The fuel consumption density due to phantom traffic jam

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Abstract. In the research, we quantified the amount of fuel consumed during a phantom traffic jam and compare it with that without the jam. We adopted an approach from a microscopic perspective where the vehicle dynamics were closely observed and monitored. The required traffic dynamics data were obtained from a previous work where the phantom traffic jam was reproduced in a laboratory setting. The test involved 22 vehicles moving a circular road with a circumferential length of 230 meters. During the test, each driver was requested to drive at the velocity of 30–km/h. Considering the proximity of each vehicle to its leader, the phantom traffic jam was instantly produced in the traffic flow. The test allowed us to quantify each vehicle acceleration, velocity, and position, from which the fuel consumption rate could be estimated at each time instant. We compared the fuel consumed by the vehicle for crossing two road segments with and without the phantom traffic jam. Utilizing a numerical integration, we quantified the required fuel for each segment. The result suggests that the vehicle during phantom traffic jam may consume the fuel as much as thrice of those without the jam.

Keywords: fuel consumption, phantom traffic jam, traffic flow, fuel economy

1. Introduction
Data suggest that the transportation sector contributes more than a quarter of the global greenhouse gas emissions including carbon dioxide (CO2), methane (CH4), a nitrous oxide (N2O) and is the largest contributor. The road transportation mode is responsible for 85.2% emitted CO2 gas, followed by shipping (12.9%) and aviation (1.4%) [1].

Many studies about driving strategy to increase fuel economy have been performed. Eco-driving with smooth vehicle dynamics is crucial in this aspect [1]. Reducing the vehicle velocity from 40 miles/h to 15 miles/h on congested traffic increased fuel consumption by 80%. Reference [2] concluded that under real driving, hybrid vehicles are about 25–50% more fuel-efficient than conventional vehicles. However, in the term of CO emission, hybrid vehicles are consistently higher. Reference [3] studied the use of a few autonomous vehicles to stabilize traffic stream and found with a small fraction of vehicles, the stop-and-go waves could be damped down, resulting in about 15% reduction of carbon dioxide and 73% for nitrogen oxides. Reference [4] measured fuel consumption and gas emissions of 459 private vehicles for 17000 sampling days in China and found that the New European Driving Cycle (NEDC) was too mild to represent the actual driving cycles. The actual cycles require higher fuel by about 30-40% than the NEDC standard. As for light-duty passenger vehicles, Ref. [5] found the required fuel is about 10% higher for the average driving. Reference [6] studied for the case of public transit buses. They found that if the average bus speed decreases from 25 km/h to 15 km/h, fuel consumption is
estimated to increase by 20–30% for diesel buses, 30–45% for natural gas buses, and most significantly (about 50%) for hybrid diesel buses.

The research main contribution is to quantify the effect of the phantom traffic jam to the fuel consumption. We believe the result is of interest of public in general as it may directly impact their driving strategy.

2. Research methods
The research intends to demonstrate the effect of phantom traffic jams to fuel consumption. The phantom traffic jam was produced in a laboratory test [7, 8]. The fuel consumption is expressed in the form of fuel density to take into account the speed vehicle, thus, producing a quantity applicable to more general conditions.

We estimate the fuel consumption rate based on the model proposed by Ref. [9]. The formula is written as:

\[
\log_{e} f = -0.679439000 + 0.135273000 \cdot a + 0.015946000 \cdot a^2 - 0.001189000 \cdot a^3 + 0.029665000 \cdot v - 0.000276000 \cdot v^2 + 0.000001487 \cdot v^3 + 0.004808000 \cdot a \cdot v - 0.000020535 \cdot a \cdot v^2 + 5.5409285 \times 10^{-8} \cdot a \cdot v^3 + 0.000083329 \cdot a^2 \cdot v + 0.000000937 \cdot a^2 \cdot v^2 - 2.479644000 \times 10^{-8} \cdot a^2 \cdot v^3 - 0.000061321 \cdot a^3 \cdot v + 0.000000304 \cdot a^3 \cdot v^2 - 4.467234000 \times 10^{-9} \cdot a^3 \cdot v^3
\]  

(1)

where \( f \) denotes the fuel consumption rate in gallon/hour, \( a \) is the vehicle acceleration in ft/s\(^2\), and \( v \) denotes the vehicle velocity in ft/s. To use the model, as our data are in m/s, m/s\(^2\), and second, we use the conversion formulas of: 1 m/s\(^2\) = 3.2808399 ft/s\(^2\) for the acceleration data, 1 m/s = 3.28084 ft/s for the velocity data, and 1 gallon/hour = 0.0010515 L/s for the fuel consumption rate data.

By observing the fuel consumption equation, we realize the data of the vehicle acceleration and velocity are required. We obtain those data from Nakayama's phantom traffic jam experiment [7, 8] (see Fig. 1).

**Figure 1.** An Instance of the Phantom Traffic Jam Produced in Refs. [7, 8]'s Experiment.
The experiment involved 22 vehicles moving in a circular road with a circumferential length of 230 meters. Thus, the initial distance for the bumper-to-bumper was only less than 10 meters. As each driver was instructed to travel at 30-km-per-hour speed, the distance is much too small. Reference [10] suggested: for the speed, the safe stopping distance is 14 m, consisting of 8 m for the driver reaction time and 6 m for the braking distance. Thus, the setting was designed to produce phantom traffic jam.

3. Results
The phantom traffic jam experiment has provided us with data of vehicle positions on the conditions with and without jam. Thus, the data are excellent to perform a comparison of the fuel consumption in both conditions.

In Fig. 2, we show the positions of the vehicles during the experiment. The figure shows the vehicle dynamics are rather low during the first part of the test duration. During the second part, the vehicle dynamics increase significantly leading to the occurrence of the phantom traffic jam where the vehicles were forced to stop temporarily to avoid a crash.

In Figure 2, we select two segments, denoted with Segment A and Segment B, where the vehicle dynamics are remarkably different. On Segment A, the jam has not occurred; meanwhile, on Segment B, the test vehicle undergoes a heavy phantom traffic jam.

![Figure 2](image-url)

**Figure 2.** The Trajectories of the 22 Vehicles in the Experiment with Two Observed Segments: A and B where the comparison of the fuel consumption density is made.
Figure 3. The Dynamics of The Observed Vehicle. The shaded areas are the consumed fuel for the vehicle to travel Segment A and Segment B (see Fig. 2). The labels `Low' and `High' are associated with Segment A and Segment B, respectively.

The dynamic of the vehicle during both segments is clearly presented in Fig. 3 where the vehicle acceleration, velocity, and position are presented as a function of time. On the same curve, we also present the fuel consumption rate during the test and clearly showing a massive surge in the fuel consumption rate during the jam. With a numerical integration method, we determine the total fuel used by the vehicle to travel Segment A and Segment B. Finally, we normalize the fuel with the time and distance covered in each segment, leading to a comparable quantity of fuel consumption density.

Finally, we note that the average amount of fuel consumed for traversing Segment B, where the traffic jam is severe, is $1.164 \times 10^{-5}$ L/(m \cdot s). However, to travel Segment A, the vehicle only requires $3.941 \times 10^{-6}$ L/(m \cdot s), or one-third of that on Segment B.

4. Conclusions and recommendations
Phantom traffic jam is a phenomenon commonly observed in metropolitan cities where the traffic density is very high. How much it costs to each vehicle owner is the central issue discussed in this paper. Based on the data of vehicles on a microscopic level where a phantom traffic jam was demonstrated in the laboratory scale, we quantify the fuel consumed during the jam and compare it to that without jam. The result suggests that the jam leads to the surging of the consumed fuel. As its implication, the study recommends adopting a more conservative driving strategy on dense traffic to reduce the fuel cost.

From a driver perspective, driving with a more conservative desired speed and smoother acceleration and deceleration is economically beneficial. From the regulatory perspective, enforcing drivers to following speed limits may also produce traffic with better fuel efficiency.
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