Experimental and empirical investigations of traffic flow instability

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Introduction

• Uninterrupted traffic flow on highways, freeways, and expressways exhibits many interesting phenomena such as phantom jam

Capacity drop and hysteresis

Wide scattering of data in the flow-density plane in congested traffic
Traffic instability, formation and evolution of oscillations
• Two main types of traffic flow theory

• **Two phase theory** based on the fundamental assumption that there is a unique relationship between speed and spacing in the steady state.
• **Three-phase theory**: no unique relationship between speed and spacing

• Free flow (F)
• Synchronized flow (S)
• Jam (J)
• \( F \rightarrow S \rightarrow J \)
Controversies in traffic flow research are due to lack of precise traffic data

In the traffic flow studies, most of the data are collected by loop detectors, and distance between two neighboring detectors is usually 1–3 km for most freeway sections showing recurrent congestion patterns.

Treiber et al. (2010) “this is of the same order of magnitude as typical wavelengths of non-homogeneous congestion patterns” and therefore definitely leads to a loss of information pertaining the finer features of traffic flow.

Daganzo et al. (1999) “no empirical studies to date describe the complete evolution of a disturbance” and thus we cannot “explain the genesis of the disturbances or the rate at which they grow”.
• The empirical observations are quite site-specific,
• cover limit road section (several hundred meters)
• contain many confounding factors (e.g., on-ramp, off ramp, bottleneck strength, traffic flow composition)
• which prevents us from forming a comprehensive understanding of traffic flow evolution.
One can minimize the impact of other complex factors in **controllable traffic flow experiment**. Therefore, it is expected to understand some true origins of traffic flow complexity via traffic flow experiments.

Sugiyama Y et al. (2008) New J Phys

Experiments and results

• 25-car-platoon experiment

Chuangxin Av. In Hefei, China 3.2 km (25 cars)

High-precision GPS devices were installed on all of the cars to record their locations and velocities every 0.1 second.
The velocity difference is small, the velocity fluctuation is small, but the spacing fluctuation is very large.
Two runs, in which the leading car is asked to move with 55 km/h
Two runs, in which the leading car is asked to move with 50 km/h
This feature clearly contradicts the fundamental assumption that there is a unique relationship between vehicle speed and its spacing in traditional car-following models.

Here are two possible explanations of this feature.

(i) In certain range of spacing, drivers are not so sensitive to the changes in spacing when the velocity differences between cars are small. Only when the spacing is large (small) enough, will they accelerate (decelerate) to decrease (increase) the spacing.

(ii) At a given velocity, drivers do not have a fixed preferred spacing. Instead they change their preferred spacing either intentionally or unintentionally from time to time in the driving process.
The standard deviation of the velocity

Concave growth pattern
Intelligent Driver Model (IDM):

\[ \frac{dv_i}{dt} = a \left[ 1 - \left( \frac{v_i}{v_{\text{max}}} \right)^4 - \left( \frac{s_0 + v_i T + v_i (v_i - v_{i-1})}{2\sqrt{ab}} \right) \right] + \xi \]

2D IDM: we assume that T is a uniformly distributed random number between T1 and T2, and T changes in the range with rate p.
Spatiotemporal evolution of velocity

experiment

2D IDM
An insensitive model (IM)

In certain range of spacing, drivers are not so sensitive to the changes in spacing when the velocity differences between cars are small.

There is a two-dimensional region $R$ in the velocity-spacing plane.

In the region $R$, 

$$|\Delta v_i| < \Delta v_c, \quad a(t + \Delta t) = \max(\min(a(t) + \xi, 0.1), -0.1)$$

otherwise 

$$\frac{dv_i}{dt} = \lambda \Delta v_i$$

Finally, if the state of the car is outside of the region

FVD model: 

$$\frac{dv_i}{dt} = \kappa [V(\Delta x) - v_i] + \lambda \Delta v_i$$
$v_i = 7 \text{ km/h}$

$\sigma_v (\text{m/s})$

$\sigma_v (\text{m/s})$

$\sigma_v (\text{m/s})$

$\sigma_v (\text{m/s})$

$v_i = 15 \text{ km/h}$

$v_i = 30 \text{ km/h}$

$v_i = 50 \text{ km/h}$

$v_i = 15 \text{ km/h}$

$v_i = 30 \text{ km/h}$

$v_i = 50 \text{ km/h}$
Motivation of the 51-car-platoon experiment

Nevertheless, due to the relative small platoon size, some features of this observed growth pattern of the standard deviation cannot be fully revealed.

For example, we do not know if the rate of concave growth will diminish in the tail of a long platoon.

Therefore, we carried out a longer 51-car-platoon experiment
Hefei old airport runway and taxiway (51-car-platton)

Since we have only 27 GPS devices, we cannot install the GPS on each car. In the experiment, the GPS devices were installed on the leading car and every two cars,
The x location and the velocity of the leading car in the two sets of the experiment.
Velocities of several typical cars in which the leading car moves with speed 5 km/h
Velocities of several typical cars in which the leading car moves with speed 12 km/h
The leading car moves with speed 25 km/h
Evolution of the platoon length and the average velocity of all cars

The leading car moves with speed 30 km/h
Evolution of the platoon length and the average velocity of all cars

The leading car moves with speed 40 km/h
When the leading car moves with **30 km/h or lower**, the standard deviation increases rather quickly along the platoon, all the way till the last vehicle.

On the other hand, when the leading car moves with a speed of **40 km/h or more**, the standard deviation also increases quickly for the first 10-15 cars in the platoon but tappers off along the platoon. The standard deviation is almost flat in the rear of the 51-car-platoon.

The standard deviation of the velocity of each car along the platoon
two example trajectory diagram in which the leading car moves with 25 km/h.
30 km/h
Based on the findings, we argue that traffic instability depends on traffic flow speed.

It is likely that there exists a critical speed between 30 km/h and 40 km/h for Chinese drivers.

Above the critical speed, the traffic flow is likely to be stable. Below the critical speed, traffic flow is unstable and will finally lead to formation of traffic jams.

We consider a platoon of cars is stable even if the disturbances grow in the platoon but eventually cap off without causing cars to come to a complete stop. If the growing disturbances eventually cause cars to make a complete stop, the platoon is considered not stable.
Empirical observations: Nanjing Airport Highway

Example 1

low-speed traffic flows are induced by moving bottlenecks
Example 2
Example 3
Trajectory diagrams in which the leading car moves with 30 km/h, but has decelerated and accelerated to 30 km/h again.
Based on the experimental findings, we argue that the traffic instability to jams might be determined by the competition between stochastic factors, which tend to destabilize the traffic flow, and the speed adaptation effect, which tends to stabilize the traffic flow.

\[
\frac{dv}{dt} = \lambda (v_l - v) + \xi
\]

for qualitative illustration rather than quantitative modeling.
In the front of the platoon, the oscillation grows quickly, since the stochastic factors dominate traffic flow dynamics. With the increase of oscillation amplitude, the speed adaptation effect strengths, and thus oscillation growth rate slows down and the oscillation growth curve bends down.

When the standard deviation of speed grows to about 1.5 m/s, its growth rate becomes very slow. Therefore, the growth of oscillation can be regarded as being almost saturated, which implies that the speed adaptation effect and the stochastic factors are roughly in balance. Traffic flow is thus stable.

With the decrease of the traffic speed, the traffic flow evolution is similar. However, before the oscillation becomes saturated, the minimum speed has decreased to zero in the rear part of the platoon. As a result, stop-and-go traffic emerges, and thus traffic flow is unstable.
Conclusion and future work

• There is No unique relationship between vehicle speed and its spacing
• Concave growth pattern of oscillation
• Traffic stability critical speed between 30 and 40 km/h
• Traffic instability mechanism

• More experimental and empirical data are needed
High speed car-following experiment

11-car-platoon, about 15 km long highway, 60,70, 80 km/h
Leading car does not move constantly

15-car-platoon, 4.8 km road
• Thanks for your attention!
• Comments are sincerely appreciated

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