

ANALYSIS OF STEADY-STATE HANDLING BEHAVIOR OF A TRANSIT BUS

Nan Yu, Saravanan Muthiah, and Bohdan T. Kulakowski

The Pennsylvania Transportation Institute
The Pennsylvania State University, University Park, PA 16802, U.S.A.

ABSTRACT

Directional stability is one of the most important aspects of active safety for any vehicle. Historically, most automotive safety systems such as Antilock Braking System, Traction Control System and stability control systems, have been introduced in lighter vehicles. The effective adaptation of such systems to heavy-duty buses requires a sound knowledge of the steering response characteristics under both steady-state and transient conditions. However, only a modest number of references are available on steering response performance for buses.

This paper analyzes the steady-state handling characteristics of a typical 12-meter (40 foot) two-axle transit bus. In this study, a series of constant radius cornering tests were conducted on the test bus at The Pennsylvania Transportation Institute test track. Two separate transducers were employed – one for measuring steering input, and one for recording lateral acceleration and yaw rate with respect to the vehicle coordinates located at the center of gravity of the bus. The test bus was found to show a general understeer behavior within the test range.

ANALYSIS OF STEADY-STATE HANDLING BEHAVIOR OF A TRANSIT BUS

Nan Yu, Saravanan Muthiah, and Bohdan T. Kulakowski

The Pennsylvania Transportation Institute
The Pennsylvania State University, University Park, PA 16802, U.S.A.

1 INTRODUCTION

Directional stability is one of the most important aspects of active safety for any vehicle. Historically, most automotive safety systems such as Antilock Braking System (ABS), Traction Control System (TCS) and stability control systems (ESP®, VDC®), have been introduced in lighter vehicles. The effective adaptation of such systems to heavy-duty buses requires a sound knowledge of the steering response characteristics under both steady-state and transient conditions. During the last few decades, much work has been done on measurement and analysis of handling and stability characteristics of passenger cars. However, only a limited number of references can be found on the same subject for transit buses. In order to explore the handling characteristics of typical transit buses, an unladen 12-meter transit bus was tested at The Pennsylvania Transportation Institute (PTI) test track and its handling performance was evaluated based on the test results. The steady-state cornering characteristics obtained for the bus are reported in this paper.

So far, little work has been published on what constitutes “good” and “bad” handling behavior for transit buses. Nevertheless, based on the fact that transit buses and cars operate in the same traffic environment, it seems reasonable to expect that many of the handling evaluation criteria established for cars would be applicable to transit buses too.

The remainder of this paper is organized as follows: Firstly, information on the test bus and its instrumentation is provided, followed by a description of the test procedures. Secondly, measurement results, derived handling characteristic parameters and their interpretations are presented. Then, a summary of handling evaluation for the test bus is provided in the conclusion part. Finally, follow-up research meant to enhance the studies conducted in this paper is proposed.

2 NOTATION

| | |
|------------|-------------------------------------------|
| α_f | slip angle of the front tire |
| α_r | slip angle of the rear tire |
| β | side-slip angle (attitude) of the vehicle |
| δ | front wheel angle |

| | |
|----------------|-----------------------------------------------------------------------------|
| δ_{ack} | Ackermann angle |
| δ_{sw} | steering angle of the steering hand wheel |
| a_y | lateral acceleration at vehicle C.G. |
| C_f | effective cornering stiffness of the front axle |
| C_r | effective cornering stiffness of the rear axle |
| D_F | cornering compliance of the front axle |
| D_R | cornering compliance of the rear axle |
| K_{ss} | steering wheel angle-side slip gradient $\partial\delta_{sw}/\partial\beta$ |
| $K_{u.s.}$ | understeer gradient $\partial\delta_f/\partial a_y$ |
| L | wheelbase |
| M_f | front axle weight |
| M_r | rear axle weight |
| r | yaw rate of the vehicle |
| R | turning radius |
| v | vehicle speed |

3 SPECIFICATIONS OF THE TEST BUS

The test bus is a 1985 model, rear engine, rear drive (RR), two-axle 12-meter transit bus with a total carrying capacity of 65 passengers. Both front and rear axles are solid axles equipped with air suspension systems and hydraulic dampers. The rear axle of the bus has dual tires.

Table 1 lists the specifications of the test bus. As evident from Table 1, a large proportion of the weight is on the rear axle. This may imply an uneasy maneuver behavior, such as oversteer for the driver.

Table 1. Bus Specifications.

| Wheelbase (m) | Curb Weight (kg) | | | | Weight Distribution | |
|---------------|------------------|-------|-----------|-------|---------------------|----------------|
| | Front Axle | | Rear Axle | | Front/ Rear | Left/ Right |
| | Left | Right | Left | Right | | |
| 6.2 | 2200 | 2088 | 4245 | 3860 | 35/65 | 52/48 |

The instrumentation set-up basically consisted of two sensors – a string potentiometer for measuring steering angle, and an inertial measurement unit (IMU), located at the center of gravity of the vehicle, for measuring lateral acceleration, yaw rate and roll angle. The analog signals from the sensors were collected with an 8-channel data acquisition device (NI DAQPad-6015) and post processed using a virtual instrument (VI) created in LABVIEW[®]. The useful ranges and sensitivities of the instruments are given in Table 2.

Table 2. Specifications of the Sensors

| Sensor | | Range | Sensitivity |
|---------------------|----------------------|-----------------|---------------------------|
| Steering Transducer | | +/- 720 deg | 20 mV/deg |
| IMU | yaw rate | +/- 100 deg/sec | 20 mV/(deg/s) |
| | lateral acceleration | +/- 6g | 34 mV/(m/s ²) |

4 TEST PROCEDURE

In order to explore the steady-state handling characteristics of the transit bus, constant radius cornering test (skid-pad test) was conducted following the procedures detailed in ISO 4138 (ISO, 1982). Essentially, the test procedure consists of driving an instrumented vehicle on a circle of fixed radius at different constant speeds. In this study, the test speed was increased from the lowest maintainable to the highest attainable speed at steady state. The vehicle response in terms of lateral acceleration and yaw rate was recorded. Table 3 summarizes the details about the constant radius test.

Table 3. Constant radius cornering test.

| | |
|-------------------------------------|--------------------------------|
| Test Track Surface | Dry asphalt pavement |
| Vehicle Loading Condition | Curb weight (Unladen) |
| Radius (m) | 30.5 |
| Nominal Testing Speed (km/h) | 8, 16, 24 and 32 |
| Data Recorded | Lateral acceleration, yaw rate |

From the analysis of the recorded data, information regarding the following aspects was obtained:

- understeer characteristics;
- equivalent cornering stiffnesses for front and rear axles;
- cornering capability.

5 ABOUT UNDERSTEER GRADIENT

A major objective of performing the steady-state test is to determine the understeer characteristics of the vehicle. There exist several conventional indicators for vehicular understeer characteristics, such as understeer gradient, stability index, and stability margin. Each of these indicators has a unique interpretation regarding understeering property and is related to the others by design parameters of the vehicle. In order to facilitate an easy comparison with available literature, the understeer gradient K_{us} was adopted as the performance measure in this paper.

For ease of analysis, it is customary to represent the vehicle by the bicycle model shown in Figure 1 (Gillespie, 1992). Let the radius of the turn, R , be much larger than the wheelbase,

$L=b+c$, of the vehicle. In Figure 1, the front wheel angle is δ and the front and rear slip angles are α_f and α_r , respectively. The two arrows in the figure represent the instantaneous directions for the velocities of the front and rear tires.

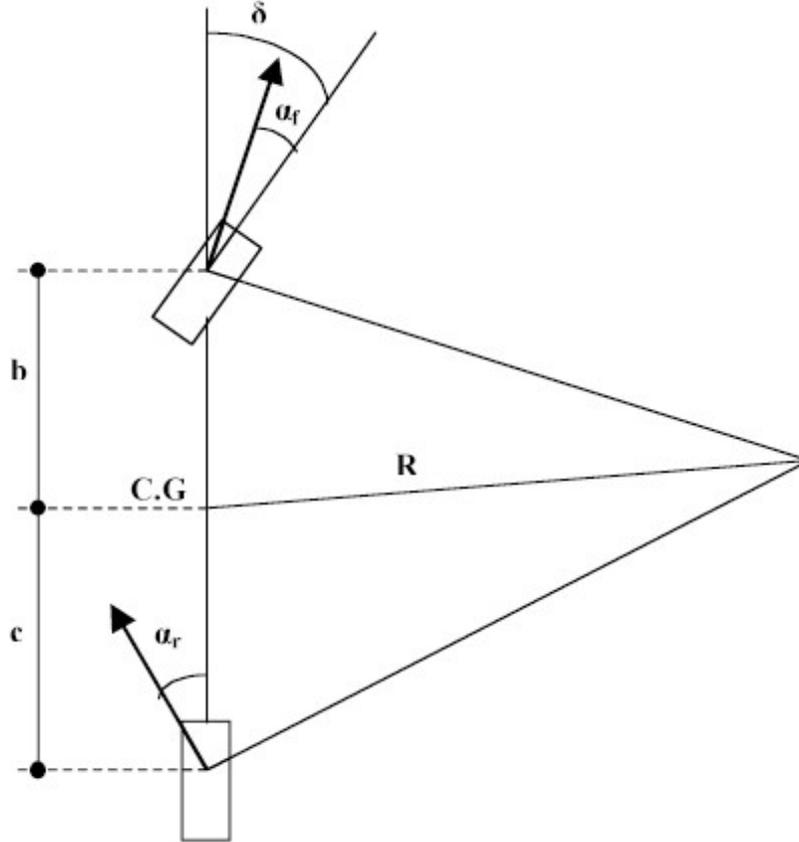


Figure 1 Bicycle model for evaluating cornering

Using basic geometry, one can show that the angle subtended by the wheelbase of the vehicle at the center of the turn is given by $\delta - \alpha_f + \alpha_r$. Now, since R is much larger than L , the angle subtended at the center of rotation can be written as L/R . Hence,

$$\frac{L}{R} = \delta - \alpha_f + \alpha_r \quad (1)$$

For small slip angles, the lateral forces are linearly related to the slip angles via cornering stiffnesses

$$\alpha_f = \frac{M_f v^2}{C_f R} \quad (2)$$

$$\alpha_r = \frac{M_r v^2}{C_r R} \quad (3)$$

Hence, using equations (1) to (3), one can write the equation for steering angle variation with speed as follows

$$\delta = \frac{L}{R} + \left(\frac{M_f}{C_f} - \frac{M_r}{C_r} \right) \frac{v^2}{R} = \frac{L}{R} + K_{u.s.} a_y \quad (4)$$

The above equation shows how the steering angle needs to be modified from the Ackerman Angle (L/R) as lateral acceleration changes. In a constant-radius cornering test, the understeer gradient K_{us} describes how the steering angle of the vehicle varies with the change in lateral acceleration.

6 RESULTS AND DISCUSSIONS

6.1 Understeer gradient (K_{us})

Figure 2 shows the plots of front wheel angle versus lateral acceleration for right and left turns. Understeer gradient can be identified as the slope of curve for the front wheel steering angle versus lateral acceleration. The understeer gradients of the transit bus obtained for left and right turns are reported in Table 3 along with the typical values of understeer gradients for cars and trucks. The positive sign of the understeer gradient indicates that the vehicle is understeering and the driver would need to keep increasing the steering angle, to negotiate the same curve, as speed increases. It is also evident from Figure 2 that the level of understeer does not change by large amount as lateral acceleration varies. This indicates a reasonably linear behavior relative to front wheel angle and hence a consistent handling manner throughout the operating range.

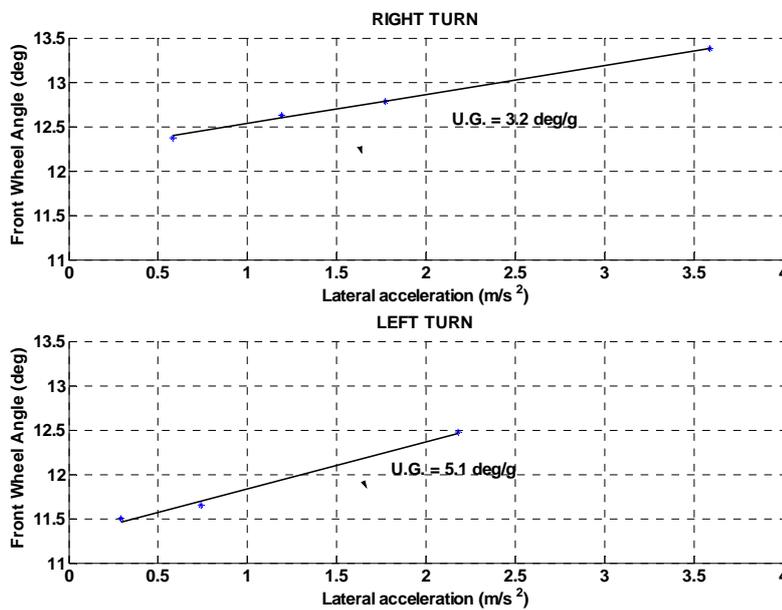


Figure 2 Front wheel angle versus lateral acceleration.

Extending the curve to zero lateral acceleration, one can get the Ackermann angle from the Y-intercept. Taking an average for the results from left and right turns, the derived Ackermann

angle is 11.7 deg, which is very close to the theoretical calculation ($\delta_{ack}=L/R=11.65$ deg). It is evident from Table 3 that the understeer level of the tested bus is close to that of cars. Hence, if one were to solely use understeer gradient as the performance measure, one would assume that the capability of the tested bus to adapt to directional changes, as perceived by average drivers in general, would be similar to that of a car and better than that for trucks.

Table 4. Understeer gradient of the bus.

| | Understeer Gradient | |
|--------------------|---------------------|------------|
| Transit Bus | left turn | right turn |
| | + 5.1 deg/g | +3.2 deg/g |
| Car | 2 ~ 4 deg/g | |
| Truck | near neutral steer | |

It is interesting to note that the bus exhibited a higher understeer level in left turns than in right turns during the test. It is felt that this phenomenon could be partly due to asymmetric weight distribution between left and right sides of the bus as shown in Table 1 and a large roll moment distribution on the rear axle. Different tire pressures and suspension properties from side to side, asymmetry in the steering system, and inconsistency in the driver operation in left and right turns may also add to the different cornering characteristics in left and right turns.

6.2 Steering wheel angle-side slip gradient ($K_{ss}=\partial\delta_{sw}/\partial\beta$)

During the last three decades, steering wheel angle-side slip gradient ($\partial\delta_{sw}/\partial\beta$) has become another widely accepted steady-state handling performance criterion. It is a more sensitive measure of vehicle directional response, which generally correlates better with subjective tests than the conventional understeer gradient (Barter, 1976; Lindqvist et al., 1986). In addition, by deriving the changing rate of steering wheel angle with respect to the sideslip angle as a function of lateral acceleration, an insight into the transient handling behavior can also be obtained for the vehicle. The derived K_{ss} versus different lateral accelerations is shown in Figure 3.

While it is not the only factor influencing “good” handling, a ‘U’ shaped K_{ss} versus lateral acceleration curve is usually desired for good handling, since it is accepted that good driver “feel” is associated with progressively increasing understeer level with increasing lateral acceleration (Metz, 2004; Whitehead, 1991). As presented in Figure 3, the K_{ss} versus lateral acceleration curve derived from the bus testing measurements forms a ‘U’ shape and satisfies this condition. The curve intercepts with Y axis (K_{ss} at zero lateral acceleration) at approximately 35.1. The ideal offset value for a good handling car should be within the range of 4 to 20 (Barter, 1976; Lindqvist et al., 1986). Generally, large offset values are associated with unresponsive steering response. Hence, the steering response of the test bus would be considered as “soggy”. However, the sideslip angle in daily driving is usually less than 10 deg. So under normal operating conditions with a K_{ss} value of approximately 35, a driver should be able to negotiate any curve with a steering wheel angle of less than 360 degrees (one turn). Based on this fact, the cornering performance of the test bus seems to be acceptable. This brings out the necessity to revise the performance evaluation criterion (as applicable for cars) before using it for transit buses.

Another usage of K_{ss} curve is for straight running performance evaluation. The higher the Y-axis intercept, the better the performance. A value of 35.1 for the test bus reflects a good straight line running performance.

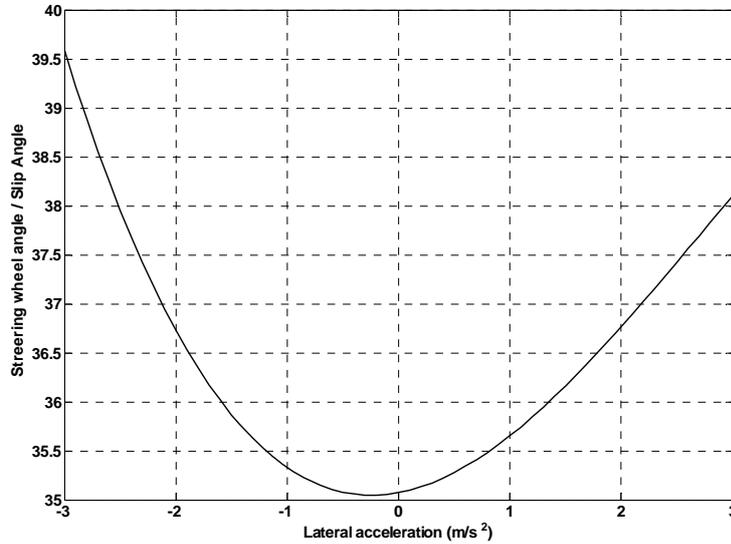


Figure 3. K_{ss} for versus lateral acceleration.

6.3 Equivalent cornering stiffness estimation

The values for the equivalent cornering stiffness for the front and rear axles were estimated using the following set of equations:

$$\left\{ \begin{array}{l} \frac{M_f}{C_f} - \frac{M_r}{C_r} = K_{u.s.} \\ \frac{M_r}{C_r} = D_R \end{array} \right. \quad (5)$$

For the test bus, solving equations (5) yields the following values

$$C_f = 2748 \text{ N/deg}$$

$$C_r = 6830 \text{ N/deg}$$

These values for the equivalent cornering stiffnesses clearly bring to light the large distribution of axle cornering stiffness towards the rear axle. Also, this distribution ratio exceeds the ratio in the weight distribution in unladen condition thus ensures the predominantly understeering characteristic of the bus.

6.4 Lateral acceleration

The maximum lateral acceleration recorded during the test was approximately 0.35 g as read from Figure 2 Front wheel angle versus lateral acceleration. This value is far below the typical

capabilities of a modern sedan (~ 0.7 g), but very close to that of a heavy-duty truck (< 0.4 g). The value of 0.35g is a reasonable level, considering the test environment and the age of the vehicle. In addition, individual driving skills might have also limited the driver's ability to maintain the vehicle in steady state at higher levels of lateral acceleration. Therefore, while the highest level of lateral acceleration attained during this test may not be representative of the limit cornering capabilities of modern transit buses, the test results do serve as a valid performance indicator for the test bus during its normal operation.

7 CONCLUSION

The steady-state response characteristics of the test transit bus show a marked improvement over the models reported earlier (Rompe and Heissing, 1986; Whitehead, 1991; Wier et al., 1974). While a 70s' bus would typically show a tendency towards oversteer at steady state, the test bus equipped with modern air suspension system remained in understeer even at relatively high lateral acceleration levels for a heavy vehicle. Although the test bus was considered "soggy" in cornering as compared to cars, its performance during the test has proved that its cornering performance is good enough for normal operation. The highest lateral acceleration achieved during the test, which is 0.35g, does not necessarily reflect the maximum cornering capability of the bus. However, as the vehicle lateral acceleration rarely exceeds 0.2 g on transit routes in North America (Jacobson, 1983), the test bus already exhibits more than enough cornering capability for its normal operation.

The handling characteristics of a vehicle are affected by weight and its distribution, road surface conditions, tire stiffness, suspension properties, and many other factors. Among all these factors, vehicle weight and its distribution are of our special interest. During service operations, the static axle loads of a transit bus can change by almost 100 % on the front axle and 40 % on the rear axle. As a result, weight distribution and yaw moment of inertia vary significantly, which will directly influence the yaw response and hence the handling characteristics of the vehicle. In this study, due to limitations of the test facilities, handling performance was evaluated under only unladen condition. Parametric studies regarding the effects of vehicle weight and various design, operation, and environmental factors on vehicle handling will be conducted in the near future.

ACKNOWLEDGMENT

The authors acknowledge, with many thanks, the assistance and cooperation of Ryan Martini and Professor Sean Brennan in making available a GPS (Global Positioning System) based instrument for correlation studies with our IMU sensor. Thanks are also due to David Klinikowski for facilitating the tests at PTI test track and to Joel Anstrom for his invaluable aid in instrumentation of the vehicle.

REFERENCE

- Barter, N. F. (1976). "Analysis and interpretation of steady-state and transient vehicle response measurements." *Vehicle System Dynamics*, 5.
- Gillespie, T. D. (1992). *Fundamentals of Vehicle Dynamics*, SAE, Warrendale, PA.
- ISO. (1982). "ISO 4138 - 1982." *Road Vehicles - Steady state circular test procedure ISO 4138-1982*.
- Jacobson, M. A. (1983). "Car handling test results: response to transient inputs." *IMechE C127/83*.
- Lindqvist, O., Andersson, K., and Plummer, J. (1986). "A study of the influence of some parameters on the stability and handling of inter-city coaches." *IMechE C211/86*.
- Metz, L. D. (2004). "What constitute good handling?" *SAE 2004-01-3532*.
- Rompe, K., and Heissing, B. (1986). "Test procedures and evaluation criteria for the handling characteristics of heavy commercial vehicles."
- Whitehead, J. P. (1991). "The handling characteristics of European intercity buses." *SAE 912678*.
- Wier, D. H., Teper, G. L., and Hoh, R. H. (1974). *Analysis of Truck and Bus Handling DOT-HS-801 152*.