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Platooning of connected automated vehicles on freeways: a bird's eye view

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Abstract

A platoon of connected automated vehicles (CAVs) is defined as a group of CAVs that exchange information, so that they can drive in a coordinated way, allowing very small spacings and, still, travelling safely at relatively high speeds. The concept of vehicle platooning is not new. Scientific articles on platooning have been published since the 1970s, and the first large-scale pilot test on vehicle platooning was carried out in the mid 1990s in California. By 1992, the first vehicle platooning experiments were successfully concluded, and the four-vehicle platoon capability was demonstrated for visitors on the I-15 HOV lanes in San Diego in 1994. The main purpose of these early research works was to improve traffic efficiency and reduce vehicle consumption, as well as to develop the existing technology, which represented a strong limitation at the time. Precisely, the development of new technologies and communications in the last decade has given a new impetus to the research on vehicle platooning on freeways, as one of the most promising forms of cooperation among CAVs. These recent studies have extended the analysis beyond traffic efficiency, including safety, sustainability, business productivity, among other objectives.

In this context, today, there are many scientific publications on vehicle platooning with different purposes, scopes, scenarios, and based on a wide diversity of vehicles and technologies (i.e. regular or segregated lanes, cars or trucks, vehicles with different SAE levels, etc.). In order to organize and consolidate the existing knowledge on the field, a comprehensive and systematic review must be performed. The present work represents a first approach to this ambitious objective. First, platooning is conceptualized in order to facilitate its analysis and comparison among studies. Second, key publications on platooning are analyzed to determine the most significant impacts that can be expected from its implementation. Finally, some important research gaps and disparate findings on the topic are identified.

Keywords: platooning; platooning impacts; connected automated vehicles; review

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1. Introduction

During the present century, advances in vehicle automation, monitoring and communications have allowed the development of different cooperation strategies among mobility agents aimed at improving traffic flow, increasing safety and reducing environmental impacts (Maiti et al., 2017; Martínez-Díaz et al, 2018; Razmi et al., 2020). Cooperation in terms of vehicle platooning started to attract interest in the 1970s, mostly involving heavy vehicles equipped with sensors designed *ad hoc* (Tsugawa, 2016), and where the equipment on the infrastructure played a decisive role. The main benefits sought from platooning were linked to potential fuel consumption savings (Browand, 2004; Lammert et al., 2014; Alam et al., 2015; Tsugawa, 2016). Research interest has evolved during last years. More attention is paid to highly automated light vehicles (Maiti et al., 2017; Bian et al., 2019; Sala and Soriguera, 2020) while the importance of the infrastructure decreases, and that of communications increases (Bian et al., 2019; Jia et al, 2019; Li et al., 2020). Moreover, research usually seeks additional potential benefits, such as traffic flow efficiency and safety improvements (Xu et al, 2013; Ye and Yamamoto, 2018; Calvert et al, 2019).

String stability of platoons is the research topic that has attracted most attention. Researchers propose different control strategies to avoid instabilities linked to close vehicle formations, and which result in trajectory disturbances propagating and amplifying along the platoon. This topic is out of the scope of this paper, as it would require a particular review. Instead, this work provides an overview on the research and developments achieved so far, focusing on the expected impacts of platooning on traffic flow, road safety, human drivers' behavior, energy consumption and emissions. An extensive literature review has allowed identifying and summarizing the most significant results, comprising both the different contexts and analysis methods considered. A semi-structured approach was used to choose the papers underpinning this review, being most of them high impact studies included in the Scopus database and containing the words *platoon* or *platooning* in the title, abstract or keywords. A quick scan allowed dismissing those dealing with traditional vehicles, urban scenarios or intersections. Backward snowballing was used to complete the set of references. Next, in Section 2, a description of platooning typologies, which influence impacts, is provided. Sections 3 to 5 respectively highlight platooning impacts on traffic flow, safety and the environment. Finally, in the conclusions section, the paper highlights those uncertain issues that require further research efforts.

2. Platooning typologies and characterization

Platooning can be classified (Table 1) according to five main criteria: *i*) the type of platooned vehicles, *ii*) the platoon length, *iii*) the information flow topology, *iv*) the formation policies and *v*) the following policies.

Regarding the involved vehicles, research on platoons usually deals with similar sizes, i.e., light (e.g. Gouy et al, 2014; Ye and Yamamoto, 2018) or heavy vehicles separately (e.g. McAuliffe et al., 2018, Calvert et al., 2019). The dynamic combination of vehicle sizes within the platoon is not common, as this creates additional difficulties in the platooning operations (Feng et al., 2019). For instance, the diversity in the mechanical features of vehicles implies problems due to different acceleration or braking rates. This may also imply a lack of comfort for some drivers (e.g. a car trapped between two large trucks). Additionally, the platooning vehicles usually have the same automation level, which, surprisingly, is rarely specified according to SAE standards (SAE, 2016). Levels with restricted human intervention are preferred for safety reasons, although current implementations feature vehicles of levels 1 and 2 fitted with special equipment, but still with active driver implication (Kockelman et al., 2016; Calvert et al., 2019).

Regarding the platoon length (i.e. the number of vehicles in a single platoon), it is common in research works to consider it as infinite. This allows simplifying and generalizing the analysis of very long platoons. In general, the longer the platoon, the larger the benefit (Feng et al., 2019), although the feasibility of very long platoons is unclear. Note that for long platoons the challenges related to the information flow, management and communications would increase. In addition, long platoons require many vehicles that fulfill the platooning attributes, simultaneously sharing the same stretch of the road for a significant length. Finally, the interactions of long platoons with other non-platooned vehicles would be especially complicated. One solution could be to restrict the platooning to the leftmost lane so as not to hinder their maneuvering (Eckhardt et al., 2016). This would also create a higher concentration of vehicles capable of platooning in a single lane, increasing the possibility of longer platoons. However, long truck platoons could accelerate the deterioration of pavements and structures (Song et al., 2021) in the platooning lane.

Table 1. Platooning classification according different criteria.

Criteria	Platooning types	Features
Vehicle type	Homogeneous	Vehicles of similar characteristics in terms of size and degree of automation
	Heterogeneous	Vehicles of different sizes and/or degrees of automation
Vehicle number	Finite	Finite number of vehicles
	Infinite	Infinite number of vehicles
Information flow topology	Nearest vehicles	Each vehicle receives/exchanges information from/with *r* vehicles ahead
	Nearest vehicles and leader	Each vehicle receives/exchanges information from/with *r* vehicles ahead, plus the leader
Formation policies*	Opportunistic (on-the-fly)	Only CAVs that happen to drive consecutively in a lane form a platoon
	Cooperative	All CAVs within a certain range try to join in a platoon
	Online, dynamic or in real time	Vehicles announce their destination and/or routes just before or during the journey
	Offline, static or scheduled	Trips are announced in advance to facilitate coordination
	Merging policies	Catch-up, slow-down or hybrid strategies
Car-following policies	Constant space gap	Followers maintain a fixed distance with the preceding vehicle
	Constant time gap	Followers maintain a fixed time with the preceding vehicle
	Variable gap	Followers maintain a variable space or time gap depending i.a. on road features

*Simplified non-exclusive classification. E.g. merging policies are part of any formation policy

Information exchange is a key operative factor. Information on other vehicles' speeds, positions, accelerations, decelerations, etc., should reach platooning vehicles in time so that they can react efficiently and safely. Several information flow topologies (IFTs) have been traditionally used in the literature, such as *predecessor following* (PF), *two-predecessor following* (TPF) and *bidirectional* (BDL). Lately, the development of powerful communication systems boosted the use of more general schemes such as *r-predecessor following* (rPLF). Some works claim that specific information about the leader should additionally reach the whole platoon. In this context, *predecessor leader following* (PLF), *two-predecessor leader following* (TPLF), *r-predecessor leader following* (rPLF), as well as *bidirectional leader* (BDL) IFTs are increasingly used (Zheng et al., 2016; Feng et al., 2019). The dynamic platoon nature, with vehicles changing their relative position over time, also adds complexity to the topology of communications (Feng et al., 2019). Figure 1 represents these configurations.

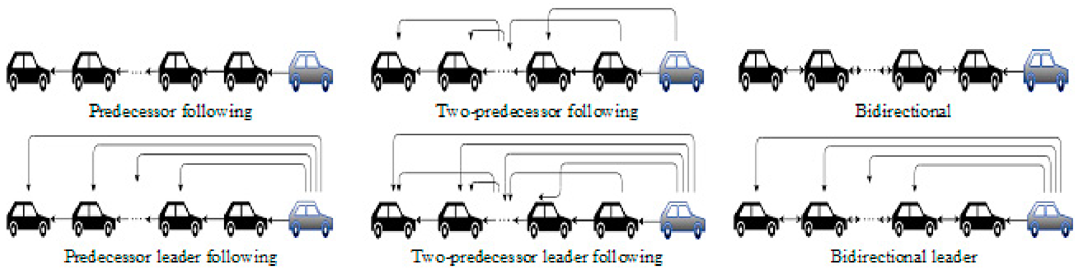

Figure 1. Most typical information flow topologies for platoons (the leader vehicle is highlighted).

The fact that more vehicles exchange information does not imply more stability or benefits. Indeed, the more information is transmitted, the greater the likelihood of communication delays, packet losses, etc., due to the congestion of communication channels (Xu et al., 2013; Zheng et al, 2018; Li et al., 2020). A tradeoff is required.

Given a sufficient rate of platooning-capable vehicles (Bergenhem et al., 2012), *cooperative* strategies foster platooning better than *opportunistic platooning* (Liang et al., 2014; Sala and Soriguera, 2020). Cooperation can be in the form of *offline, static or scheduled platoon planning*, especially useful in case of freight transport, which allows coordination among companies (Bhoopalam et al., 2018). However, side issues exist, like the still mandatory rest stops for drivers in the sector (Goel, 2014) or the *a priori* unsuitability of vehicles with certain loads forming a platoon (e.g. living beings with dangerous products) (Meisen et al., 2008). At the operational level, creating/dissolving a platoon is not trivial. The join/merge/split operations must be smooth and safe. For example, the *catch-up strategy* (e.g. Liang et al., 2014; Ko, 2019) consists in platoons maintaining their speeds while joining vehicles accelerate to catch them up from the back. Adversely, in the *slow-down strategy,* platoons slightly decelerate to facilitate the joining of vehicles from behind (e.g. Meisen et al., 2008; Ko, 2019). Intermediate solutions also exist (e.g. Saeednia and Menéndez, 2016; Farag et al., 2019). Different platooning schemes assume that vehicles can join platoons at the back, in the middle or at the front, with different operational features (Maiti et al., 2017, Farag at al., 2019). These options, hardly addressed in the literature, also apply to splits, which vehicles must announce beforehand so that the immediate followers quickly close the left gap.

While in a platoon, vehicles are subject to pre-established car-following policies. With the *constant space gap* (e.g. Jia et al., 2019; Li et al., 2020) or the *constant time gap* (e.g. Bian et al., 2019; Wang et al., 2020) policies, followers drive respectively maintaining a fixed distance or time. The values of these gaps vary across the studies, depending, i.a, on vehicles' size and automation level. Constant time headways -vehicular headway is defined as the time gap plus the time needed for the vehicle to travel its length at the travelling speed- between 0.6 and 1 s are common in the literature, while space gaps -vehicular spacing is defined as the space gap plus the vehicle length- vary more. For example, Zhou et al. (2017) considered a spacing of 7 m for truck platooning, while Zheng et al. (2018) accepted 25 m for all platoons. The *nonlinear distance strategy* (e.g. Orosz, 2016) seeks to improve string stability and the overall benefits of platooning i.a. accounting for the effect of road features (e.g. slopes) on the mechanical capabilities of vehicles, especially of trucks. Other less used policies exist, some very complex and difficult to implement in practice, and some very simple, only imposing minimum distances for the sake of safety (e.g. Zhou et al., 2017). A few authors (e.g. Vukadinovic et al., 2018) have also proposed car-following policies for the leader from other platoons or individual vehicles travelling ahead in the same lane.

3. Platooning effects on traffic flow

Platooning is expected to have a positive impact on traffic throughput because of vehicles maintaining small spacings, i.e., occupying less space while travelling at relatively high speeds, thus increasing capacity (Nowakowski et al., 2015; Lioris et al., 2017). The magnitude of the improvement will depend on the scenario, e.g. the penetration rate of CAVs, the platoons' length, the car-following policies, the road features, etc. In the most favorable cases, capacity could be doubled or tripled at urban intersections (Kockelman et al., 2016; Lioris et al., 2017), and quintupled on freeways (Kockelman et al., 2016; Sala and Soriguera, 2020). In addition, vehicle (especially heavy vehicle) coordinated driving increases traffic homogeneity (Nieuwenhuijze et al., 2012). Detrimental effects on traffic flow could also appear. For example, long platoons could cause congestion if their integrity is lost near bottlenecks. Implementing coordinate route assignment for platoons could attenuate this problem (Bhoopalam et al., 2018). Excessive platoons' length could also cause undesirable disturbances if hindering the maneuverability of human-driven vehicles (HDVs) wishing, for example, to change lanes (Nowakowski et al., 2015; Calvert et al., 2019). HDVs could force the cut-in abruptly interrupting the platoon strings. Alternatively, HDVs might accelerate/brake to surpass the platoon. In any case, these would limit the traffic flow improvements and generate risky situations. Accelerations/decelerations to maintain the platoon structure could also result in shockwaves and even in dangerous situations if not addressed properly. Although beyond the scope of this work, string stability is a prerequisite for platooning strategies, not only to improve traffic flow, but also to avoid unsafe and traffic damaging situations (Nieuwenhuijze et al., 2012; Calvert et al., 2019). In particular, some authors argue that, due of their greater disruption to other vehicles, truck platooning should not be allowed in saturated traffic flow (Calvert et al., 2019). These mixed traffic scenarios, with CAVs sharing roads with HDVs, are particularly complex and are widely researched (Razmi et al, 2020). Dedicated lanes for CAVs could minimize these interactions and favor platoon formation (Kockelman et al., 2016; Talebpour et al., 2017; Razmi et al, 2020). Moreover, speed limits could be higher in these lanes without compromising safety and increasing traffic flow benefits (Ye and Yamamoto, 2018). Tsugawa et al. (2016) specifically addressed the use of dedicated lanes for truck platooning, observing the doubling of capacity, albeit under ideal conditions. A "smoothing effect" characterized by significantly higher bottleneck discharge flows has also been observed in the adjacent lanes due to less disruptive vehicle lane changing (Cassidy et al., 2008). However, dedicated lanes are only reasonable for particular traffic conditions and for appreciable penetration rates of CAVs. Authors quantify these minimum rates between 15% (Yang et al., 2019) and 50% (Xiao et al., 2019), which indicates that more research is needed. Potential negative effects of dedicated lanes must be further analyzed. For example, a possible congestion increase in the non-dedicated lanes because of the non-cooperating vehicles having less capacity available (i.e., less lanes). Some researchers opt for dynamically dedicate lanes to platoons when appropriate (e.g. Zhong, 2018; Razmi et al., 2020), being their use optional to avoid sudden lane changing maneuvers (Talebpour et al., 2017). The case of CAVs sharing these lanes with high occupancy vehicles (HOV), or general HDVs paying a toll, has also been considered (Xiao et al., 2019; Liu and Song, 2019).

4. Platooning effects on safety and human behavior

The relationship between platooning and road safety can be analyzed focusing on the platoon itself or on its interactions with other vehicles. Some effects regarding this latter perspective have already been appointed, such as HDVs performing risky maneuvers to, for example, surpass a long platoon (Axelsson, 2017). More effects have been identified. Driving simulator studies have shown that humans change their driving behavior when interacting with platoons. HDVs usually try to imitate platoon intervehicle distances and/or accelerate to run parallel to platoons when their speeds are higher (Skottke et al., 2014; Razmi et al, 2020). Although the contribution of these effects to the total accident rate has yet to be quantified (Razmi et al, 2020), dangerous situations should be expected, as humans have longer reaction times than CAVs and are more error-prone (Schakel, 2010; Yang et al., 2019). Human trust in technology is dynamic and evolves over time and with extended exposure to automation (Ghazizadeh et al., 2012), which could be one factor behind this behavioral change (Al Haddad et al., 2020) of HDVs interacting with platoons. Previous experience with advanced driver assistance systems like cooperative adaptive cruise control (CAAC) is associated with greater confidence and bolder behavior of drivers interacting with platoons. Indeed, drivers already tend to drive more aggressively if their vehicles are equipped with these systems (Bianchi et al., 2014; Balk, 2016). However, CACC reduces stress and fatigue, which could mitigate these negative effects (Stanton and Marsden, 1996). In addition, the longer the interaction time with the platoon or the more significant the platoon (e.g. long truck platoons), the shorter HDVs' accepted distance to the vehicles ahead (Gouy et al., 2014; Yang et al., 2019). More research is needed to fully understand these interactions in different scenarios, and to address remaining questions such as the role of drivers' gender, age, physical and mental condition, driving experience, etc.

Within a platoon of CAVs, the lower reaction times, vehicle coordination and an inferior human role are expected to reduce the number of rear-end collisions (Xu et al., 2013; Bhoopalam et al., 2018). In a simulation environment and for a penetration rate of 40% of CAVs, Rahman and Abdel-At (2018) observed a significant reduction in the longitudinal crash risk along a dedicated lane for platoons following a constant time headway policy of 0.6 s. However, they did not account for possible disturbances caused by lane changing or alterations in HDVs' behavior. These authors also observed that safety conditions, albeit to a lesser extent, also improved with the presence of the same rate of CAVs without vehicle segregation. Again, there is need for further studies considering all possible external and internal boundary conditions (Axelsson, 2017). Diverse platoon formations should be considered, as vehicles' size, engine capabilities, etc. influence the quality of emergency braking (Bhoopalam et al., 2018).

Unless platoons consist of SAE level 5 vehicles, the human factor cannot be disregarded yet. Indeed, CAVs will require drivers to resume the control of the driving task whenever they cannot handle a situation. Given the short distances among vehicles and the relatively high driving speeds of platoons, both the drivers' reaction time and the quality of these reactions will be critical to avoid multiple vehicle collisions. In a study performed by Varotto et al., (2015) with ACC-equipped vehicles, drivers needed on average 3.85 s to resume control after sensor failure, which could be one cause for disengagement of CAVs in platooning scenarios. Eriksson and Stanton (2017) observed that reaction times rose to 6.06 ± 2.39 s if drivers were performing a secondary task. Conversely, studies analyzing real data of non-platooned CAVs collected in California found much lower drivers' reaction times to take control of the vehicle after disengagement. These had a stable distribution at 0.83 s, being the differences dependent on the type of disengagement (the cause, if it was active or passive, etc.), the previous number of miles travelled in the vehicles and the type of road (Dixit et al., 2016). Reaction times increased with increased vehicle miles travelled, probably due to greater trust in the technology (Lv. at al., 2018). Favaro (2019) analyzed the reactions of 40 human drivers placed in 36 simulated autonomous technology disengagement scenarios. Vehicle speed was found to significantly affect the takeover, much more, for instance, than driver's age: vehicle drift from the lane centerline increased over 116% in high-speed settings. Zhang et al (2019) endorsed this fact, and additionally noticed that reactions were faster and more appropriate in very risky situations, if drivers had experienced previous similar situations and if they were not performing another visual task during the automated driving. Zeeb et al. (2016) confirmed the negative role of distraction, whereas Roche et al. (2020) found a link between drivers' stress level and takeover overreactions. To what extend these tendencies apply to platooning scenarios and their consequences is still a research niche. As leaders play a special role in platoons, reactions of drivers in this position should be specifically analyzed.

5. Environmental impacts of platooning

Most authors agree that platooning will have positive environmental effects. Indirectly, it tackles congestion, which is linked to overconsumptions and harmful emission peaks. As a direct effect, platooning lowers air drag (Wadud et al., 2016; Turri et al, 2017). As aerodynamic drag accounts for 50%–75% of tractive energy requirements at typical highway speeds (Kasseris, 2016), its reduction would contribute to lower energy consumption and emissions (Scora and Barth, 2006). The relevance of these direct benefits depends on several factors. Zabat et al. (1995) used wind tunnel tests and numerical simulations to assess fuel savings for van platooning in different scenarios comprising varied intervehicle space gaps and platoon lengths. The overall savings ranged from 10% to 30%, but values between 20%–25% were the most frequent. Longer platoons (Zabat at al., 1995; Bhoopalam et al., 2018) and smaller space gaps (Zabat at al., 1995; Zhang et al., 2020) result in higher savings, while the role of speed is less important than for individual vehicles (McAuliffe et al., 2018; Zhang et al., 2020). Consumption-related benefits are especially significant for truck platooning, consistently with trucks' lower aerodynamic efficiency, particularly on highways (Nowakowski et al., 2015; Bhoopalam et al., 2018) and with short intervehicle space gaps. For gaps of 3-4 m, Browand et al. (2004) observed in track tests fuel consumption savings of 11%, which descended to 8% for gaps between 8-10 m. Humphreys et al. (2016) confirmed this tendency using simulation. Heavy loads slightly reduce savings (Lammert et al., 2014, Zhang et al, 2020). The vehicles' relative position within the platoon does also have a large impact on individual consumptions (Zhang et al, 2020). In track tests, leaders were found to save 2.7% to 5.3% of the average fuel needs, while followers increased these figures to 2.8-9.7% (Lammert et al, 2014). Lu and Shladover (2011) reported reductions in fuel consumption of 18% and 23-24%, respectively for the leader and the followers in a test performed with a 3-truck platoon on a real road. Davila et al. (2013) observed that benefits for the followers were the double of those for the leader, using computational fluid dynamics. In this context, some authors have proposed strategies to distribute the total savings during a common trip among all members of the platoon. For example, if the same vehicles regularly platoon together as in a coalition, they could share the benefits by taking turns as leaders (Bhoopalam et al., 2018). Such measures would promote platooning based on expected savings (Zhang et al, 2020). Finally, it is observed that fuel savings could even rise further if additional strategies such as cooperative look-ahead control were implemented (Alam et al., 2015).

Most of the former studies comprised vehicles with low-medium automation levels and petrol or diesel engines. Higher energy savings are expected for fully automated electric vehicles (Stephens et al., 2016). First, they will allow for smaller intervehicle spacings and squeeze eco-driving modes. Second, energy savings while platooning are higher than fuel savings (Alam et al., 2015), and electric engines are expected to have marginal internal losses. The elimination of long rest periods for drivers will also allow optimizing consumptions (Zhang et al, 2020).

6. Conclusions

Future mobility based on CAVs aims at reducing undesirable traffic externalities, i.e. congestion, accidents and environmental damage. The analysis performed in this paper confirms that platooning has great potential in this regard. First, the frequent formation of medium-length platoons could lead to an increased road capacity due to small intervehicular space gaps. In addition, string-stable platoons could promote the ability of cooperating vehicles to reduce traffic instabilities and, therefore, enhance traffic flow stability and throughput. Second, coordination within vehicles and a lesser driver responsibility would reduce the accident rate. Third, especially truck platooning would lead to reduced energy and fuel consumptions, thus decreasing harmful emissions. However, further research is needed. Studies on vehicle platooning must consider increasingly realistic (and complex) contexts to fully reach these benefits. Table 2 summarizes the main research gaps identified. Other research questions remain in topics like string stability, platoon planning/routing in logistics, or network design accounting for platooning. This overview should serve as an incentive to new research contributions on this promising form of cooperative driving.

Table 2. Most important research gaps identified.

Research gap	Description	Key affected domains
General IFT	Platoon formation will be mostly dynamic, with vehicles fluently joining/leaving platoons, thus not maintaining a specific IFT, as current studies assume.	All
Heterogeneous platoons	The feasibility of platoons of vehicles of different sizes and/or automation capabilities would boost platooning and lead to a better exploitation of its potential benefits.	All
Mixed environments	The large number of possible scenarios makes it necessary to dive deeper into this topic, accounting for as many different factors as possible.	Traffic flow and safety
The human factor	Drivers' behavior within and out of platoons must be further examined, covering their expected responsibilities and their identifying (e.g. age) and circumstantial (e.g. fatigue level) features.	Traffic flow and safety
Communication mechanisms and quality	The information to be exchanged and its update interval must be determined so that platoons, given their dynamic nature, circulate efficiently and safely, but without compromising communication networks. Interoperability, privacy and protection against cyber-attacks are also due.	All
Non-linear systems and non-deterministic system disturbances	Most studies consider vehicle dynamics within the platoon to be linear and disregard stochastic external disturbances that can affect the platoon. Both assumptions allow simplifying the analyses, but affect any derived results, as none of them matches reality.	All

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