Physics of Autonomous Driving based on Three-Phase Traffic Theory

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We have revealed physical features of autonomous driving in the framework of the three-phase traffic theory for which there is no fixed time headway to the preceding vehicle. A comparison with the classical model approach to autonomous driving for which an autonomous driving vehicle tries to reach a fixed (desired or “optimal”) time headway to the preceding vehicle has been made. It turns out that autonomous driving in the framework of the three-phase traffic theory exhibits the following advantages in comparison with the classical model of autonomous driving: (i) The absence of string instability. (ii) Considerably smaller speed disturbances at road bottlenecks. (iii) Autonomous driving vehicles based on the three-phase theory decrease the probability of traffic breakdown at the bottleneck in mixed traffic flow consisting of human driving and autonomous driving vehicles; on the contrary, even a single autonomous driving vehicle based on the classical approach can provoke traffic breakdown at the bottleneck in mixed traffic flow.

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It is generally assumed that future vehicular traffic is a mixed traffic flow consisting of human driving and autonomous driving vehicles [1–9]. Autonomous driving vehicles should considerably enhance capacity of a traffic network that is limited by traffic breakdown at network bottlenecks [10].

A study of real field traffic data shows [11] that the physics of TPACC has not been known. However, no studies of autonomous driving based on the three-phase theory (for short, three-phase ACC – TPACC) should be given by formula [12]

\[ a^{(TPACC)} = K_{\Delta v}(v_{\ell} - v) \]  

where \( K_{\Delta v} \) is a dynamic coefficient (\( K_{\Delta v} > 0 \)).

In other words, accordingly to [2], drivers do not try to reach a particular (desired or optimal) time headway to the preceding vehicle, but adapt the speed while keeping time headway \( \tau_{(\text{net})} = g/v \) in a range \( \tau_{\text{safe}} \leq \tau_{(\text{net})} \leq \tau_{G} \), where \( \tau_{G} = G/v \). This speed adaptation occurs within the synchronization space gap \( G \) adapting the speed to the speed of the preceding vehicle without caring what the precise space gap \( g \) to the preceding vehicle is as long as it is not smaller than a safe space gap \( g_{\text{safe}} \). This speed adaptation occurs within the synchronization space gap that limits a 2D-region of synchronized flow states (dashed region in Fig. 1(b)) determined by conditions

\[ g_{\text{safe}} \leq g \leq G. \]  

\[ \text{(2)} \]

In this Letter, we reveal the physical features of TPACC-vehicles on mixed traffic flow as well as compare TPACC with autonomous driving based on the classical approach.

To understand physical features of autonomous driving in the framework of the three-phase theory, we introduce

\[ a^{(ACC)} = K_1(g - v_{\tau_d}^{(ACC)}) + K_2(v_{\ell} - v), \]  

where \( v \) is the speed of the ACC-vehicle, \( v_{\ell} \) is the speed of the preceding vehicle; and below \( v, v_{\ell} \), and \( g \) are time-functions; \( K_1 \) and \( K_2 \) are coefficients of ACC adaptation. It is well-known that there can be string instability of a long enough platoon of ACC-vehicles [1] that occurs under condition \( K_2 < (2 - K_1(\tau_d^{(ACC)})^2)/2\tau_d^{(ACC)} \) found by Liang and Peng [3].

However, there is another basic physical problem of the classical autonomous driving: Even when the above-mentioned condition for string instability is not satisfied, i.e., any platoon of ACC-vehicles is stable, already a small share of ACC-vehicles in mixed traffic flow can deteriorate traffic while provoking traffic breakdown at network bottlenecks [10].

A study of real field traffic data shows [11] that the basic feature of classical autonomous driving systems – a desired time headway is fundamentally inconsistent with a basic behavior of real drivers. To explain the empirical data, in the three-phase traffic theory is assumed when a driver approaches a slower moving preceding vehicle and the driver cannot pass it, the driver decelerates within a synchronization space gap \( G \) adapting the speed to the speed of the preceding vehicle without caring what the precise space gap \( g \) to the preceding vehicle is as long as it is not smaller than a safe space gap \( g_{\text{safe}} \). This speed adaptation occurs within the synchronization space gap that limits a 2D-region of synchronized flow states (dashed region in Fig. 1(b)) determined by conditions

\[ \text{(1)} \]
The acceleration (deceleration) of the TPACC-vehicle does not depend on time headway, where \( \tau_{\text{safe,n}} = \frac{g_{\text{safe,n}}}{v_n} \) is a safe time headway and it is assumed that \( v_n > 0 \). Thus, in contrast with the classical ACC model (11) (Fig. 1(a)), there is no fixed desired time headway to the preceding vehicle for the autonomous driving vehicle based on the three-phase theory (Fig. 1(b)).

The speed adaptation within the 2D-traffic flow states of the three-phase theory used in TPACC model (4)–(7) changes the dynamic behavior of autonomous driving basically in comparison with the classical ACC model (11).

Simulations of string instability of ACC-vehicles are shown in Fig. 1(c). Speed disturbances in traffic flow consisting of 100% ACC-vehicles occur at an on-ramp bottleneck at which on-ramp inflow with the rate \( q_{\text{on}} \) and upstream flow with the rate \( q_{\text{in}} \) merge. String instability of ACC-vehicles leads to the emergence of moving jams upstream of the bottleneck (Fig. 1(c)). Contrarily, at the same set of the flow rates \( q_{\text{on}} \) and \( q_{\text{in}} \) as well as the same other model parameters no string instability of any platoon of the TPACC-vehicles is realized: In Fig. 1(d), all speed disturbances occurring at the bottleneck decay upstream of the bottleneck. It turns out that as long as time headway between TPACC-vehicle is within the range \( [\tau_{\text{safe,n}}, \tau_G] \), speed disturbances decay over time. This is because within this range the acceleration (deceleration) of TPACC-vehicle does not depend on time headway.
At a larger value of $K_2$ in (1) as well as at the same desired time headway $t_d^{(ACC)} = 1.3$ s and the same set of the flow rates $q_{on}$ and $q_{in}$ as those in Fig. 1 platoons of ACC-vehicles become stable (Fig. 2 (a)). However, it turns out that considerable speed disturbances appear at the bottleneck. This case is shown in Fig. 2 (b, c) in which ACC-vehicle 2 merges from the on-ramp onto the main road following ACC-vehicle 1 moving on the main road. To satisfy the desired time headway $t_d^{(ACC)}$, ACC-vehicle 2 should decelerate to a lower speed than the minimum speed of ACC-vehicle 1. This deceleration of ACC-vehicle 2 forces the following ACC-vehicle 3 to decelerate while approaching ACC-vehicle 2. Simulations show that the occurrence of large speed disturbances at the bottleneck is a basic problem of ACC-vehicles based on the classical approach in which the ACC-vehicles try to reach a desired time headway $t_d^{(ACC)}$.

These large speed disturbances at the bottleneck caused by ACC-vehicles (Fig. 2 (b, c)) do not occur in
traffic flow consisting of TPACC-vehicles (Fig. 2 (d–g)). This is because within the range of time headway [5] the acceleration (deceleration) of an TPACC-vehicle does not depend on time headway. This explains small amplitudes of speed disturbances caused by TPACC-vehicles 2 and 3 at the bottleneck (Fig. 2 (e, f, g)). The speed disturbances caused by TPACC-vehicles are so small (Fig. 2 (f)) that in the same speed-scale as that used for the classical ACC (Fig. 2 (c)) they cannot almost be resolved. Only at considerably larger speed-scale the speed disturbances become visible (Fig. 2 (g)).

Traffic breakdown in a flow of manual driving vehicles is a phase transition from free flow (F) to synchronized flow (S) (F→S transition) occurring in a metastable free flow with respect to the F→S transition. The larger the amplitude of speed disturbances at the bottleneck, the more probable the nucleus occurrence for the breakdown, i.e., the larger the probability of traffic breakdown $P_{(B)}$ at the bottleneck [10][11].

In the next future, we could expect a mixed traffic flow in which the share of autonomous driving vehicles is small (Fig. 3). Single TPACC-vehicles moving in a such mixed traffic flow cause very small speed disturbances at the bottleneck (Fig. 3 (b–d)). Indeed, we have found that probability of traffic breakdown remains in this mixed flow the same as that in traffic flow consisting of manual drivers only (curve 1 in Fig. 3(a)). Contrarily, probability of traffic breakdown can increase even when a very small amount of classical ACC-vehicles is in a mixed traffic flow (curves 2 and 3 in Fig. 3(a)). This deterioration of traffic through classical autonomous driving is explained by the occurrence of a large amplitude speed disturbance caused by a classical ACC-vehicle at the bottleneck (Fig. 3(e–g)): Already a single ACC-vehicle can initiate traffic breakdown at the bottleneck (Fig. 3(e–g)).

If the share of autonomous driving vehicles in mixed traffic flow increases (Fig. 4), the probability of traffic breakdown caused by ACC-vehicles that deteriorate traffic can increase considerably (Fig. 4, curve 3). Contrarily, long enough platoons of TPACC-vehicles in mixed traffic flow decrease the breakdown probability (Fig. 4, curve 2). This physical feature of TPACC-vehicles is also explained by the speed adaptation effect of the three-phase theory that is the basis of TPACC [11]: At each vehicle speed, the TPACC-vehicle makes an arbitrary choice in time headway that satisfies conditions [9]. In other words, the TPACC-vehicle accepts different values of time headway at different times and does not control a fixed time headway to the preceding vehicle.

By autonomous driving in the framework of the three-phase theory (TPACC) there is no fixed desired time headway to the preceding vehicle. In the Letter, we have shown that this physical feature of TPACC leads to the following advantages in comparison with the classical approach to autonomous driving: (i) The absence of string instability. (ii) Considerably smaller speed disturbances at road bottlenecks. (iii) Autonomous driving vehicles based on the three-phase theory decrease the probability of traffic breakdown at the bottleneck in mixed traffic flow; on the contrary, even a single autonomous driving vehicle based on the classical approach can provoke traffic breakdown at the bottleneck in mixed traffic flow.

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[1] Autonomous driving vehicles are also called automated driving or automatic driving or else self-driving vehicles. Under automated driving or automatic driving vehicles are often understood autonomous driving vehicles that are connected each other (vehicle-to-vehicle (V2V) communication) or/and with infrastructure (V2X communication).

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