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Learning an Alternative Car-Following Technique to Avoid Congestion with an Instructional Driving Simulator

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***Abstract*—This paper addresses the problem of traffic congestion through a learning perspective, highlighting the capabilities of Information and Communication Technologies to transform society. Recent physical and mathematical analysis of congestion reveals that training drivers to keep a safe distance systematically contributes to the emergence and maintenance of interference congestion (so-called phantom traffic jam). This paper presents the WaveDriving Course (WDC), a simulated learning environment designed to help drivers progress from the traditional Drive-to-keep-Distance (DD) technique to a new car-following (CF) principle better suited for wave-like traffic, Drive-to-keep-Inertia (DI). The WDC is based on the ordinary knowledge of the driver (e.g., going through a series of traffic lights), and presents this situation in terms of two possible simultaneous behavioral strategies. The driver has the opportunity to verify that it is possible to achieve the same objective with different consequences. Finally, the WDC checks to what extent this learning generates transfer patterns in the analogous case of CF. The paper focuses on results concerning the first WDC module: the traffic-light analogy. Forty-two participants followed the whole learning procedure for about 30 min. An evaluative CF test was administered before and after visioning the tutorial and practicing on the simulator. Overall, transference from this traffic-light analog to the CF situation (posttest) was successful. Results confirm the adoption of the expected DI strategies (speed variability decreased, distance and distance variability to leader increased, fuel consumption decreased, platoon elongation decreased etc.). The need to improve the WDC teaching of the appropriate CF distance is discussed.**

***Index Terms*—Devices for learning, educational simulation, self-assessment technologies, traffic congestion.**

I. INTRODUCTION

By 2050, two thirds of the world's population is expected to live in cities [1]. One outcome of the intensification of this urban resettlement trend is traffic congestion. The literature points to the economic costs of traffic congestion such as increased prices of goods, time spent travelling and unemployment [2], [3], and health issues, as traffic pollution causes more deaths than car crashes in some countries [4]. Internationally, road-safety education is incorporated into schools from K-12, including topics such as pedestrian safety or driver education. In Spain, road-user education and training are compulsory as a horizontal topic in primary school education, targeting promotion of road education and respectful attitudes that help prevent traffic accidents [5]. Road-safety education in secondary school is merged with other subjects, with the aim of helping students understand their rights and duties as road users [6]. In Israel, learning road safety is compulsory in K-12 [7]. In secondary schools, three main topics are addressed: driving education, vehicle operation and traffic code and laws. A more recent official outline recommended that learning about driving in traffic should be organized as active learning, inquiry- and problem-based learning, identifying misconceptions and addressing them, event analysis, role-playing and simulations and a wide use of technologies and multimedia [8]. The present study is set within the scope of these educational national standards, exploring the design and active problem-based learning with interactive simulations, geared toward teaching safe driving and co-existing in greater harmony with fellow drivers. The main objective of this work focuses on the last step of driver education: the driver in training and the adult driver (from 16 to 18 years old and over) who access a training process through the usual formal channels (for example, a driving school) to learn, or improve, driving a car.

This paper proposes a way to learn to drive adaptively in congested traffic by using simulations and models. Model-based learning, used mainly in STEM (science, technology, engineering and mathematics) related domains, focuses on developing and using models of various systems [9]. A model is a representation, a simplified version of reality, of a system or phenomenon that supports explaining and predicting the

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system's behavior [10]. Model-based learning can be enacted in various ways, for example by having students construct or use prepared models, as in the present study [11]. According to Kerner [12], "Congested traffic is defined as a state of traffic in which the average speed is lower than the minimum average speed that is still possible in free flow" (p. 13). Under this definition, different situations such as road cuts, floods, accidents or traffic lights may all cause congestion. These situations can be grouped into two: traffic jams due to lane blocking, and speed interference jams, also known as phantom traffic jams [13], a type of traffic congestion that pervasively emerges in traffic for no apparent reason, and is the focus of this research. This second type arises because it is mathematically impossible to drive while trying to maintain the safety distance and that there are no traffic jams due to the backward fluctuations resulting from the increasing delays produced by drivers' reaction times. Presently, driving courses teach students about individual safety measures, such as keeping a certain distance from the car they are following. However, what they do not teach is how interactions between cars lead to congestion, and what behaviors may promote smoother and faster driving in such situations. The present learning design focuses on the latter, raising awareness of how driving actions taken for granted (e.g., keeping a distance from the car ahead) concern individual safety but also are a systemic issue facilitating traffic jams.

A. The Solution: Rethinking Car-Following

The simulation design is based on recent developments concerning car-following (CF) models in the field of traffic engineering research and theory [14]. In the last 10 years, knowledge about the formation of traffic congestion has changed substantially. A central element of this new perspective is a shift from pairs of cars (leader, follower) to broader systemic interactions (e.g., internal dynamics of cars that platoon, or group closely). Controlled experiments exploring these phenomena under the so-called Nagoya paradigm [15], [16] replicated the formation of traffic jams even when there is no external impediment such as an accident. Drivers followed each other in a 230-m perimeter circle under the premise follow the vehicle ahead in safety and try to maintain cruising velocity. Participants drove and maintained free flow. But when the number of drivers rose to 22, backward fluctuations broke the free flow, and several vehicles stopped momentarily to avoid crashing. At a given point, even a single car's braking was transmitted back through the column of cars, forming the typical shockwave that eventually brought some cars to a complete halt. Put simply, the adoption of the standard safety distance was the ultimate cause of the occurrence of phantom traffic jams, because safety distance arranges car platoons to favor the spread of disturbances in a waveform. This CF strategy only works well when the speed of the car ahead is constant, a scenario more often the exception than the rule in road traffic [17], [18].

Most CF models assume that drivers' systematic adoption of a safety distance is natural or rational [19], [20]. Millions of observations worldwide confirm this CF behavior: the systematic approach of following the leader (coupling). However, no psychological theory presumes a genetic or biological endowment ready for the massively observed CF behavior. Some living organisms (ants, bees, caterpillars and the like) exhibit complex behaviors derived from such genetic or biological endowments, but not humans. Another reason to keep the safety distance as a natural disposition is mathematical modelling based on cinematics. However, if the Nagoya perspective is correct, there should be a shift from complex differential equations to wave mathematics. Recent perspectives on the Traffic Flow Theory increasingly focus on waves as a heuristic to model and describe traffic flows from a macro perspective [21].

B. The Challenge: Changing Driving Behavior

Transforming traffic flows and eliminate traffic jams requires adopting a different perspective. Current CF strategies adopted by each driver promote traffic jams. However, nothing prevents drivers from adopting a different CF strategy from the one massively observed. To understand these issues, a fruitful model to consider is that each car produces a disturbance, which results in a wave oscillation in space. Interaction between the waves can be understood through classical wave mathematics and physics [22]. Based on this approach, two main options emerge for a collection of cars when one car creates a disturbance — such as moving slightly slower or faster than the others. The first is constructive interference that increases the oscillation, causing the disturbance to magnify (i.e., summing waves). The second is destructive interference, whereby the waves cancel each other out and reduce the disturbance (i.e., offsetting waves [23].

Commonly, drivers worldwide are instructed to keep a safe distance, or Drive-to-keep-Distance (DD), from cars ahead. When a driver keeps a safety distance following a leader moving at a uniform speed, with free-flow conditions, disturbances are not transmitted. But in other traffic contexts (e.g., entering or leaving conurbations at peak hour), traffic flows become dense (i.e., a perfect means of wave transmission). The leader's oscillations then become regular, and the Drive-to-keep-Distance (DD) principle only increases that perturbation (by simple sum or reaction times), eventually producing traffic jams due to constructive interference of waves (or a sum of waves). The alternative is for drivers to learn to create a destructive interference, offsetting the leader's oscillations, and preserving inertia, or Drive-to-keep-Inertia (DI) [24], [25]. To offset traffic waves, drivers must calculate not only the safety distance but also the leader's average speed amidst stop-and-go cycles to keep a uniform CF speed, that is, to apply the so-called Drive-to-keep-Inertia (DI) principle. Some studies indicate that drivers can not only DD but also DI, as requested [24], [26], [25]. In sum, drivers are capable of both increasing and offsetting the leader's oscillations. Based on this developing knowledge, transforming traffic flows, eliminating traffic jams and achieving uninterrupted traffic flows is possible. However, we need to broaden drivers' knowledge and perspectives of CF under dense traffic. Previous studies showed that drivers can follow a leader with oscillating speed and keep their speed relatively constant upon request. While they can adopt these energy conservation behaviors, they do it blindly; that is, they adopt that behavior if the experimenter requires it, but they know nothing about its implications for the broader traffic context. In line with recent theoretical developments as the Goals and Driver Education Framework [27, 28, 29, 30] this broader insight requires the teaching-learning of DI as strategic procedural learning, helping individual drivers to understand how their driving behaviors impact traffic flow, the genesis of phantom traffic jams and what kinds of driving behaviors could help avoid them. Although amenable to a high degree of automation, the DI technique must be consciously applied depending on driving conditions to anticipate and avoid the potential risks involved in traffic situations, as well as to drive more efficiently. Based on previous studies [24], [25], we have termed this adaptive, anti-jam driving technique WaveDriving [31].

II. THE WAY FORWARD: DESIGNING A SUITABLE LEARNING ENVIRONMENT

The WaveDriving Course (WDC) is a multimedia learning platform aimed at providing drivers experiences that could transform their CF knowledge and behavior [24], [25]. Considering classical approaches to memory and cognition such as the Multicomponent Working Memory Model [32], [33], we would broadly expect learners to attend to some visual and verbal stimuli, retaining them in their working memory system, then integrating them with information from their long-term memory [34]. At a higher level, theories for instructional message design [35], [36] draw on these assumptions to identify adequate multimedia principles to improve learning. Table 1 presents some examples of the WDC as a learning environment in terms of the 4C/ID Model [37].

TABLE I
THE FOUR COMPONENTS OF INSTRUCTIONAL DESIGN MODEL [33] AND LEVELS 0/1 OF THE WDC

	4C/ID description	Level 0	Level 1
C1	Construction of new schemes: induction of experiences (generalisation and discrimination of cognitive schemes)	Learning to accelerate and decelerate with keyboard	Learning to catch traffic lights in green while adopting a constant speed
C2	Elaboration of schemes: integrating new information with pre-existing schemes	Arrow-up on the keyboard same function as press on the gas pedal to accelerate; Arrow-down same as release pedal / press brake pedal to decelerate	Schemes concerning pace regulation (e.g., passing through a moving revolving door without pushing it)
C3	Automation of schemes (I): compilation of knowledge that matches conditions and actions	Learner gets used to pressing arrow-up on the keyboard to accelerate and arrow-down to decelerate; If releasing the key, the same speed is maintained	Learner attends to certain cues (e.g., traffic-light timers; the red cars' approaching speeds) as feedback to fine-tune their speed
C4	Automation of schemes (II): repetition and strengthening of schemes that are applied specifically and quickly	After some practice, managing speed on the keyboard is assumed as a secondary task required to adapt higher driving goals	The learner gets used to reading feedback indicators swiftly and to reaching the correct passing speed effortlessly

C = Component

Computer simulations designed for learning driving normally focus on experiences that promote elementary driving knowledge such as accelerating, decelerating or steering: that is, the main actions and reactions of a novel driver in a driving environment [38], [39]. Simulation environments are also effective in showing new or unusual traffic environments or circumstances, and in learning and training new driving behaviors [40], [41], [42], [43]. One learning environment that attends to driving in emergent traffic and congestion is TrafficJams [44], in which a group of people drive their cars together on a single simulated road. Unlike the WDC, this learning environment attends not specifically to the DD and DI CF strategies but to other issues of keeping a safe distance (with a specific strategy), braking and accelerating and shifting between lanes. The focus here is on the collective behavior, and individual behaviors are less distinct and life-like than in the WDC. The WDC targets two main purposes. The first is to teach an alternative CF technique, WaveDriving, which focuses not only on keeping the safety distance (DD) but also on preserving inertia when following an oscillating leader (DI). Accordingly, during the activity, drivers in the WDC are encouraged to compare the differing effects of adopting DD versus DI through different tasks and scenarios. The second main purpose of the WDC is to help drivers understand the close connection between adopting DD (normative CF technique) or DI (the alternative CF technique) and the emergence of congestion in a platoon of followers. To achieve these goals, some ordinary elements and circumstances (e.g., rearview mirror, presence of traffic lights, passing road sections with different speed limits) have been implemented in the WDC, as well as some very unusual or impossible ones (e.g., adopting bird's-eye views from different angles and positions over the whole platoon at will, displaying traffic lights on each single car, connecting cars with springs, activating radar-like displays). Like other recent attempts to model and understand complex systems [44], the WDC leverages uncommon paths or perspectives to frame participants' analysis and comprehension of CF at large.

The WDC aims to explain that traffic congestion depends on how we face and manage certain flow disturbances. Understanding this wave-like character can help drivers adjust their driving behaviors appropriately. To adapt to the local changes in traffic and understand their broad consequences (what will happen ahead, what will happen behind), drivers need to evaluate and integrate multiple perspectives. This complexity requires learning processes and practice. The circumstances of transfer are vital to understanding why some driving behaviors (or driving tasks) will transfer properly and others will not [38]: transfer will occur most easily if the behavior is at least once well practiced; when the initiation of the skill is prompted externally, the context will help the driver initiate this alternative behavior.

A. The Vision: Mirroring the Driving School

The WDC is analogous to a driving school. Both combine theoretical and practical lessons, involve increasingly demanding driving situations and evaluate performance continuously, providing the learner feedback. However, the WDC has been conceived to work online, making it available to thousands of drivers, enriching their driving knowledge and potential feedback (e.g., a WaveDriving certificate). This approach involves certain design, structure and time constraints. Fig. 1 presents the WDC structure: lectures, practice and evaluation. Fig. 2 presents the learning modules: Lessons 0-3 specific driving achievements.

Objectives of the session

1. **Without ever jumping a red light**, find out **what constant speed** allows you to **cross the traffic lights** just as they go **green**

Fig. 1. The WDC structure.

B. The WDC Structure: Information and Guide, Practice and Evaluation

The WDC transcends the standard driving experience. Left to their dispositions and knowledge, participants would have to resort to basic trial-and-error or random search heuristics to explore and understand how the WDC operates [36]. This would require time and perseverance. Therefore, the WDC's driving demands have been purposely simplified (no overtaking, lane changing or merging), focusing on the main issue: the effects of CF manipulations on the line of vehicles. Designed as an online tool, the WDC also tries to optimize the learning experience, working under certain time constraints (each tutorial-then-practice block on the simulator takes roughly 5 min). Tutorials (the driving school teacher) assume modelling [45] and play a fundamental guiding role, proposing specific goals to practice, encouraging attention to the effects of different manoeuvers, and synthesizing the novice-to-expert knowledge paths, highlighting the cause-consequence pairs that help one discern what is important to do and what conclusions can be drawn from the experiences. Each WDC tutorial assumes a few main goals that are then divided into more specific sub-goals, achieved by timed exposure to certain visual and verbal stimuli (Appendix I). WDC tutorials adopt the basic design principles of multimedia documents [36], following the Cognitive Theory of Multimedia Learning in particular [35], [46].

The WDC simulator always presents the same visual and operative resources available onscreen. When the driver clicks to enter a particular level, the main two or three objectives of the session (already mentioned in the corresponding tutorial) are displayed again. Once the participant is ready, clicking on the "start" button (and waiting for a short countdown) places them as if driving a car on the right lane, holding the wheel, and assuming full control of the car (being able to accelerate, change visual perspective, etc.). Ordinary elements are displayed (wheel, cockpit, windshield screen, speedometer, rearview mirror). The road ahead may vary, always showing two lanes but presenting different objects (e.g., traffic lights, cars, speed limits) depending on the requirements targeted by each level. Cars on the right lane (participant) are always green; cars on the left lane (DD drivers) are always red. The simulator's screen presents other specific features: nine semi-transparent icons (to activate the traffic light, springs, radar, etc.) are displayed on the left, and a toggled bar (an alternative way to control speed besides up-and-down arrow keys) is displayed on the right. Clicking on certain screen buttons

Knowing the controls	Traffic lights: first analogy	Springs: second analogy	Speed, platooning and phantom jams	Car-following with no aids
Module A: Landing	Module B: Teaching WaveDriving			Module C: Evaluation

Fig. 2. The WDC modules.

presents different gadgets (e.g., a traffic light mounted over each car on the scene) designed to help participants understand the contents and goals of the particular practice session. Driving at Level 0, designed to learn the controls, participants follow a leader at a constant speed; all other levels are built by different scenarios involving speed variation.

The basic structure of the evaluation is pretest and posttest. The evaluation scenario consists of a group of 10 cars following a leader that stops-and-goes cyclically. The participant drives the first car after the wavering leader. No additional visual help is available, only speed (keyboard, mouse) and the rearview mirror. Participants are simply presented with these instructions: 1. You will carry out a car-following task for two and a half minutes. 2. You will follow that car without visual aids. Once the task is finished, participants receive some feedback in the form of a Driver-Car-Diagram (Fig. 1, bottom right).

C. The Learning Modules: Levels 0-3

The WDC includes three modules (Fig. 2): A. Knowing the controls (Level 0); B. Teaching WaveDriving (Levels 1–3); and C. Evaluation (Level 4). The sessions on the simulator are time-limited (around 2.5 min), and tutorials take no longer than this to address what the learner should practice at each level. Nevertheless, participants can decide how many times to watch the tutorials and practice the WDC. Thus, the minimum time a learner would need to complete the WDC is roughly 30 min.

Module A: Knowing the controls. Tutorial 0 (Fig. 2A) informs about time for each practice session and anticipates two broad practice goals (see Appendix I, Scenes 2-3). Then, an explanation of the alternative ways to manage the speed follows (pressing arrow-up on the keyboard to accelerate or arrow-down to decelerate; using the mouse on the scrolling bar on the left of the screen). Attention is then brought to the rearview mirror (several cars follow behind). Finally, attention is brought to the screen buttons that control several visual resources: (a) the multi-camera (four aerial positions consecutively accessed by repeating mouse clicks), (b) the helicopter (camera viewing the very last cars of the following platoon and indicating the very last car's speed), (c) the radar (providing a bird's-eye view of the movement of the whole group [or groups] of cars along the road lanes; cars can go green, yellow, or red if they respectively progress, slow down, or stop), (d) traffic lights (clicking on the icon makes traffic lights mounted on each car appear, red-yellow-green colors change in consonance with making the most of the movement phase and the traffic-light color, as the radar does), and (e) two types of car-connecting springs. The remaining screen buttons (rural/urban scene, day/night, full screen, exit) are mostly irrelevant (aesthetic functions). Once the tutorial (2.16 min) is viewed, the learner is invited to enter the simulator and practice (3 min), and then to repeat if they wish.

Module B: Teaching WaveDriving (Levels 1–3). We now broadly describe Levels 1–3 (see section D for a detailed description of Level 1). These levels are interconnected and comprise the knowledge and behaviors that participants must integrate into their conceptual and behavioral repertoire to learn DI. Level 1, the traffic-light analogy, attempts to promote a basic understanding: adopting a uniform speed is a better strategy for confronting predictable stop-and-go sequences in traffic (here, the green-yellow-red traffic-light cycles) than adopting the safety-distance criteria of systematically approaching the legal distance limit marked by the specific situation (here, the red light cyclically requiring "stop"). Level 2, the spring analogy, fosters a different yet complementary assumption: adopting a uniform speed facing stop-and-go traffic requires rethinking distance. Safety distance always must be preserved, nearly as a constant, but in close connection with a new concept: the anti-jam distance. The only way to adopt a uniform speed following a wavering car is to change the CF strategy altogether. And if Level 1 proposes uniform speed as correct, Level 2 presents the other side of the coin: for this uniform speed to be kept, it should be equal to the average speed of the leader, so the anti-jam distance is mobile, variable and must expand and retract to maintain drivers' inertia. Level 3, the paradox of speed, focuses more explicitly on the effect of changing speeds on the whole platoon of followers. Cars on the left lane continuously accelerate and decelerate (due to a repetitive set of gantries changing speed limits, from 20 to 40 km/h); cars on the right lane adopt a uniform speed (25 km/h). Even though the neat average speed is higher in the left lane, to accelerate and decelerate systematically is inefficient: the learner may observe that cars in the left lane move away first, whereas cars in the right lane reach them little by little. Congested groups emerge continuously among the followers in the left lane (as in the Nagoya experiment); cars follow smoothly behind the learner in the right lane.

Module C: Evaluation (Level 4). The evaluation module adopts the same viewpoint before and after learning with the WDC: participants follow a leader that stops-and-goes, with no aids available. Five main groups of variables are measured: participant's mean and standard deviation of speed while following the leader, participant's mean and standard deviation of distance to the leader, participant's risk coefficient (time dangerously spent within the safety-distance area), average and standard deviation of the whole platoon of followers (road space occupied) and participant's fuel consumption during the task. The simulation calculates fuel consumption based on typical values for cars. It uses vehicle speed to compute fuel consumption at each moment. Overall fuel consumption is a successive summation of time intervals multiplied by the corresponding consumption. If the WDC is successful, measures should change from a DD pattern (higher speed dispersion, lower distance and distance dispersion, longer risk periods assumed, higher dispersion of platoon elongation and higher fuel consumption) to a DI pattern (lower speed dispersion, higher distance and distance dispersion, shorter or null risk periods, lower dispersion of platoon elongation and lower fuel consumption). Some other variables are of interest. For example, average speed should not differ significantly between DI and DD (an average speed lower than the leader's, under DI, may indicate a poor understanding of the appropriate CF distance).

D. Level 1: The Traffic-Light Analogy

There are four standard driving modes: accelerating, cruising, decelerating and idling. The transition modes (accelerate, decelerate) pollute more than the stable ones (cruise, idle). Low speeds pollute more than moderate speeds [47]. It makes no sense to accelerate a vehicle and reach a certain speed knowing that, given the traffic conditions, that speed will only force us to brake and stop. However, millions of drivers repeat this behavior many times each day. When facing dense traffic at peak hours and finding jammed cars ahead, drivers accelerate to reach safety distance, then stop, and join the cycle, contributing to the problem, not the solution.

Level 1 constructs a situation where two alternative strategies are easy to compare: two lanes, 20 vehicles per lane, and several gantries ahead, holding traffic lights. The learner drives the first car in the right lane. All cars in the left lane are virtual DD robots programmed to accelerate then stop, keeping safety distance (never passing the traffic light in red). All cars following the participant in the right lane are also DD robots. Traffic lights display a timer. Participants are invited to see that a traffic light is first green, for 2 s (1, 0), only to turn yellow (from 4 to 0 s), and red (14 s, regressing to 0), finally displaying a stable green. There is no way for drivers to pass the traffic light in green even with hard acceleration, so what to do? What is a reasonable approach to that situation? Level 1 focuses on two goals, addressed to participants at the beginning of the lesson: 1. Without ever jumping a red light, find out what constant speed allows you to cross the traffic lights just as they go green. 2. Observe the situation as a whole, compare and think: which platoon spends and pollutes less? Participants are invited to click on the traffic-light button onscreen, so that a traffic light is displayed above each car. Then a comparison [48], [49] between traffic lights and leading cars is highlighted: traffic lights turn green (cars ahead move), then yellow (cars slow down), then red (cars stop). DD-bots on the left lane surrender to the traffic-light invitation: they just imitate the traffic-light cycle. Thus these cars cyclically stop-and-go, transmitting, in turn, these traffic-light variations to the cars that follow them. Participants on the right lane are invited to adopt an alternative strategy, guessing the speed they should adopt to reach the traffic lights exactly when they go green. The consequence: 19 DD-bot followers displaying a green traffic light while following the participant at a constant speed (Appendix II).

III. THE STUDY

This study complements the presentation of the WDC simulation and learning environment. It investigates the WDC impact on three variables: driving behaviors in the simulation, transfer of the driving behaviors to other scenarios within the simulation, and learners' attitudes towards and experiences with the learning environment.

A. Goals of the Study

Drivers worldwide learn DD in driving schools and are expected to apply it in the pretest. We expect that experiences with the simulator at Level 1 will introduce changes in participants' perception of efficient CF strategies, resulting in their adopting DI strategies in the posttest. Previous studies described how DD and DI differ and the benefits of DI driving [31]. Overall, the following hypotheses can be made about the impact of Level 1:

Hypothesis 1 (H1): We do not expect pretest/posttest differences for average speed. Hypothesis 2 (H2): The posttest should yield a significantly lower speed dispersion, H3: a greater average distance to the leading car, H4: greater distance variability to the leading car, H5: lower risk periods (i.e., the time the follower remains closer to the leader than safety distance requests), H6: lower fuel consumption, H7: lower average platoon elongation, and H8: a lower dispersion of the platoon elongation.

No hypotheses about people's perception and experiences with the simulation and tutorial are presented, because of the exploratory nature of this part of the study.

B. Method

1) **Participants**

Participants were students and workers from a Spanish university campus, and people related to them. They participated voluntarily, and were recruited through emails, advertisements and direct approach. The study involved 42 people, 92% working or studying at the university; of these, 26 were women and 16 were men. Their mean age was 29 years, SD = 13. Thirty-three had a driving license. With regard to driving experience, 20 people had been driving for less than 5 y, five between 6 and 15 y, nine for more than 15 y, and nine were in the process of obtaining their license at the time of the study (drivers in training). Planned comparisons between drivers and drivers in training showed no significant differences in initial driving behaviors (see section C). As for driving distances, 26 participant drivers drove less than 10,000 km per year, four drove between 10,000 and 20,000 km, and one drove more than 20,000 km per year. Urban driving characterized 60% of the cases, followed by motorway driving, then driving on rural roads.

2) **Materials**

Instruments included sociodemographic and attitude questionnaires and the learning environment simulator and tutorials.

The sociodemographic questionnaire, delivered through Google Forms, included items regarding name, age, gender, possession of a driving license, driving experience, annual mileage and habitual driving environments.

Attitude questionnaires examined participants' experiences with both the tutorials and the activity with the simulator (Levels 0 and 1). Tutorials were examined with four items using mixed directionalities with 7-level Likert-type scales regarding the tutorial's agreeableness (disliked to liked), interestingness (not interesting to interesting), duration (short to long), and level of difficulty (difficult to easy). Participants were also offered an opportunity to see the tutorial again (1 = yes; 2 = no). Simulator practice was assessed by asking participants about their liking (1 = I liked it; 7 = I didn't like it), its usefulness (1 = it is not useful; 7 = it is useful), real-life applicability (1 = not applicable; 7 = applicable), and timing (1 = short; 7 = long). They were offered to repeat practice (1 = yes; 2 = no) and use of the WDC simulator (Levels 0, 1, and evaluation).

The learning materials used are the following. In Level 0, participants followed a car travelling at a constant speed of 9 m/s (30.6 km/h). In the evaluation, participants followed a car travelling with stop-and-go cycles of a sinusoidal function built at a median speed of 9 m/s (30.6 km/h). Tutorials included Levels 0 and 1, described in the theoretical framework (see also Appendices I and II).

During the activities, driving behaviors were logged, parsed and analyzed for the following variables: participant speed (average and dispersion), participant distance to leader (average and dispersion), participant risk (time spent holding too short a distance to leader, i.e., shorter than safety distance requires), fuel consumption and variations concerning the length of a platoon of 10 DD-bot followers (average length and dispersion of the 10 DD-bot followers).

3) **Design and procedure**

The study followed a pretest-intervention-posttest single-group design. The intervention lasted approximately 30 min. It was conducted in a university laboratory. Each participant was seated before a Windows computer with a 24-in screen. The experiment included the following steps: (1) Participants filled out a consent form; (2) The experimenter explained that the study had four phases (Module 0, evaluation, Module 1, evaluation), and that practice on Levels 0 and 1 was preceded by a tutorial on how the simulator works; (3) Participants completed the demographic questionnaire, (4) viewed the first tutorial (Level 0: know the controls), and answered the corresponding tutorial questionnaire, then practiced on the simulator (Level 0), and answered the simulator questionnaire; (5) Participants then entered the evaluation level on the simulator, following this basic instruction: "Without putting your safety at risk, follow this vehicle that stops-and-goes. You will not have any visual aids"; (6) Participants then viewed the second tutorial (Level 1: the traffic-light analogy), answered the tutorial questionnaire, entered the simulator (Level 1) and answered the simulator questionnaire; (7) Participants entered the evaluation level on the simulator again and received this basic instruction: "Without putting your safety at risk, follow this vehicle that stops-and-goes, in the way you consider efficient. You will not have any visual aids". Finally, after finishing the posttest, participants were appropriately debriefed.

4) **Data analysis**

Questionnaire responses were flipped in the same direction and then analyzed for the whole group using descriptive and inferential statistics to compare pretest and posttest results. The simulator included a data-mining component that collected and computed the driving behaviors. These were then analyzed for the whole group and compared for the pretest and the posttest. The analysis was conducted with the statistical package IBM-SPSS for Windows, version 22.0.

C. Results

To explore the impact of previous driving experience, drivers and drivers in training were compared using t-tests. No significant differences emerged between them for the variables evaluating tutorials and practice on the simulator in Levels 0 and 1 (Appendix III). Differences between drivers and drivers in training were also sought for variables concerning practice in the pretests and posttests. Here also, no significant differences emerged (Appendix IV). The absence of differences between both groups is probably due to the simplicity of the CF scenario proposed, but it also points to a generalization of peer-following adaptations observed in pedestrian behavior [50]. Because of this lack of difference between the two groups, their results have been combined.

1) **Descriptive Analysis**

DI driving involves a number of patterns: smaller changes in speed, greater distances from the leader with greater fluctuations and a general decrease in risky behaviors. Such changes would also result in lower fuel consumption. To test our hypotheses regarding type of driving, we compare these variables for the pretest and posttest driving sessions (Table 2).

TABLE II

PERFORMANCE MEASURES FOR PRETEST AND POSTTEST SIMULATOR DRIVING

	Pretest		Posttest	
Variables	*M*	*SD*	*M*	*SD*
Average speed (m/s)[1]	7.93	.59	7.35	1.28
Speed dispersion (m/s)	4.53	1.80	2.75	1.81
Average distance to the leader (m)	74.66	55.33	124.50	93.02
Distance dispersion (m)	25.75	11.87	39.05	30.40
Risk (s too close car-following)	2.62	5.57	.12	.50
Fuel consumption (l)	15.11	5.39	10.53	4.95
Average platoon elongation (m)	125.72	5.33	122.62	8.86
Dispersion of platoon elongation (m)	33.55	14.00	19.79	13.60

[1] Units are simulated, designed to relate to real-world experiences, keeping the proportions of car size, distance, and so forth. Risk, in s: too close, disregarding safety distance

The participants showed quite consistent changes before and after following Level 1 in the WDC. Drivers moderated speed fluctuations with an effect on fuel consumption. To maintain inertia, drivers adopted larger CF distances to the leader. Participants learned to play with distance to maintain inertia regardless of the leader's speed variations. Correspondingly, the dispersion of the 10 DD-bot car followers (following a steadier participant) was also reduced in the posttest.

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Table 3 presents descriptive statistics for the questionnaire responses given after participants watched the tutorials and practiced on the simulator.

TABLE III
PARTICIPANT'S EVALUATION OF TUTORIALS 0 AND 1, AND PRACTICE ON LEVELS 0 AND 1

	Tutorial 0		Tutorial1	
Item	*M*	*SD*	*M*	*SD*
In general, did you liked the tutorial?	5.19	1.91	5.61	1.87
Was the tutorial interesting?	5.17	1.88	6.07	1.65
Was it short or long?	2.59	1.30	3.05	1.18
Was the tutorial easy to follow?	5.44	1.50	6.15	1.35
	Level 0		Level 1	
	M	*SD*	*M*	*SD*
Did you like the experience on this level?	5.22	1.75	5.78	1.56
Was this practice useful?	5.24	1.68	6.00	1.41
Do you think that is applicable to real life?	5.27	1.63	5.90	1.34
Was there enough time for practice?	3.95	1.32	3.42	1.18

When asked if they wanted to see the tutorials or practice on the simulator again, 95.1% (Tutorial 0), 97.6% (Tutorial 1) and 100% of participants (Simulators 0 and 1) declined.

Participants generally liked both tutorials and found them relatively interesting, of medium duration, and experienced a medium level of difficulty in following them. The experiences with the driving course were also generally liked, and perceived as useful and applicable; they reported sufficient time to practice.

2) Inferential Analysis

Comparisons of means of performance measures was conducted using Student *t* tests. A higher average speed was observed in the pretest compared with the posttest, $t\ (41) = 2.93$, $p < .01$, Cohen's $d = .580$. Speed dispersion was also greater in the pretest, $t\ (41) = 7.10$, $p < .005$, $d = .986$. Average distance to the leader was greater in the posttest, $t\ (41) = -5.06$, $p < .005$, $d = .0.651$, as was distance variability, $t\ (41) = -3.22$, $p < .003$, $d = .576$. In line with these results, a higher risk index was observed in the pretest, $t\ (41) = 3.05$, $p < 0.005$, $d = .632$. Greater fuel consumption was also observed in the pretest, $t\ (41) = 5.57$, $p < .005$, $d = .886$. Finally, average elongation of the platoon of followers (10 virtual DD-bots) was higher in the pretest, $t\ (41) = 2.05$, $p < .05$, $d = .424$, and dispersion of the platoon elongation was higher in the pretest, $t\ (41) = 7.19$, $p < .005$, $d = .997$ (Table 2). Most of effect the sizes obtained have medium-large sizes according to Cohen's [51] convention.

Comparisons of means of participants' evaluations of tutorials and practice on simulator was conducted using Student *t* tests. To summarize the results, Tutorials 0 and 1 were functional, helping participants build adequate expectations for practice on the WDC. Differences between the pretest and posttest confirm that Level 1 was successful in changing CF strategies from DD to DI.

Regarding liking of the tutorial, no significant differences were observed between the evaluations conducted on Tutorial 0 versus Tutorial 1, $t\ (40) =1.47$, $p = .15$ (Table 3). However, Tutorial 1 was seen as significantly more interesting, $t\ (40) = -2.49$, $p < .05$, Cohen's $d = .510$. Although Tutorial 0 (135 s) was actually longer than Tutorial 1 (124 s), it was judged to be shorter, $t\ (40) = -2.46$, $p < .05$, $d = .373$. Finally, Tutorial 1 was perceived as easier to follow than Tutorial 0, $t\ (40) = -3.46$, $p < .001$, $d = .495$. Participants did not show differences in their wish to see again any tutorial in particular (p = n.s.).

Participants liked practicing with Level 1 more than with Level 0, $t\ (40) = 2.25$, $p < .05$, $d = .338$. Practicing Level 1 was considered more useful, $t\ (40) = -2.82$, $p < .01$, $d = .486$, and more applicable to real life than Level 0, $t\ (40) = -2.31$, $p < .05$, $d = .425$. Finally, participants judged (correctly) the time available in Level 1 (150 s) to be shorter than in Level 0 (180 s), $t\ (40) = 2.95$, $p < .005$, $d = .427$. Participants did not show differences in their wish to repeat practice of any level in particular (p = n.s., Table 3).

D. Discussion

Participants showed changes in their driving behaviors after driving in the WaveDriving simulation. Compared with their earlier driving behaviors, their later speeds decreased and fluctuated less, reducing their fuel consumption. They adopted larger CF distances, and increasingly changed distance from the car in front of them to reduce changes in inertia. Finally, the platoon of the participant's car and the robot cars shortened and its size fluctuated less.

Results confirm that the traffic-light analogy is powerful enough to create knowledge transfer: from passing changing traffic lights to following a leader that systematically stops-and-goes. Drivers understood and accepted that following a car that accelerates (green), decelerates (yellow), and then stops (red) is not the only or the most efficient alternative. As a consequence, performance changed significantly from pretest to posttest. Drivers' speed dispersion decreased, becoming more uniform (H2), and, as a consequence, the average distance (H3) and distance variability (H4) increased in the posttest. Following a wavering leader at a uniform speed causes less speed variability but requires more distance (than safety distance) to adapt to the leader's swinging pattern. As a consequence, there is less risk exposure (H5: more distance is kept because safety distance is only a segment in the extension-retraction CF following sequence) and less fuel consumption (H6: more uniform speed maintained). Finally, the platoon of DD-bot followers does not expand (H7), and it moves (H8) as much as when participants adopt the DI technique. Together, these behavior changes indicate a shift from DD to DI driving, supporting our main hypothesis. The DI technique promotes more efficient, but also safer, traffic flows concerning the drivers following behind [52].

It seems that the design of the WDC simulation and tutorials produced an important change in people's simulated driving behaviors in the rather short time of less than 1 h. The results of our study reinforce the cumulated design principles underlying the WDC. These principles include signaling, redundancy, temporal contiguity, and modality or embodiment, and were studied previously [35], [46], see Appendix I eight-row.

However, the particular combination of principles is new, and is specific to the driving learning school environment.

The only unconfirmed hypothesis refers to average speed (H1). A proficient DI method involves maintaining practically the same average speed as the leader, but this result was not confirmed: average speed was significantly lower in the posttest. This result, however, is in line with our expectations: Level 1 focuses on the importance of adopting a uniform speed to be more efficient, and drivers understood the idea and transferred it to the evaluation task. Only Level 2 (the spring analogy) teaches about decomposing CF distance into two distances: safety distance + anti-jam distance. Future studies requiring drivers to complete the first two WDC levels should confirm this expectation.

Participants' experiences with the driving course were positive: they generally liked the experience and perceived it as useful and applicable to real settings. They believed that they had enough time to practice. They preferred practice with Level 1 to that with Level 0, and considered Level 1 more useful and applicable to real life.

With respect to the tutorials, generally participants liked both and found them relatively interesting and of medium duration, and experienced a medium level of difficulty in following them, with no significant differences between the different tutorials.

Tutorial 1, which introduced the traffic-light analogy and supported learning how to assume the very same goal (i.e., passing traffic lights in green) more efficiently (holding uniform speed, avoiding stop-and-go cycles and their undesired consequences), was seen as more interesting, and longer, but easier to follow than Tutorial 0, which merely explained how the different visual and operative resources work on the WDC simulator. Also, Level 1, the practical session after Tutorial 1, was better liked and found to be more useful and applicable than Level 0, the practical session after Tutorial 0. Participants may have had some fun changing visual perspectives and positions, changing day to night, and the like, but Tutorial 0 and Level 0 only attempted to explain how the simulator works. Tutorial 1, however, invited participants to learn and discover something new that could be relevant to their everyday lives. Participants distinguished and enjoyed the more practical and relevant side of the WDC.

Some limitations of this work must now be considered for future studies, for example, having a somewhat larger sample, with drivers of older average age. Also incorporating a follow-up test to check if and to what extent the acquisition of the DI technique is maintained. It would also be pertinent to include a control group to determine the effect of the set (tutorial and practice in the simulator) versus mere practice in the simulator on learning. Although recent studies have analyzed this aspect globally [53], the incremental contribution of each of the modules remains to be determined. Finally, it would be important to introduce some diversification both in visual parameters (eg, type of scenarios driven) and in performance parameters (eg, average speed following the leader), thus achieving a greater generalization of the results.

IV. CONCLUSION

In this article, we propose that it is possible to improve traffic flows and reduce congestion if we change our CF strategies. So far, we have been adopting the DD strategy as if it were the only possible strategy, but mathematics, physics and studies conducted to date indicate that DI is a more functional and efficient CF alternative. Note that these are two opposing strategies for two key parameters: speed variability and CF distance.

The present study presents a pretest/posttest comparison of the first level of the WDC, the traffic-light analogy, a conceptual device capable of promoting the correct transfer learning of the first key parameter: speed variability. Learning the most efficient way forward when passing traffic lights (the source analog) should promote some transfer to the CF situation (the target analog). Besides this main goal, the present study compares attitudes towards the WDC introductory tutorial/practice (Level 0: how the simulator works) with the substantial tutorial/practice (Level 1: rethinking passing traffic lights). Our basic assumption is that Tutorial 0 simply explains how the "machine" works, whereas Tutorial 1 addresses significant and practical issues relevant to driving activity. Results indicate that Tutorial 1 was perceived as significantly shorter, easier and more interesting than Tutorial 0. Results for practice (Level 0 vs. Level 1) are in line with results observed with theory (Tutorial 0 vs. Tutorial 1). Level 1 was better liked, and perceived as shorter, more useful and applicable than Level 0.

Overall, being exposed to Tutorial 1 and then practicing Level 1 on the WDC yielded the expected learning transfer to performance. The posttest yielded lower speed dispersion, greater average distance and distance variability, and a lower risk index and fuel consumption than the prettest. Also, the platoon of DD-bot followers occupied less road space on the posttest. However, average speed differed: it was significantly lower on the posttest. This result indicates that CF distance during the posttest was greater than needed. Level 1 promoted an adequate learning transfer to maintaining uniform speed (lower speed variability). But this level alone does not generate the expected transfer in terms of average CF speed, which should not differ from pretest to posttest.

Most driving simulators (also the gaming industry) focus on realism and perceptual-motor skills (i.e., basic psychological processes of attending, sensing and perceiving, then reacting while driving). Rather than for testing or gaming, the WDC presents a unique application of driving simulators for learning how different individual actions within the line have broader consequences for traffic flows. The WDC invites the learner to transcend their personal view and to elaborate larger collective implications. The WDC recurs to unusual tools and perspectives: participants drive through unreachable points of view (e.g., bird's-eye views from different angles and perspectives concerning the whole platoon), using non-existent tools (e.g., traffic lights mounted above cars) and higher-level psychological processes (e.g., integrating the coming information with previous knowledge into new mental models to adopt specific behaviors). Hence, the WDC enlarges the family of common driving simulators, making alternative

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behaviors possible and contributing to reaching more sustainable, uninterrupted traffic flows.

APPENDIX

Appendix I. Design Template. Tutorial 0. Scenes 1-24
https://cutt.ly/kgzsebF

Appendix II. Some key parts concerning Tutorial 1: The Traffic Light Analogy

Fig. 3. The cars on the left lane accelerate because these drivers think they'll reach the traffic lights in green . . . but they do not arrive on time and they have to stop. So running a lot doesn't help me achieve my goal. (voiced in 12 s).

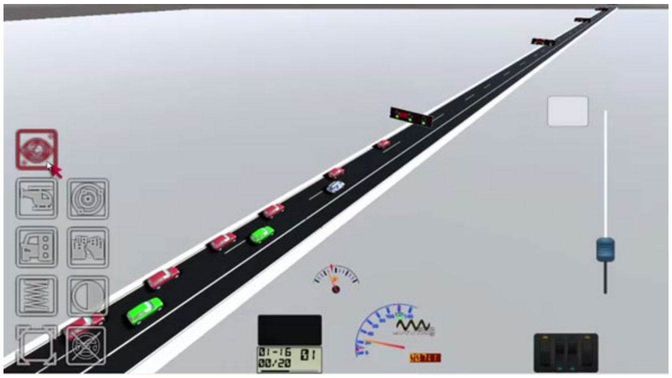

Fig. 4. With the multi-camera, I can control the speed of arrival from other perspectives. (voiced in 13 s).

Fig. 5. Let's activate the "traffic lights" option and see what happens . . . (voiced in 7 s)

Fig. 6. Because the red vehicle has to brake at the traffic light, it is a red light for the vehicles that follow it . . . The first driver determines what happens to the entire platoon. (voiced in 11 s).

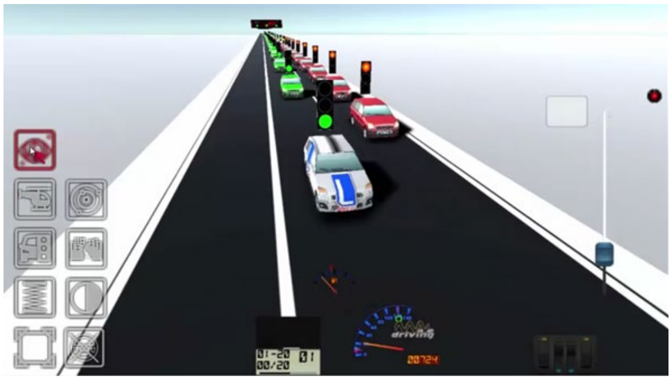

Fig. 7. What we do ahead affects far back. A single driver can create very different traffic scenarios. (voiced in 9 s).

Appendix III. Tutorial and Practice Evaluation by Drivers and Drivers in Training

TABLE IV
MEDIAN DIFFERENCES BETWEEN DRIVERS (D; N = 32) AND DRIVERS IN TRAINING (DI; N = 9) AFTER MANN-WHITNEY U TESTS

	Tutorial 0			Tutorial 1		
Variables on T	D	DT	U	D	DT	U
Did you like the T?	6.0	3.0	114.5	6.5	6.0	125.5
Was the T interesting?	6.0	6.0	137.5	7.0	7.0	144.0
Was it short or long?	2.0	3.0	103.0	3.0	3.0	126.0
Was it easy to follow?	6.0	6.0	85.0	6.0	7.0	105.0

All comparisons were non-significant, p >.05, two-tailed *M-W U*. T = Tutorial

TABLE V
MEDIAN DIFFERENCES BETWEEN DRIVERS (D; N = 32) AND DRIVERS IN TRAINING (DI; N = 9) AFTER MANN-WHITNEY U TESTS

	Level 0			Level 1		
Practice on WDC	D	DT	U	D	DT	U
Did you like the level?	5.5	5.0	133.0	6.0	6.0	120.5
Was practice useful?	5.5	6.0	137.0	6.5	6.0	140.5
Applicable to real life?	6.0	5.0	119.0	7.0	6.0	110.0
Enough practice time?	4.0	4.0	105.5	4.0	4.0	107.5

All comparisons were non-significant, p >.05, two-tailed *M-W U*.

TABLE VI

MEAN DIFFERENCES BETWEEN DRIVERS (D; N = 32) AND DRIVERS IN TRAINING (DI; N = 9) AFTER MANN-WHITNEY U TESTS

	Pretest			Posttest		
Practice on WDC	D	DT	U	D	DT	U
Average speed (m/s)	7.97	7.78	123.0	7.27	7.64	112.5
Speed dispersion (m/s)	4.42	4.93	125.0	2.80	2.57	145.0
Average D to L (m)	78.4	61.1	120.0	129.6	105.9	131.0
D dispersion (m)	25.9	25.2	140.0	39.72	36.57	138.0
Risk	1.91	5.22	117.5	.15	.00	135.0
Fuel consumption (l)	14.7	16.7	115.0	10.9	9.08	138.0
Average PE (m)	126.2	124.0	110.5	121.8	125.7	97.0
Dispersion PE (m)	32.7	36.6	122.0	18.2	14.7	145.0

All comparisons were non-significant, p >.05, two-tailed *M-W U*. D = Distance, L = Leader, PE = Platoon Elongation

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