

Experimental Determination of the Effect of Cargo Variations on Steering Stability

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ABSTRACT

Mission demands for U.S. military tactical trucks require them to transport a broad array of cargo types, including intermodal containers. The wide range of mass properties associated with these diverse cargo requirements has resulted in potential for steering stability issues. The potential for steering stability issues largely originates from the high mobility characteristics of single-unit military tactical trucks relative to typical commercial cargo carriers. To quantify the influence of cargo variations on stability, vehicle dynamics experiments were conducted to obtain steering stability measurements for a tactical cargo truck hauling a broad range of rigid cargo loadings. The basic relationship for the understeer gradient measure of directional response behavior and observed data trends from the physical experiments were used to evaluate the relationship between the steering stability of the truck and the mass properties of the cargo. The results of the evaluation demonstrated that the steering stability condition, quantified based on the understeer gradient, can be characterized reasonably well as a function of (1) the vehicle weight, (2) the product of the vehicle weight and longitudinal center of gravity, and (3) the vehicle vertical center of gravity. The results also indicated the need to account for the influence of cargo variations on tire cornering stiffness for high confidence predictions of understeer gradient magnitudes.

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INTRODUCTION

The U.S. military logistics community has embraced intermodal containers as primary transportation units for military material and with this has challenged the military's tactical truck operational capabilities. The U.S. military's tactical truck mission is to transport all necessary material from the primary depots to the front line dispersing areas. This mission requires the tactical truck to haul many different cargo loadings with large variations in mass properties (i.e., weight and position of the center of gravity in the lateral, longitudinal, and vertical directions). Large variations in the mass properties of the cargo result in significant variations in the mass properties of the truck, which in turn produce significant, and potentially hazardous, variations in the truck's steering stability.

To explore the effect of large cargo variations on the steering stability of a military tactical cargo truck, the U.S. Army Engineer Research and Development Center (ERDC)

conducted full-scale vehicle dynamics experiments with the truck. The experiments were designed to produce steering stability data for the truck hauling a broad array of rigid cargo loadings. The data were used to evaluate the relationship between the steering stability of the truck and the mass properties of the cargo loadings. The study, which also evaluated rollover stability, is described in detail by Jones and Priddy [1], and the resulting relationship for rollover stability was described by Priddy and Jones [2]. This article summarizes the evaluations related to steering stability with emphasis on the methodology used to evaluate the relationship between steering stability and the mass properties of the cargo. Details on the specific characteristics of the cargo truck evaluated in the testing cannot be provided herein, but the experimental methodology and the observed influence of cargo variations on stability are fully described.

BACKGROUND

Although commercial heavy duty trucks operating on the U.S. transportation system can carry heavier loadings involving potential for broader variations in cargo mass properties than military tactical cargo trucks, steering stability is typically not an issue for commercial carriers. According to the University of Michigan Transportation Research Institute 1989 Turner Trucks study [3], typical 80,000 pound 5-axle tractor trailer trucks have stable steering behavior. The stable behavior of tractor trailer trucks largely relates to their limited directional maneuver capabilities, whereas the high mobility designs of single-unit military tactical trucks give them relatively high directional response. The combination of higher directional response and heavy cargo with broad weight distribution variations leads to the potential for steering stability issues in military cargo trucks, and similar designs in the commercial heavy duty truck sector can also experience these types of stability issues. Since steering stability is typically not a problem for commercial carriers, the literature is largely void concerning the influence of cargo variations on steering stability of cargo trucks. That lack of information prompted the interest within this study to characterize the nature of the relationship between cargo variations and steering stability. Based on specific goals within the study, an experimental approach was taken.

Previous research has demonstrated that stability and safety metrics for heavy duty trucks [3,4] and light passenger vehicles [5,6,7] can be characterized well using relatively simple regression models based on vehicle characteristics. Fancher *et al.* [3] used the results of vehicle dynamics simulations to develop regression models between stability metrics and vehicle characteristics, and the regression models were then used to assess the relative safety of Turner truck concepts based on the stability metrics, which included both rollover and steering stability. Ervin [8] had previously demonstrated the strong relationship between safety metrics for commercial heavy trucks derived from accident statistics (e.g., percent rollovers per single vehicle accident) and stability metrics computed using vehicle dynamics simulations. Winkler *et al.* [4] later concluded that regression models based on vehicle characteristics worked “surprisingly” well (R-squared values of 0.90 to 0.97) at characterizing various stability metrics for heavy trucks derived from vehicle dynamics simulations. Therefore, physical testing was conducted to gather extensive truth data for the steering stability of the tactical cargo truck, and regression analysis was used to quantify the relationship between cargo variations and the stability performance.

DESCRIPTION OF EXPERIMENTS

Steady-state circular turn tests were used to obtain the steering stability data [9]. The experiments were conducted on a smooth, level, paved surface. The test lane had a width of 10 feet and a nominal centerline radius of 175 feet. Each steady-state circular turn test was composed of several constant-speed runs in one turn direction. For example, a single steady-state circular turn test might include constant-speed runs at approximately 5, 10, 15, 17.5, 20, 22.5, 25, and 27 miles-per-hour in a left-turn direction. Data acquisition was conducted over a period of thirty seconds during each constant-speed run so that the average lateral acceleration and steer angle could be determined. By incrementally increasing the speed, the lateral acceleration was progressively increased until the truck approached roll instability based on visual monitoring for wheel liftoff conditions by a human observer on the ground. Liftoff precursors such as bursts of high longitudinal tire slip and light skipping to and from the pavement made it easy for the human observer to visually and audibly detect the initiation of tire liftoff, and the speed was consistently increased until at least one tire was off the pavement throughout a significant portion of the test run.

Ninety-four steady-state circular turn tests were conducted. The tests produced steering stability data for the truck hauling 47 unique rigid cargo loadings in both left-turn and right-turn directions. The 47 loadings provided a broad mixture of cargo mass properties, spanning throughout the full range of expected center of gravity magnitudes bounded within realistic dimensional constraints. The cargo loadings were achieved using a specially designed, high-resolution, reconfigurable, steel-framed payload simulator. The cargo mass properties included 6 different weights, 16 different longitudinal center-of-gravity positions, 16 different vertical center-of-gravity positions, and 4 different lateral center-of-gravity positions. The tested cargo loadings essentially included a full factorial experimental design for center of gravity variations in the lateral, longitudinal, and vertical directions at the full rated cargo weight. At the lower cargo weights, center of gravity variations were selected to cover the range in the longitudinal and vertical directions only, since the full rated loadings provided the maximum range for characterizing the effects of lateral center of gravity offsets.

DATA ANALYSIS

Steering Stability Metric Definition

The goal of the analysis was to determine the effect of variations in the mass properties of the cargo on the steering stability of the truck. Steering stability was quantified based on the understeer gradient measure of directional response behavior. The basic understeer gradient relationship derives from the physics of steady-state cornering, the cornering force properties of tires, and the steering geometry of a vehicle in a constant radius turn [10]. This relationship is shown below.

$$\delta - \delta_a = \left(\frac{W_f}{C_{af}} - \frac{W_r}{C_{ar}} \right) a_{LT}$$

where δ = steer angle at the tires
 δ_a = Ackerman steer angle
 W_f = weight on the front tires
 W_r = weight on the rear tires
 C_{af} = cornering stiffness of the front tires
 C_{ar} = cornering stiffness of the rear tires
 a_{LT} = lateral acceleration

The differential between the front and rear ratios of weight over tire cornering stiffness (contained in the brackets) represents the basic understeer gradient (K). The Ackerman steer angle (δ_a) is a function of the vehicle wheelbase length and the turn radius and, as such, is a constant for constant radius turn testing. Therefore, the basic understeer gradient relationship was recast into an alternative form for the analysis procedures used in this study, wherein the steer angle data for each test were normalized by subtracting the steer angle measured at the slowest speed from the steer angles measured at all speeds in a test. This approach allowed the steering stability to be assessed without requiring attention on the Ackerman steer angle for the truck, which involved multiple steered axles. The form of the resulting understeer gradient equation for the directional response performance is shown below, where it can be seen that the understeer gradient K is simply the slope of the measured trend between steer angle and lateral acceleration.

$$\delta_N = K a_{LT} + c_N$$

where δ_N = normalized steer angle at the tires (deg)
 K = understeer gradient (deg/g)
 a_{LT} = lateral acceleration (g's)
 c_N = normalized intercept (deg)

Figure 1 shows examples of measured directional response data trends collected during the study. The trends shown represent the three distinct steering stability conditions that can occur for a vehicle [10]. For K greater than zero (i.e., upward trending with positive slope), the vehicle is in an understeer condition, which is inherently stable. For K equal to zero (i.e., trending near zero with no slope), the vehicle is in a neutral steer condition, which is also inherently stable. However, for K less than zero (i.e., trending downward with negative slope), the vehicle is in an oversteer condition, which is inherently unstable. Based on this characterization of the potential steering stability conditions, a key objective for the study was to determine what types of cargo loadings would produce an oversteer condition for the truck.

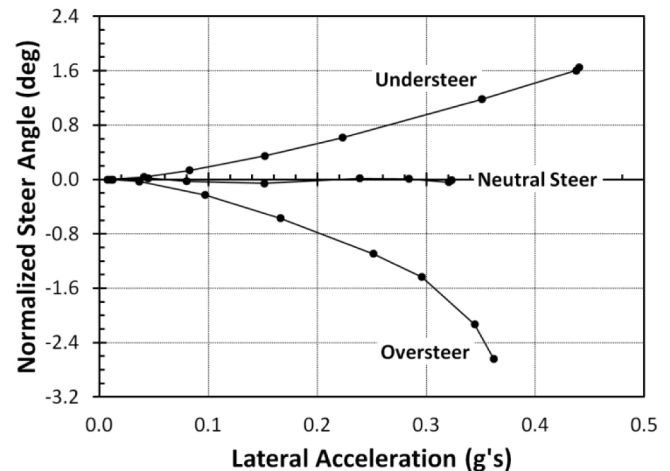


Figure 1. Example trends measured during the study that illustrate the three potential steering stability conditions.

As Figure 1 demonstrates, the trends are not necessarily linear, which means the understeer gradient is not actually a constant but rather varies as a function of lateral acceleration. However, the nonlinearity of the trends was ignored, and linear regression was used to quantify a representative slope for each test trend without forcing the normalized trends through zero. The linear regression slope values were referred to as the characteristic understeer gradient (K^*), which is the specific metric used in this study to quantify the steering stability of the truck for the various cargo loadings. This approach was valid because the objective for the metric was to indicate whether the cargo loadings produced unstable or stable steering stability while providing some indication of the relative degree of stability or lack thereof.

The characteristic understeer gradient values were calculated for each of the 94 steady-state circular turn tests. Those K^* values were then used to assess whether the cargo loadings produced understeer, neutral steer, or oversteer conditions for each turn direction. This was accomplished by defining ranges of K^* for each of the three stability conditions, where the challenge was to define a K^* range for neutral steer. Based on the assumption that the stability condition was essentially neutral if the driver's hands on the steering wheel rotated through an arc of 1 inch or less for lateral accelerations up to 0.45 g's, the K^* range for neutral steer was defined as -0.4 to $+0.4$ deg/g. This also resulted in understeer being defined as K^* greater than $+0.4$ deg/g and oversteer being defined as K^* less than -0.4 deg/g. The resulting stability assessments based on K^* were compared to subjective stability assessments based on visual impressions from the measured directional response data trends, and the two assessment methods were in perfect agreement. This agreement between the two assessment methods verified that the K^* method achieved the target objectives described above for the steering stability metric.