is steeper. The initial acceleration rates are much too

small.

   With a value of $\alpha = 1.29$ (4.23) and $\beta = 0.045$ in the linearly-decreasing acceleration

model, a resulting curve can be drawn that will coincide with the one in Figure VIII-4 of the 1954

Blue Book for passenger cars starting from rest on level surfaces under normal acceleration. A

curve for maximum accelerations of passenger cars is also shown in Figure VIII-4. With a value

of $\alpha = 1.75$ (5.75) and $\beta = 0.045$ in the linearly-decreasing acceleration model, a resulting curve

can be drawn that will coincide with the full acceleration curve. These parameter values are in

agreement with those shown in Table 2 for maximum accelerations of 1935-1937 automobiles, as

was intended. However, the 'normal' motorist accelerations are 73.6 % of the maximum

automobile accelerations at start-up, and drop to 60% at 30 mph and then below 60% at faster

speeds. Instead of "being six-tenths the maximum rate" at any given speed as declared, they are

simply 0.458 mps^2 (1.5 fps^2) lower at all speeds. Yet, the linearly-decreasing accelerations that

were accordingly adopted for normal driving, with $\alpha = 1.29$ (4.23) and $\beta = 0.045$, are surely more

realistic than estimates simply intended to be 60% of vehicle maximum values.

Although the 1954 Blue Book cited Beakey's report *(3)* in one of the curves plotted in

Figure VII-19 regarding maximum automobile accelerations, it did not reference the findings

from his observations of normal motorist accelerations. This is probably because Beakey did not

include a table or figure in his paper directly displaying his observed normal motorist

accelerations related to speed. Consequently, it appears that the Blue Book may have missed the

best information available on which to base design accelerations.

For use in the design of acceleration lanes, the 1954 Blue Book contains Figure VII-20,

showing the distance automobiles travel on level surfaces related to starting and final speeds.

The acceleration rates are supposedly based on the same data as used in Figure VIII-4 pertaining

to normal motorists. With a value of $\alpha = 1.15$ (3.78) and $\beta = 0.0368$ in the linearly-decreasing

acceleration model, a resulting curve can be drawn that will coincide closely with the one in

Figure VII-20 for passenger cars starting from rest on level grades. The curve from the model in

this instance deviates slightly from the design curve at speeds reached that exceed 72 mps (45

mph) possibly because the nonlinear test-driver results of Loutzenheiser *(2)* were used rather than

the 60% of maximum acceleration estimates. This yielded acceleration estimates for design

which are slower at start-up than were observed for average motorists, and faster at high speeds.

However, it produced better estimates of observed motorist behavior than estimates based on

60% of maximum automobile accelerations. The reason for different sets of accelerations, interpreted from the same data, being used for the design of acceleration lanes in contrast to those used for the design of stop-controlled intersections, is surely that different AASHO subcommittees or task forces prepared these different sections and interpreted Figure VII-19 differently.

Above-Normal Accelerations for Design

The 1954 Blue Book indicated that most drivers accelerate somewhat more rapidly than 'normal' when crossing a major highway, and consequently an "assumed" curve was presented in Figure VIII-4 with higher than normal accelerations for passenger cars, for use in intersection design. Most drivers are usually willing to accelerate faster than normal to squeeze into a tight gap, so this seems like a reasonable hypothesis for some aspects of intersection design. However, the maximum acceleration rate acceptable to 85% of all motorists for squeezing into a tight gap is likely not the same as the usual acceleration rate of the fastest motorists, and there may be no association between the two, so inferences about the applicability of Beakey's data in this situation must be considered with caution. Also, intersection design is mostly based on turning vehicles, and some studies such as Bonneson *(12)* have found turning accelerations to differ from through vehicles.

The above-normal acceleration curve for passenger cars in the 1954 Blue Book was located between the normal acceleration and maximum vehicle acceleration curves, 1/3 from the normal curve at all speeds. With a value of $\alpha = 1.43$ (4.70) and $\beta = 0.045$ in a linearly-decreasing acceleration model, a resulting curve can be drawn that will coincide with the "assumed" acceleration curve.

The 1954 Blue Book also considered buses and trucks as potential stopped vehicles crossing a major roadway, and noted that their rates of acceleration are substantially lower than passenger cars. It was noted that the high gear ratios in low gears that are necessary for starting heavily-loaded trucks and truck combinations in motion result in very low accelerations. The text states that from unpublished studies of truck operations it was determined that the accelerating times for SU and C-50 design vehicles should be assumed to be 135% and 160%, respectively, of passenger cars. The curves for SU and C-50 vehicles in Figure VIII-4 correspond to assumed acceleration times that are exactly 135% and 160% of the above-normal acceleration times shown in the curve for the "assumed" acceleration of P vehicles. With a value of $\alpha = 0.84$ (2.77) and $\beta = 0.055$ in a linearly-decreasing acceleration model, a resulting curve can be drawn that will coincide with the one in Figure VIII-4 of the Blue Book assumed for the SU vehicle. With a value of $\alpha = 0.62$ (2.04) and $\beta = 0.055$ in a linearly-decreasing acceleration model, a resulting curve can be drawn that will coincide with the one in Figure VIII-4 assumed for the C-50 vehicle. It should be observed that the 135% and 160% factors were applied to acceleration times, not acceleration rates. All three assumed acceleration relationships, for P, SU, and C-50 design vehicles, were based on the presumption of above-normal accelerations by motorists at stop-controlled intersections, and would not seem applicable for situations where normal motorist behavior should be expected or where below-normal accelerations need to be accommodated for safety. The parameters derived for the design curves in Figure VIII-4 of the 1954 Blue Book are summarized in Table 2 for comparison with the parameters from observed accelerations.

EVOLUTION OF DESIGN ACCELERATION RATES

While acceleration rates for design policies were based on passenger car data that were already 17 to 19 years old in the 1954 Blue Book, they remained essentially unchanged for 36 more years until the 1990 Green Book. As shown in Table 1, the 1965 Blue Book contained the same acceleration information as the 1954 Blue Book. The 1957 and 1973 Red Books *(16)* simply referred to the prior Blue Books for information involving vehicle accelerations.

Although one new figure and an addition to another were added to the 1984 Green Book, the other exhibits pertaining to acceleration were still essentially the same as in the 1954 Blue Book. The extended figure presented normal truck acceleration distances, but the source of the data, type of truck, and weight-to-power ratio were undisclosed. The new figure was a redundant copy of the figure displaying passenger car acceleration distances, but with an expanded domain. The figure showing acceleration times also had its domain expanded.

Although Figure VII-19 presenting the acceleration data that served as the source for the design rates from the 1954 Blue Book was included in the 1965 Blue Book, it was not presented again in later editions. Furthermore, the sources for the acceleration rates were no longer disclosed, just as the actual values of the acceleration rates used to create the exhibits were never revealed. This could have been to avoid divulging that most of the underlying data were over 50 years old, sketchy at best, and pertained to the operation of vehicles from a different era having 3-speed manual transmissions and different physical characteristics.

The word "assumed" disappeared from the curves for acceleration times for the SU and WB-50 (previously C-50) vehicles in the 1984 Green Book (Figure IX-21). Furthermore, the text became a little garbled and no longer indicated clearly that these acceleration curves were only

assumptions!

1990 Revisions

Accelerations for cars were increased in Figure IX-34 and Figure II-16 of the 1990 edition of the Green Book. The plot in Figure II-16 appears to be a little more accurate and properly referenced. The reference source of the data for passenger cars in Figure IX-34 appears to be faulty. With a value of $\alpha = 1.71$ (5.6) and $\beta = 0.043$ in the linearly decreasing acceleration model, a resulting curve can be drawn that will coincide with the one in Figures II-16 and IX-34 for passenger cars starting from rest on a level road under normal acceleration.

The source of the revised accelerations for P vehicles in normal travel conditions was reported as being Appendix F of NCHRP Report 270 *(17)*. This, in turn, was based on data in ITE's *Transportation and Traffic Engineering Handbook (18)* which indicated that normal acceleration, averaged over a range in speed from 0 to 64.4 kph (40 mph), was 1.48 mps^2 (3.3 mph/sec or 4.84 fps^2). This information was obtained from unpublished data collected in conjunction with NCHRP Report 111 using a chase-car, equipped with an accelerometer, that endeavored to match the speed change rates of an undisclosed sample of other cars in traffic.

NCHRP Report 270 plotted an acceleration versus speed chart similar to the 1965 Blue Book Figure VII-17 and noted that a line corresponding to the ITE Handbook accelerations for speeds above 56.35 kph (35 mph) indicated faster motorist accelerations than the 1935-37 vehicle accelerations that were considered in the design policy. These were also faster than the assumed rates for "normal" driving given in the Blue Book. Since most passenger cars in 1984 had more pickup capability than those of the mid-1930s which served as the basis for the standards, and were lighter and had automatic rather than manual transmissions, it was perhaps

feasible to expect that motorists might be accelerating more quickly under normal conditions

than they did in the mid-1930s. However, motorists with newer cars usually have to travel being

mixed into traffic streams with older cars and trucks, and cannot usually travel faster than the

slowest vehicle ahead when starting from rest. This tends to condition motorists to accelerate at

a rate similar to normal traffic, except perhaps during episodes of urgency or impatience.

Moreover, even the older cars have more acceleration capability than is utilized by motorists, so

it could also be expected that having more excess vehicle performance capability might not

induce much change in motorist behavior.

Augmented to the acceleration vs. speed chart in NCHRP Report 270 were curves of the

maximum acceleration capabilities of two recently manufactured cars, and a line representing a

forecast of the maximum vehicle acceleration capability that was expected to be exceeded by

90% of passenger cars in use during the next 11 years. ITE's data from observed accelerations

exceeded some of these curves of maximum vehicle capabilities at higher speeds, so a

hypothetical "design" car curve slightly slower than these maximum vehicle capabilities was

created in NCHRP Report 270 with accelerations set at 1.48 mps^2 (3.3 mph per second) between

speeds of 0 and 56.35 kph (35 mph).

With so little information available, many vastly different feasible design car curves

could be drawn, and NCHRP Report 270 offered the suggested curve only as "one such choice".

From this hypothetical design-car curve, a set of slightly discontinuous average acceleration rates

were interpolated: 1.48 (3.3), 1.34 (3.0), 1.12 (2.5), 0.895 (2.0) and 0.671 (1.5) mps^2 (mph/sec)

for speeds of 0 0-32.2 (0-20), 32.2-48.3 (20-30), 48.3-64.4 (30-40), 64.4-80.5 (40-50), and 80.5-

96.6 (50-60) kph (mph), respectively. These rates were then applied to develop part of a chart

similar to Blue Book Figure VII-18.

Apparently the NY DOT applied these rates to expand the chart into Figure II-16 in the 1990 Green Book. Again, as in the original AASHO formulation, vehicle maximum acceleration capability data dominated the information that was considered. Very little information from actual traffic behavior was involved, since the curve for the hypothetical design car was simply drawn between four sets of maximum vehicle acceleration curves and one set of five unpublished data points based on actual traffic observations from preliminary work in the project presented in NCHRP Report 111 (reported as having been collected only "for planning project operations" *(15)* and possibly did not have rigorous chase-car spacing control). Test-car motorist accelerations from 1935-37 were included on the plot and were rejected without any justification beyond simply being declared as too slow for current design uses.

NCHRP Report 270 seems to have offered this conceptualization, based on conjecture and limited data, as a suggestion for AASHTO to re-examine and update its acceleration information. As the report title indicated, the subject of NCHRP Report 270 pertained to parameters affecting stopping sight distance, relating more to deceleration rather than acceleration. AASHTO apparently instead accepted this mostly hypothetical construct as a definitive basis for policy revisions. The text of the Green Book states that the revised time-distance data for the P-vehicle were "developed from studies performed...", which allows users to infer a more rigorous observational data foundation than the actual speculative underpinnings.

Figure IX-33 in the 1990 Green Book is exactly the same as Figure IX-21 in the 1984 edition for SU and WB-50 vehicles. For P vehicles, the curve for normal acceleration was discarded, and the design accelerations for the curve for passenger vehicles stopped to cross a

major roadway, based on faster than normal accelerations, were increased, thereby reducing

acceleration times. This revision was likely made in response to the changes made in Figures II-

16 and IX-34 to increase accelerations. With changes to the P curve and no changes to the SU

and WB-50 curves, the relationship between the acceleration times became approximate at about

140% and 170% of the P values, respectively, instead of the 135% and 160% as previously

hypothesized.

Although the acceleration rates for P vehicles were increased in Figure IX-33, thereby

reducing the acceleration times, they were not increased quite enough to be consistent with

accelerations used in Figures II-16 and IX-34. A linearly-decreasing model with $\alpha = 1.65$ (5.4)

and $\beta = 0.044$ coincides with the P curve in Figure IX-33, but a model with $\alpha = 1.71$ (5.6) and β

$= 0.043$ coincides with the others. It is unclear how these changes relate to the philosophy of the

1965 Blue Book that passenger car accelerations are 10% faster than normal when crossing major

roadways from rest.

A new chart for acceleration time and speed for passenger cars starting from rest under

normal acceleration rates on level grades was provided as Figure IX-34A. The data conform to a

linearly-decreasing acceleration model as described above for Figures II-16 and IX-34. A new

table, Table IX-7, was also added with final speeds and acceleration distances and times for

normal acceleration of passenger cars on level grades. These values generally conform with the

model although there are some differences apparently due to rounding.

The 1994 Green Book represents a shift to metric units. No new figures or tables

pertaining to acceleration were introduced. Close scrutiny reveals that the translation of some

curves is only approximate. The accelerations for the WB-15 vehicle in Figure IX-33 differ in

1994 from the WB-50 vehicle in the same figure in 1990. However, the text still declares that

the accelerating time is intended to be 170% of the P-vehicle, so the discrepancy is likely

unintended. This implies that the design accelerations for the SU and WB-15 vehicles in the

1994 Green Book were probably intended to be the same as in all previous editions, as originally

hypothesized based on the maximum accelerations of 1935-37 passenger cars and speculations

about trucks drawn from unpublished data. Of course, the trucks from that era were somewhat

different than the 36,329 kg (80,000 lb) variety operating on roadways in 1994. Other caveats in

the 1994 version were presented at the beginning of this paper.

RECOMMENDED DESIGN PARAMETERS

In designing for motorists accelerating to the design speed or to some desired speed at the

end of acceleration, v_{des}, a linearly-decreasing acceleration model is recommended where

$$\beta = (\alpha \pm Gg) / v_{des} \tag{9}$$

$$v = v_{des} - (v_{des} - v_0) e^{-\beta t} \tag{10}$$

$$d = v_{des} t - (v_{des} - v_0)(1 - e^{-\beta t}) / \beta \tag{11}$$

$$t = d / v_{des} + (v - v_0) / (\alpha \pm Gg) \tag{12}$$

Consequently, only parameter values for α are needed, based on the design vehicle type. When

starting from rest, the initial speed, v_0, will be 0. On level terrain, the grade, G, will be 0 (it

might also need to be set to 0 if further research indicates that motorists do not begin to

accelerate faster on downgrades or more slowly on upgrades). The values for β which follow are

offered simply as averages extracted from observations, for comparison with results from

different sources, which may or may not apply to a specific situation.

For average accelerations of passenger cars, an acceleration model with $\alpha = 2.0$ (6.6) and

β = 0.12 seems consistent with most observations of average motorist behavior. For design, an

acceleration model with α = 2.2 (7.2) and β = 0.11 corresponds to passenger cars operated by

drivers at accelerations 10% above average, and α = 1.8 (6.0) and β = 0.13 corresponds to

passenger cars operated at accelerations 10% below average. For average SU drivers, parameters

of α = 1.5 (5.0) and β = 0.13 are recommended. For WB-15 trucks, the recommended parameters

are α = 0.37 (1.2) and β = 0.02 for average driver acceleration behavior, and α = 0.15 (0.5) and β

= 0.01 for including the accelerations of most loaded trucks. These parameters are summarized

in Table 2 under the section containing recommendations for design. These values differ

substantially from the Green Book. The starting acceleration for SU trucks is almost double, P

vehicles are 22% higher, but the WB-15 is cut almost in half for average drivers, and cut in half

again to accommodate most drivers. The acceleration distances and times resulting from these

values are shown in Figure 3 in the format of the Green Book.

The recommended parameter values for normal passenger car operations yield an average

acceleration of 1.44 mps^2 (4.72 fps^2) over a speed range from 0 to 40.3 kph (25 mph), which is

slightly less than the average of 1.5 (4.9 fps^2) found in NCHRP Report 383 *(13).* However, the

measurement traps in NCHRP 383 were 61 to 122 meters (200 to 400 feet) long, and an average

vehicle would accelerate from 0 to 40.3 kph in less than 61 meters, so it is not clear how to

compare such results.

The recommended parameter values for average tractor-trailer truck operations are

slightly slower than the maximum vehicle performance capabilities shown in Table 2, accounting

for truckers who do not always operate their rigs at their maximum capabilities, even though they

are diesel-powered. Using these parameters, as shown in Figure 4, approximately half of the

measurements of tractor-trailer truck acceleration times and distances collected at three locations

on level terrain in Michigan *(19)* are faster, and the other half are slower, suggesting that these

parameters are reasonable indicators of average behavior. For average acceleration of tractor-

trailer trucks to 9.7 kph (6 mph) in first gear, the recommended model indicates an acceleration

distance of 7.44 meters (24.4 feet) in 6.5 seconds rather than 8.1 meters (26.4 feet) in 6 seconds

as indicated in the Green Book for railroad grade crossings.

The parameter values recommended for the purpose of encompassing the operations of

most loaded tractor-trailer trucks (as opposed to the average acceleration which would account

only for about half of the trucks) yield acceleration estimates that closely match most of the

slower accelerations observed in the Michigan data, and are exceeded by only a couple of

observations. It is suggested that these parameters are suitable for design use since they closely

fit observations of actual acceleration behavior without too many exceedences, as shown in

Figure 4. For loaded trucks accelerating to 9.7 kph in first gear, the recommended model

indicates an acceleration distance of 18.3 meters (60 feet) in 16 seconds to accommodate most

trucks, for an average acceleration of 0.143 mps^2 (0.47 fps^2), which is 0.307 mps^2 (1.0 fps^2)

slower than assumed in the Green Book for railroad crossings. It might be true that even the

slowest truck drivers might try to accelerate more quickly over railroad crossings than at other

locations, due to the added perils at railroad crossings. However, grades and rough crossings

may deter faster accelerations. Furthermore, when queued at a traffic signal beyond and clear of

a crossing, they may not perceive a reason to accelerate more rapidly after the signal turns green

in order to allow trailing vehicles to move forward quickly when a train is approaching.

A linear relationship also seems to exist between speed and motorist decelerations.

Beakey's data *(3)* show strong linear relationships with $\alpha = 3.23$ (10.6) and $\beta = 0.165$ for average

motorists. Motorists traveling at higher speeds tended to end decelerations at higher rates. A

linear model with $\alpha = 3.0$ (9.8) and $\beta = 0.133$ was fitted ($R^2 = 0.97$) to the average decelerations

of motorists observed stopping in NCHRP 154 *(20)*. These relationships correspond to motorists

slowly increasing the pressure applied to their brake pedals, and thus gradually increasing their

decelerations as their speeds decrease, until easing off the brake when nearly stopped perhaps to

reposition their vehicles (if they actually come to a full stop), or to avoid a jerk at the end

(deviating slightly from linearly-increasing deceleration for the final few feet).

CONCLUSIONS AND RECOMMENDATIONS

The linearly-decreasing model of acceleration related to speed of travel performs

successfully for both maximum vehicle acceleration and normal motorist-chosen acceleration

(and deceleration) for both passenger cars and trucks. Although the corresponding equations are

a little complicated, the accuracy and consistency resulting from using this model offer

significant advantages over trying to apply different constant acceleration rates over various

ranges of travel speeds. It is not acceleration that is constant during speed changes, but the rate

of change in acceleration.

While the linear-acceleration model tends to display excellent data fits, there are

relatively few data points in the available data that were collected for very slow speeds

immediately after vehicle start-up. The extrapolation of the linear-acceleration model in the

range of very slow speeds at start-up may not be completely accurate, but it probably does not

make any practical difference because travel distances at speeds near zero are negligibly short.

Although the variable in the model for initial velocity can easily be set to values other than zero

when not starting from rest, there is no data to indicate that this model adequately describes the start of acceleration for vehicles already in motion.

While grades affect the maximum accelerations of vehicles and constant grades can be easily accounted for in the linearly-decreasing acceleration model, the available data do not reveal if grades affect the starting accelerations chosen by motorists in normal traffic flow.

Studies published in the literature over the past 60 years pertaining to the observed acceleration characteristics of motorists in actual traffic streams have presented remarkably consistent data obtained by different techniques and in different countries at different times. These data sources provide a rich repository of thousands of acceleration observations and can be used as a basis to establish acceleration characteristics for use in design. Adopted design values, however, seem to have been based mostly on the maximum acceleration performance of vehicles in conjunction with conjecture about how much of this capability is normally utilized by drivers. Design values appear to underestimate actual accelerations at slow speeds and overestimate actual accelerations at higher speeds. Improvements in safety might be achieved by revising design values to comply better with observed motorist behavior.

Vehicle maximum accelerations, as shown in Figure 1, exhibit different characteristics than the accelerations actually chosen by motorists in normal traffic steams, a sample of which are shown in Figure 2. Motorists start accelerating using a large portion of the maximum acceleration capability of their vehicles, but then reduce acceleration at a much higher rate than the attenuation in vehicular capabilities. Consequently, forecasts of expected motorist accelerations based on future changes expected in vehicle performance capabilities may not reflect actual motorist behavior very reliably.

Attention needs to be directed to accommodating more than just the average motorist in a vehicle class. While existing design acceleration values in the Green Book might attempt do this, it is not clear if or how it is accomplished. It would be valuable to designate the 85th or 95th percentiles in data presentations, as well as in design, in addition to the average values.

 "Normal" acceleration in most research seems to pertain to through vehicles, frequently queue leaders, starting from rest at signalized intersections. Some accelerations that are faster than normal should be expected when traffic merges into or travels through tight gaps at stop-controlled intersections, as assumed in AASHTO design values. However, there is not much suitable data to establish this. Furthermore, little appropriate data were found, for example, to establish an acceleration profile for 85th-percentile left-turning and right-turning vehicles when merging into or through tight gaps on a cross street. Some data show slightly faster accelerations by through-traffic in middle lanes than in outside lanes under normal conditions, so accelerations during turns might be expected to differ, too. Some data showed initial accelerations for left-turning passenger cars under normal conditions being the same as for through passenger cars, but with accelerations reduced more profoundly thereafter in the turn. Right turns under normal conditions might be expected to exhibit even lower accelerations due to shorter turning radii.

While values for α show remarkable consistency in normal accelerations at various sites for both left-turns and through movements, the values for β display some variation, likely due to different target speeds at the end of acceleration or different turning radii affecting occupant comfort. This makes it difficult to establish a design value for β that would likely be universally applicable (although one curve for all situations seems to be presumed in the Green Book). For designing for motorists accelerating on level pavement from rest to the design speed of a

roadway, it is recommended that $\beta = \alpha / v_{design}$. This simplifies acceleration rates to require only

one parameter, α, to be used along with the design speed, v_{design}. It implies a different treatment

than the one chart for all design speeds in the Green Book.

Rather than present tables and figures in the Green Book which tend to conceal the

acceleration rates used, it would be valuable to disclose the acceleration rates and assumptions so

they can be modified when needed by the user as appropriate for different types of applications.

The acceleration standards presented in the 1994 Green Book are still based to a large

extent on rather old and rather limited research data, and a lot of conjecture. While each edition

of the Blue Book and Green Book dealt with this limitation by asserting that "due to rapid

changes being made in vehicle operating characteristics, current data on acceleration and

deceleration may soon be outdated", this disclaimer seems to be misguided since chronological

data suggest that the acceleration rates chosen by drivers have been remarkably consistent over

time, and relatively unaffected by improved vehicle performance capabilities.

Rather than selecting acceleration values for situations involving only normal or above-

normal accelerations, values are also needed in design for below-normal accelerations. For

traffic signal preemption near a railroad crossing, for example, it would be appropriate to select

below-normal accelerations for setting preemption timings to clear a queue that might be backed

up onto the track, because the lead vehicles may proceed leisurely being unaware of any

urgencies arising behind them. Since the Green Book is the most widely accepted source for

design information, it would be appropriate to provide more complete information needed in

additional design applications.

Using the linearly-decreasing acceleration model, as recommended, the equations for

time, distance and speed become more complicated, but accelerations may be characterized by a single parameter, α, which seems to be remarkably stable by vehicle type and over time. Design acceleration would be clarified and simplified. Additional field studies are still needed to develop improved values for the average and percentile values of motorist accelerations with different vehicles under various design conditions.

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List of Tables

TABLE 1 Evolution of Design Accelerations

Source	Acceleration Rates[a]	Acceleration Distances (a)	Acceleration Distances (b)	Truck Acc. Distances	Acceleration Times	Adjustments for Grades	Acceleration Time-Speed	Acceleration Time-Space
54 Blue Book	Figure VII-19 p. 493		Figure VII-20 p. 494		Figure VIII-4 p. 507	(no table no.) p. 319		
65 Blue Book	Figure VII-17 p. 355		Figure VII-18 p. 356		Figure VIII-4 p. 397	(no table no.) p. 401		
84 Green Book		Figure II-12 p. 36	Figure IX-22[b] p. 784	Figure IX-22 p. 784	Figure IX-21[b] p. 783	Table IX-8 p. 796		
90 Green Book		Figure II-16 p. 40	Figure IX-34 p. 749	Figure IX-34 p. 749	Figure IX-33[c] p. 748	Table IX-8 p. 765	Figure IX-34a p. 750	Table IX-7 p. 764
94 Green Book		Figure II-16 p. 40	Figure IX-34 p. 706	Figure IX-34 p. 706	Figure IX-33[d] p. 705	Table IX-9 p. 721	Figure IX-35 p. 707	Table IX-8 p. 719

[a] Basic information in exhibits grouped within boxes appears to be unchanged among editions.
[b] Data domain expanded beyond prior versions.
[c] SU and WB-50 vehicle accelerations unchanged in 1990 from 1984.
[d] P and SU vehicle accelerations unchanged, but 1994 WB-15 differs from WB-50 in 1990.

TABLE 2   Acceleration Parameters

Description	Type	α[a]	β	Information Source
Derived from Vehicle Performance Tests				
P @ 25 lb/hp	Veh. Max.	2.94 (9.65)	0.0503	TE Handbook, 1992 *(4)*
P @ 30 lb/hp	Veh. Max.	2.49 (8.15)	0.0452	TE Handbook, 1992 *(4)*
P @ 35 lb/hp	Veh. Max.	2.16 (7.09)	0.0409	TE Handbook, 1992 *(4)*
1935-1937 automobiles	Veh. Max.	1.74 (5.72)	0.0451	Loutzenheiser, 1937 *(2)*
WB-15 @ 100 lb/hp	Veh. Max.	0.89 (2.93)	0.0286	TE Handbook, 1992 *(4)*
WB-15 @ 200 lb/hp	Veh. Max.	0.58 (1.90)	0.0199	TE Handbook, 1992 *(4)*
WB-15 @ 300 lb/hp	Veh. Max.	0.48 (1.56)	0.0180	TE Handbook, 1992 *(4)*
WB-15 @ 400 lb/hp	Veh. Max.	0.45 (1.47)	0.0200	TE Handbook, 1992 *(4)*
70 Chevrolet sedan	Veh. Max.	3.36 (11.0)	0.0803	NCHRP 185, 1978 *(5)*
71 Chevrolet ¾-ton truck	Veh. Max.	5.19 (17.0)	0.1478	NCHRP 185, 1978 *(5)*
75-95 RVs (slowest 10%))	Veh. Max.	2.5 (8.2)	0.104	Glauz, 1981 *(7)*
P @ 40 lb/hp (slowest 10%)	Veh. Max.	2.85 (9.36)	0.0853	Glauz, 1981 *(7)*
Derived from Traffic Observations				
Faster motorists	Motorists	1.82 (5.96)	0.0798	Beakey, 1937 *(3)*
Average motorists	Motorists	1.74 (5.72)	0.0995	Beakey, 1937 *(3)*
Slower motorists	Motorists	1.78 (5.82)	0.1344	Beakey, 1937 *(3)*
Inner-lane cars	Motorists	2.27 (7.45)	0.1487	Dockerty, 1966 *(9)*
Outer-lane cars	Motorists	1.88 (6.17)	0.1201	Dockerty, 1966 *(9)*
Thru passenger cars, max.	Motorists	2.02 (6.63)	0.1184	Bonneson, 1992 *(11)*
Thru passenger cars, min.	Motorists	2.02 (6.63)	0.1326	Bonneson, 1992 *(11)*
Left passenger cars, max.	Motorists	2.02 (6.63)	0.1339	Bonneson, 1990 *(12)*
Left passenger cars, min.	Motorists	2.02 (6.63)	0.3157	Bonneson, 1990 *(12)*
Trucks	Motorists	1.67 (5.47)	0.1229	Bellis, 1960 *(8)*
Trucks	Motorists	1.49 (4.87)	0.1455	Dockerty, 1966 *(9)*
Tractor-trailer trucks	Motorists	0.15 (0.5)	0.01	Gillespie, 1986 *(19)*
Derived from Established Design Values				
P (max. veh. accel.)	Design	1.75 (5.75)	0.045	Blue Book, 1954 Fig. VIII-4 *(15)*
P (design accel.)	Design	1.43 (4.70)	0.045	Blue Book, 1954 Fig. VIII-4 *(15)*
P (normal accel.)	Design	1.29 (4.23)	0.045	Blue Book, 1954 Fig. VIII-4 *(15)*
Acceleration lanes	Design	1.15 (3.78)	0.0368	Blue Book, 1954 Fig. VII-20 *(15)*
SU	Design	0.84 (2.77)	0.055	Blue Book, 1954 Fig. VIII-4 *(15)*
C-50	Design	0.62 (2.04)	0.055	Blue Book, 1954 Fig. VIII-4 *(15)*
P (design accel. dist.)	Design	1.71 (5.6)	0.043	Green Book, 1990 Fig. II-16 *(1)*
P (design accel. time)	Design	1.65 (5.4)	0.044	Green Book, 1990 Fig. IX-33 *(1)*
Recommended for Design				
P motorists (above ave.)	Design	2.2 (7.2)	0.11	
P motorists (ave. thru)	Design	2.0 (6.6)	0.12	
P motorists (below ave.)	Design	1.8 (6.0)	0.13	
P motorists (ave. left)	Design	2.0 (6.6)	0.22	
SU motorists (ave.)	Design	1.5 (5.0)	0.13	
WB-15 motorists (ave.)	Design	0.37 (1.2)	0.02	
WB-15 motorists (below ave.)	Design	0.15 (0.5)	0.01	
Decelerations from Traffic Observations				
Average motorists	Motorists	3.23 (10.6)	0.165	Beakey, 1937 *(3)*
Average motorists	Motorists	3.0 (9.8)	0.133	NCHRP 154, 1974 *(20)*

[a] Parameters α and β are associated with accelerations in units of meters per second per second (feet per second per second) and speeds in meters per second (feet per second).
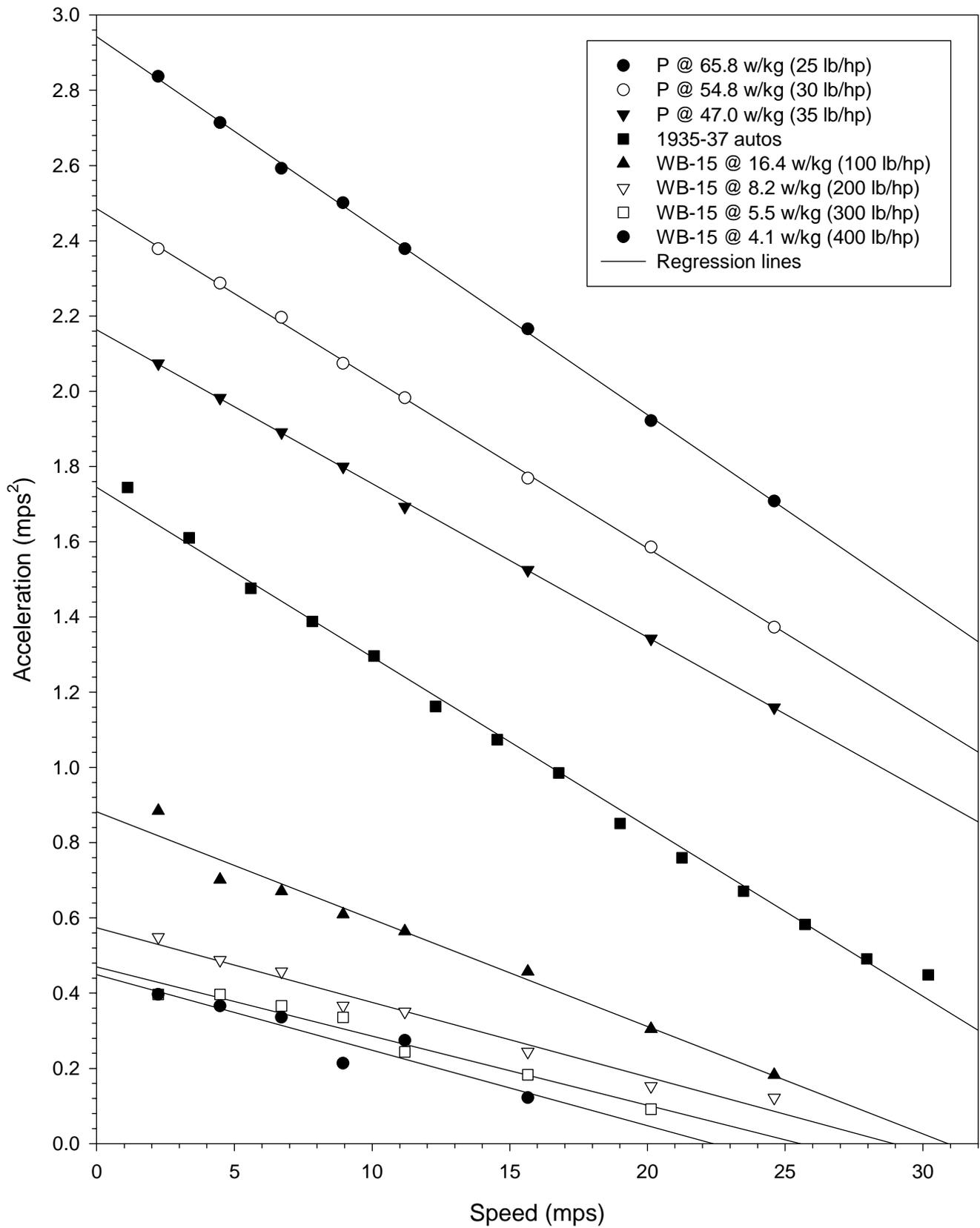
List of Figures

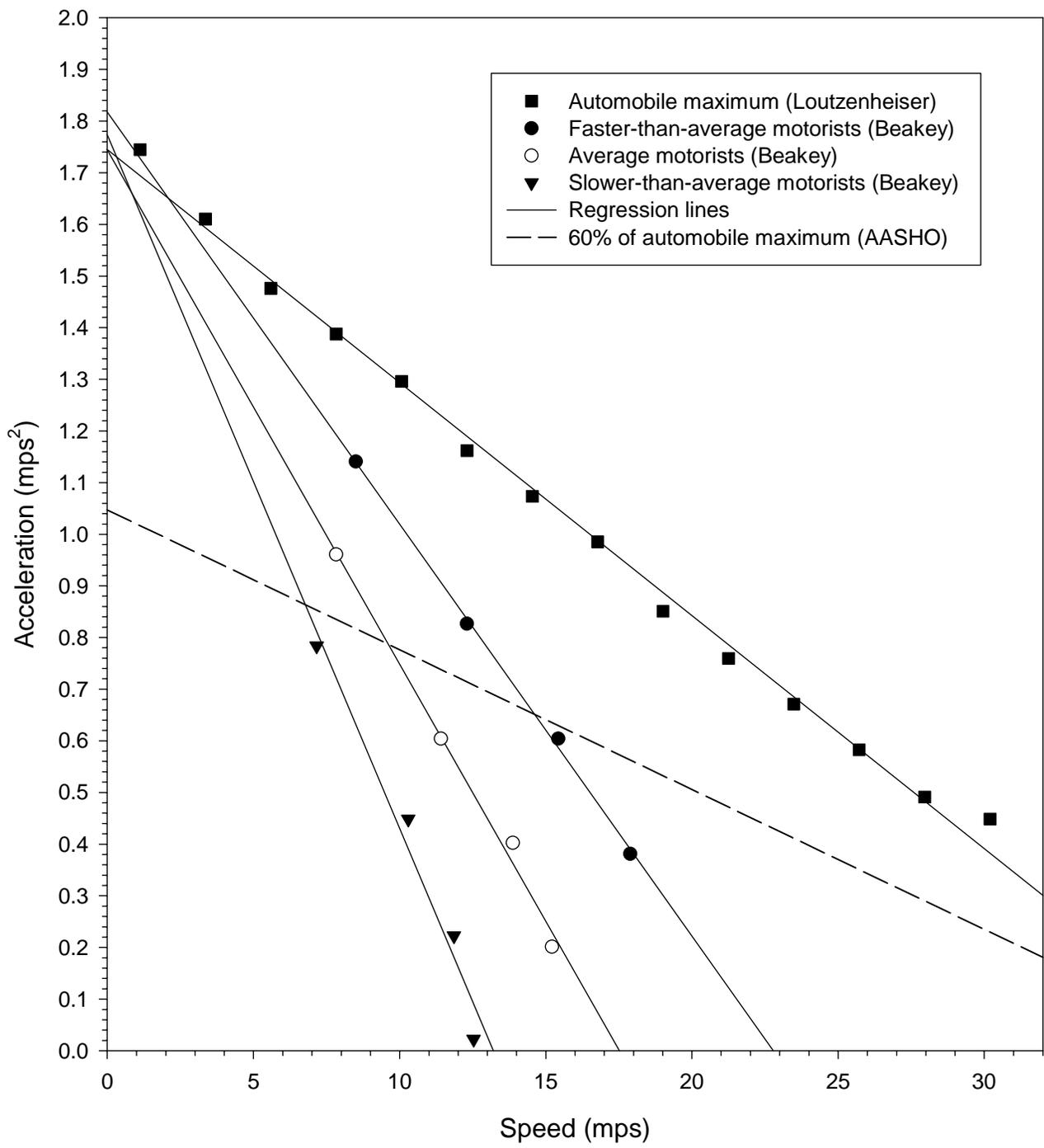FIGURE 1 Vehicle Maximum Accelerations
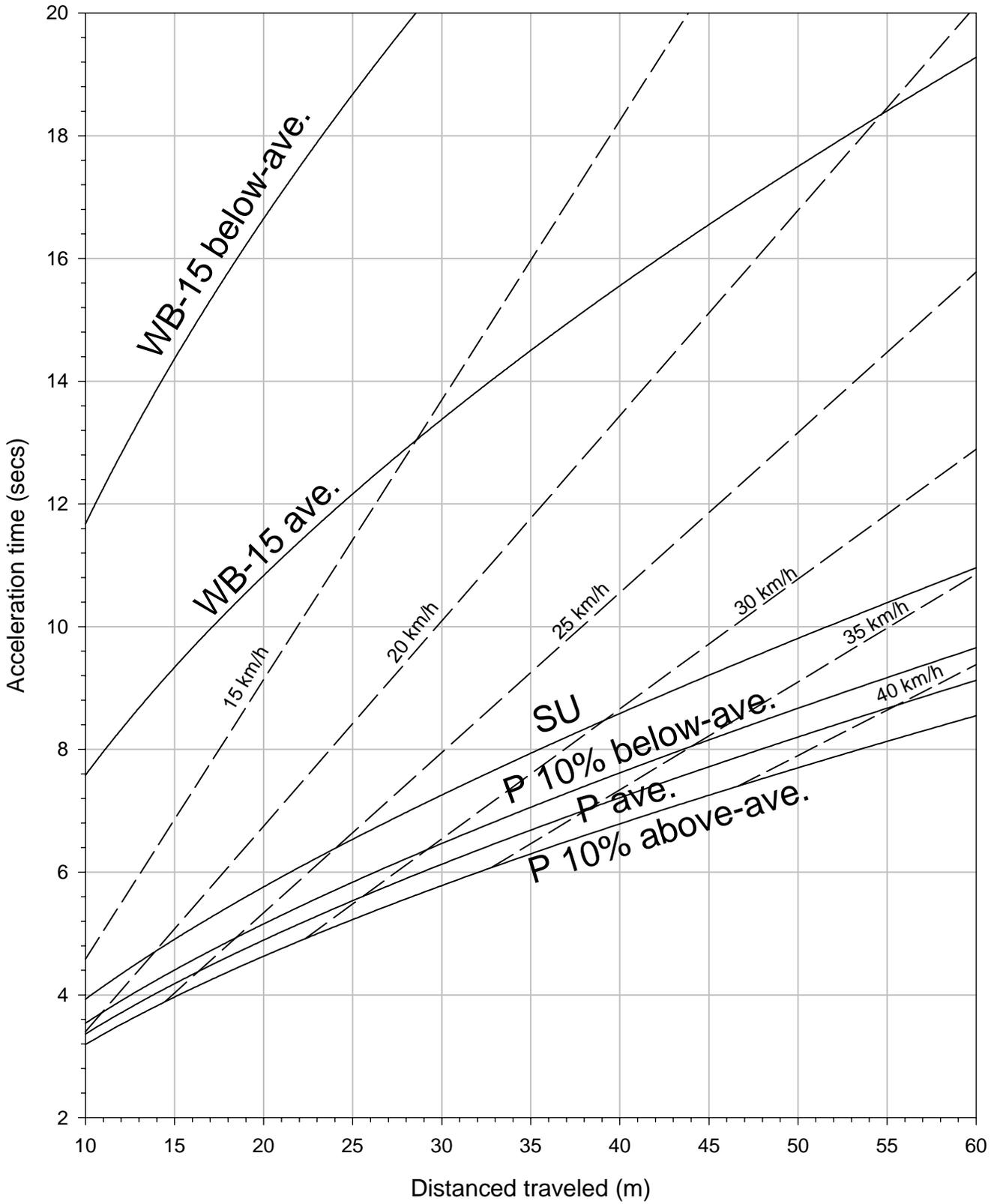
FIGURE 2 Observed 1935-37 Traffic Accelerations

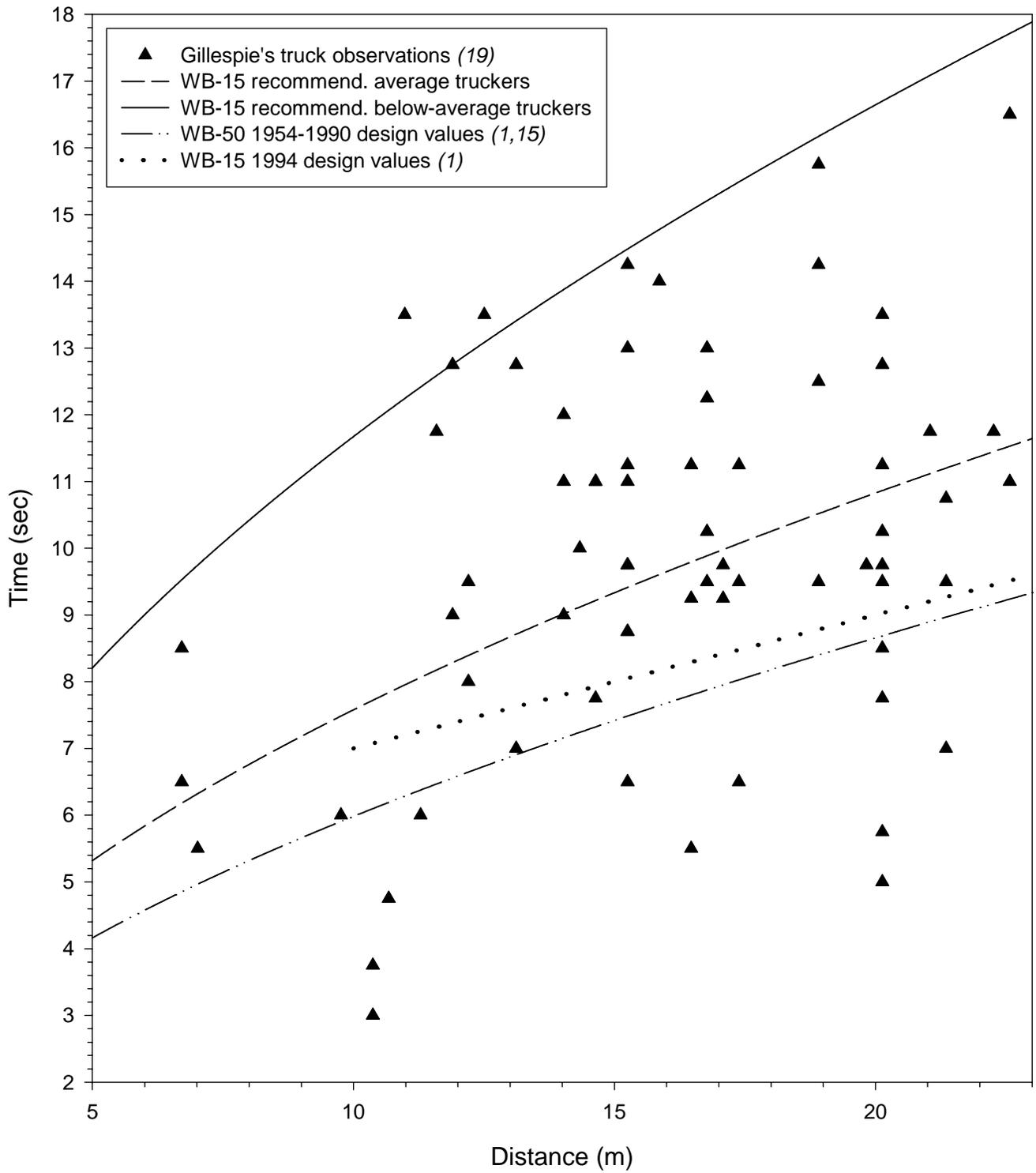FIGURE 3 Times and Distances from Stop for Recommended Design Accelerations

FIGURE 4 Times and Distances from Stop for Heavy Truck Accelerations