Optimizing Stability in Public Transport: Counterweight Designs to Combat Bus Toppling

Abstract

Due to the noticeable toppling effect caused by their high center of gravity, buses are hazardous, especially while cornering at high speeds. This study investigates the use of counterweights to improve weight distribution and lower the center of gravity as a possible way to reduce such risks. We devised a workaround utilizing static counterweights, namely 460 kg of rocks set on the inner wheels (920 kg in total) during simulations, since creating a dynamic counterweight system on the simulator would prove challenging. It was predicted that this configuration would balance the destabilizing centrifugal forces by increasing the regular reaction forces at the wheels nearer to the center of the turn. Bus stability was examined in simulation testing with and without the counterweight system under the same conditions. The findings show that counterweights considerably decrease the chance of toppling. It completely eradicated the toppling effect at modest speeds. Compared to baseline trials, the counterweights consistently decreased the toppling occurrences at more incredible speeds. This study emphasizes how counterbalance systems can be a valuable and affordable way to improve bus safety and stability. This preliminary investigation highlights the viability and importance of straightforward, static solutions in tackling important transportation safety issues, even though dynamic counterweight systems may provide additional enhancements.

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Keywords

ENGINEERING MECHANICS,

Ground Vehicle Systems,

Toppling,

Center of Gravity,

Counterweight

Introduction

Unlike a tram, a bus can viably and reliably transport passengers across far-flung destinations. This includes forested areas, hilly areas, and mountainous terrain. Although this may be an efficient means of travel for many passengers, this is not necessarily safe. In 2020, around 553 bus accidents occurred within Uttar Pradesh alone; this figure increased to 583 in 2021 and 664 in 2022. Of the accidents in 2020, roughly half were caused by poor driving and maneuvering skills due to several subtle yet lethal road irregularities. [1] To avoid such dire consequences, we devised a system that utilizes a dynamic counterweight system to balance the bus and effectively cancel out substantial amounts of human error seen while driving. Several experiments have been conducted on a simulator to test this method's applicability. A proposed counterweight system has been designed accordingly and can be installed in other forms of transport. The paper discusses how the center of gravity of a bus can be determined.

Forces acting on a bus

Even in the absence of a net force acting in a particular direction, every object on Earth's surface is affected by various forces. Particularly, buses are impacted by several factors, such as:

- The weight (W) Of the bus. Gravity is unanimously influential on matter on the surface of a planet. On planet Earth, a bus experiences a constant acceleration of $9.81\, ms^{-2}$ Towards the center of the Earth, which is then multiplied by its mass. It can be split into its $\cos(\theta)$ and $\sin(\theta)$ Components essential to determine the forces acting towards and against stabilizing the bus.
- The normal force (F_N). This force acts perpendicular to the surface of contact and helps balance the force encountered by the weight of the bus. It is seen in the areas where the bus comes in contact with the ground, which would be at its tires.
- The centrifugal force (F_c). This fictitious force acts when a bus is in circular motion. This force acts away from the center and is only observed in a non-inertial frame of reference. Since it is acting away from the center, it's one of the leading forces attempting to topple the bus over.
- The frictional forces (F_f). These forces act when two surfaces are in contact with each other. These are generated due to the microscopic irregularities on the road's surface with the tires. These act in the opposite direction of the motion of the bus and, as mentioned earlier, also play the role of centripetal force, directing the bus toward the center of the turn. In this scenario, dynamic friction is involved in "slowing down" the bus. Different surfaces will have different coefficients of friction.
- The drag forces/air resistance (F_d). These forces act when anybody is in motion within a fluid atmosphere. In this case, the bus is in motion within a Nitrogen-oxygen-rich atmosphere. This can be considered the frictional forces generated by the external atmosphere. In this scenario, however, this force has a somewhat limited contribution when analyzing when a bus topples over. [2]

Since buses have a high ride height and a relatively short track width, and since their chassis and panels are made out of steel, this gives them an alarmingly high y_{CG} value. Hence, a sizeable turn can lead the center of gravity to move past the track width, after which there's nothing to counteract this unwanted turning effect, causing the bus to topple over. [3]

On the simulator, BeamNG.drive, we ran multiple trials on a bus, similar to those used in real life, to confirm this train of thought.

Understanding the center of gravity

The center of gravity of an object determines where the entire weight of the object acts, disregarding its orientation. The coordinates of the center of gravity of a bus will require measurements along the x-, y-, and z-axes.

Measuring the weight along the x-axis (horizontally)

The weight along the horizontal axis can be determined by measuring the track width of the bus. The track width is the length of the axle and should be measured from the center of each wheel or if possible, by separating it from the frame and then measuring it to reduce random error. Place weight pads on the wheels on either side and measure the weight recorded.

$$x_{CG} = \frac{W_L \cdot L}{W_L + W_R}$$

where W_L is the weight measured on the left wheel of the bus, L is the track width of the bus, and W_R is the weight measured on the right wheel of the bus.

Figure 1.1a: The image of the left side of the bus with the weighing scales.

Figure 1.1b: The image of the right side of the bus with the weighing scales.

Measuring the weight along the y-axis (laterally)

The weight along the lateral axis can be measured by measuring the wheelbase of the bus. The wheelbase is the distance between the front and rear axles, and should be measured from the center of each wheel. To account for any error, measure the front and rear axles and deduce their average. Next, place large weighing pads at the front and rear axles and measure their respective readings. The following formula deduces the lateral location of the center of gravity:

$$y_{CG} = \frac{W_r \cdot l}{W_f + W_r}$$

where W_r is the weight measured at the rear axle, l is the wheelbase and W_f is the weight measured at the front axle.

Figure 1.2a: The image of the left side of the bus with the weighing scales.

Measuring the weight along the z-axis (vertically)

The vertical location of the center of gravity can be measured by measuring the track width of the bus. and once again, should be measured from the center of each wheel, or if possible, by detaching it from the frame and then measuring it. Measure both the front and rear axles to account for any error and take the average of the values. Next, place the bus on a platform which tilts and measures the angle turned. Gradually increase the angle until the bus topples over and note the angle turned. Using the following formula, the vertical center of gravity can be determined:

$$z_{CG} = \frac{L}{2} \cdot \tan(\theta)$$

where L is the track width of the bus and θ is the tilt angle.

Conveniently, in the simulator, where relevant testing was done, the coordinates can be located by enabling the debug option in the software.

Proposed Methodology

The suggested model includes a gas cylinder connected to several capillary tubes to distribute gas to a set of pistons. Every piston is connected to a matching metal box built into a cubby at the bus floor's sides. The metal boxes protrude outward into the cubbies as the pistons are turned on during a rotation. To counteract the destabilizing influence of centrifugal force, this system ensures that the wheels with reduced normal response force stay level on the ground. After the rotation, the metal boxes are retracted to their initial locations by an electromagnet built into each piston. By dynamically modifying the bus's weight distribution in real time, this method improves stability and lowers the chance of tipping. The usual reaction force on the inner wheels is successfully raised by utilizing this model, which enhances overall safety during abrupt or fast turns. This suggested model combines mechanical and electromagnetic solutions to produce a workable, adaptive stability mechanism, a novel way to tackle the inherent instability associated with a high center of gravity in buses.

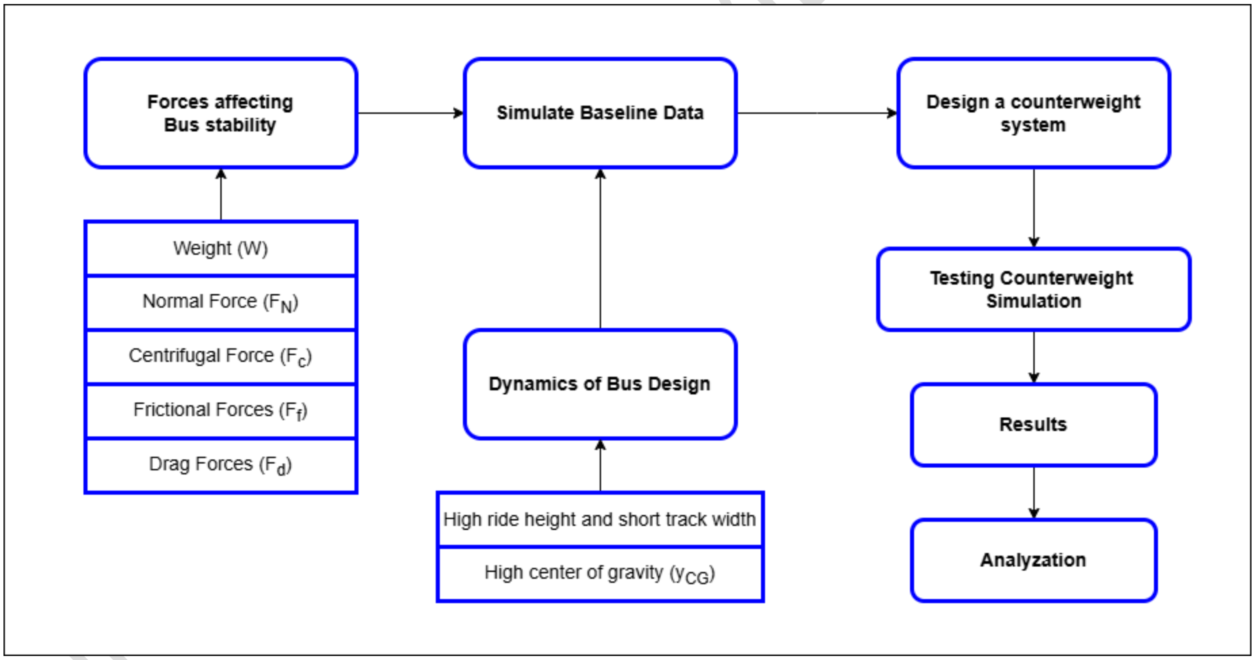

Fig 2: A flowchart to outline, understand, and solve the issue

Results and Discussion

Fig 3: Track Overview

Table 1: Speed and Number of Topples for original data before added weights.

Speed (mih^{-1})	Number of topples out of 10 trials
35	4
40	6
45	6
50	9

As we can see in Table 1, as the speed of the bus increases, its momentum increases, and hence, its center of gravity becomes significantly more straightforward to topple over. In hindsight, buses should've been manufactured with a more extensive track width to counter the unnecessary torque generated. However, with production already being so accustomed and geared to the production of conventional buses, and with buses holding a sizeable market share, namely 90% of all public transportation in India, it makes all the more sense to introduce a counterweight system that will keep the wheels from lifting from the ground.

Due to software limitations, we could not implement a dynamic counterweight system. Instead, we came up with a workaround for our counterweight system. For the simulation, we used 460 kg of rocks on the inner wheels to increase the normal reaction force (F_N) at the wheels closer to the center of the turn. Theoretically, this would help counter the toppling effect caused by the centrifugal force, tipping the bus over. We ran 40 additional trials, keeping all conditions the same, except adding the counterweight system in place this time.

Table 2: Speed and Number of Topples for new data after added weights.

Speed (mih^{-1})	Number of topples out of 10 trials
35	0
40	4
45	5
50	8

With the addition of the make-shift counterweight system, we determined that the counterweight system aligns with our hypothesis at lower speeds. However, since the system cannot dynamically adjust the weight, the weight must remain fixed, and the difference in the results, hence, diminishes.

Fig 4: A collage of the bus experiments

Conclusion

Buses have a high center of gravity by design, which puts passengers and pedestrians in serious danger of injury. Redesigning buses to have a lower center of gravity might improve stability, but it would be excessively costly, time-consuming, and resource-intensive, postponing general adoption. On the other hand, installing the suggested counterbalance system on already existing buses is more feasible and affordable. This method works with various bus models, is cost-effective during installation, and is viable in the long term. The study illustrated the possibility of a static counterbalance system as an instant safety improvement by showing how well it mitigates the toppling effect during cornering. The suggested dynamic counterbalance system also gives engineers a conceptual framework for creating sophisticated, flexible bus stability methods. This study emphasizes how crucial it is to use creative but workable ways to solve pressing public transportation safety issues.

We first need to analyze the forces acting on the bus to understand which forces are acting on the bus and precisely locate the force causing the bus to topple over unnecessarily. In this case, the force causing the bus to rotate is the normal force at the inner wheels, which creates an unneeded torque about the outer wheels, resulting in the bus toppling over in the event of a turn. This imbalance in the normal forces on either side is apparent when analyzing a bus's build and design. A typical bus has a high ride height and a short track width, resulting in it possessing a high center of gravity, specifically on the vertical axis. Henceforth, we surmised a counterweight system and tested a static version of it on the simulator BeamNG.drive due to simulator limitations. With the simulator conveying positive results, we can safely conclude the system's appropriateness and applicability in the progressive real world.

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Authors

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