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When Fairness Backfires: A Chronoceptive Design Approach to Intelligent Transportation Systems

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Highlights

What are the main findings?

- Chronoceptive ramp metering designs significantly improve user acceptance and perceived fairness compared with standard ramp metering, despite providing the same underlying traffic-control benefits.
- Shorter signal cycles, countdown timers, and three-phase signals reduce perceived waiting times and increase preference for ramp metering, with the 45 s cycle design achieving the highest acceptance rates.

What are the implications of the main findings?

- Intelligent transportation systems should be designed not only for objective efficiency but also for users' subjective perception of time, as perceived benefits strongly influence acceptance and compliance.
- Chronoceptive design offers a practical human-centred framework for reducing public resistance to traffic-control measures and improving the real-world effectiveness of ITS deployment.

Abstract

Intelligent transportation systems (ITSs) and traffic control promise substantial efficiency and safety improvements but frequently face public resistance and driver compliance issues. Many drivers perceive such control measures as unfair or unnecessary, despite measurable system-wide benefits. This study investigates how chronoception—the subjective perception of time—affects user acceptance of ITS control strategies and how signal design can be adapted to reduce perceived delays. We introduce a chronoceptive design framework that integrates insights from cognitive psychology into traffic-control design. Using ramp metering as a case study, we conduct virtual experience stated preference experiments with 101 participants, comparing standard and chronoceptive ramp metering designs featuring shorter signal cycles, three-phase lights, and countdown timers. The results show that chronoceptive signal designs significantly improve user acceptance (by up to 12%) and reduce perceived waiting times, despite identical or slightly longer objective travel times. These findings reveal a systematic bias between factual and perceived benefits and highlight the potential of chronoceptive design to enhance compliance and fairness perception. This study contributes a new human-centred design paradigm for traffic control that aligns objective performance with user perception and outlines how chronoception and perceived fairness can be operationalised in traffic control. The source code and survey data can be found open-source on GitHub.

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1. Introduction

Roads liberate people to go wherever they want whenever they want. Once emblematic of personal freedom and progress attracting ever-growing demand, those roads have increasingly become symbols of frustration in the daily commute [1]. Traffic jams occur particularly during holiday peaks and daily commuting periods. Examples of this significant issue can be found worldwide, leading to externalities such as wasted time, increased fuel consumption, and economic damage on a global scale. As a result, the costly impact of congestion causes damage to quality of life, health, and economic performance [2,3].

Intelligent transportation systems (ITSs) can help to manage traffic, significantly reduce congestion, and improve traffic flow patterns on highways and urban transportation networks [4]. Ramp metering improves the flow on highways by limiting the inflow of vehicles via on-ramps under congested regimes [5]. Variable-speed-limit control improves the flow on highways by reducing and increasing traffic speeds dynamically to account for anticipated congested regimes [6] and to harmonise speed in the spirit of the slower-is-faster principle [7]. Signalised intersection management in urban, arterial road networks enhances road safety and harmonises flows across cities [8].

Perceived fairness in the realisation of public acceptance and compliance is crucial to the success of ITSs [9,10]. Despite their proven benefits in reducing travel times and crash rates [11], these measures face significant public opposition, as they restrict individual freedom and are perceived as unfair [1,12–15]. This public opposition impedes successful implementation and functioning in real-world contexts for two reasons: (i) public resistance inhibits decision-making outcomes and policy implementation in favour of these control strategies, and (ii) compliance issues due to low user acceptance and adherence sabotage the functioning of these control strategies in practice [16,17]. This manifests the problem of conflicting interests between selfish individuals and the system perspective (societal goals).

Although waiting at ramps (ramp metering) or driving at slightly slower speeds (variable speed limits) can improve travel times, the public often remains highly dissatisfied with these measures [13,18,19]. This contradiction can be explained by differentiating perceived from factual benefits for road users. Studies have shown that human travellers fail to (objectively) perceive the benefits due to cognitive biases that interfere with their time perception (chronoception) processes [13,20,21]. What is considered optimal based on quantified efficiency objectives might not be perceived as optimal by the users, invalidating common traffic management strategies.

Chronoception—the perception of time—is a construction rather than a mechanism in the brain [22] and is affected by various cognitive biases, such as chronostasis [23], time dilation [24], temporal compression [25], the telescoping effect [26], and Vierordt's law [27]. In the context of travel time perception, studies indicate different chronoception for waiting times at on-ramps or signalised intersections and delayed moving in congested regimes [28,29], which in turn affects user acceptance and compliance with signals [1,20,30].

Despite this growing body of work, an important research gap remains. Existing traffic-control research primarily evaluates ITS with respect to objective performance indicators such as flow, speed, delay, and total travel time. Conversely, research on travel-time perception and user acceptance shows that perceived waiting, uncertainty, and loss of autonomy strongly affect subjective evaluations of traffic-control measures. However, these two perspectives are rarely integrated into a concrete design framework that modifies traffic-control interfaces in order to align objective system benefits with users' perceived benefits. In particular, limited empirical evidence exists on whether small, operationally feasible signal-design changes (i.e., shorter cycle times, three-headed signals, or countdown timers), can improve perceived benefits and acceptance under otherwise comparable traffic conditions.

If perceived travel and waiting times are systematically biased, then fairness evaluations and user acceptance based on these perceptions must also be distorted. Hence, control policies that are beneficial in objective terms can be rejected due to subjective misperception [31]. This work sets out to extend the preliminary understanding of chronoception in the context of traffic-control measures by analysing subjective chronoception as a hidden mediator of perceived fairness in traffic control. More precisely, this work develops a methodology for chronoceptive traffic-control designs to enhance user acceptance by addressing psychological stress reactions related to waiting. The proposed approach aims to minimise perceived travel time by combining recent insights from the literature on perceived travel time, travel time variability, waiting time, time in motion, and number of stops.

Accordingly, this study seeks to answer the following research question: *How can ITSs be designed to align objective efficiency improvements with users' subjective perceptions of fairness and travel time?* To address this question, we analyse how specific ramp metering signal configurations influence perceived waiting times and user acceptance and evaluate whether chronoceptive design principles can mitigate fairness-related resistance to traffic control. We conduct virtual experience stated preference experiments followed by a questionnaire survey to identify chronoception-optimal controller designs that users prefer over uncontrolled scenarios. The results of the experiments from 101 participants indicate that dedicated, chronoceptive design changes can significantly increase acceptance of ITS control strategies and highlight the potential of chronoceptive design for traffic control.

This study establishes a unique link between empirical studies of chronoception and traffic engineering and control. It highlights how human-centred design in the context of chronoception (and thus perceived fairness) can be operationalised in ITSs and traffic control. Doing so, this work makes four contributions to the literature:

- **Conceptual contribution:** It introduces the concept of chronoceptive design—a human-centred approach to ITSs that accounts for biased time perception as a hidden mediator of fairness and user acceptance.
- **Methodological contribution:** It develops a replicable virtual experience stated preference methodology that bridges cognitive psychology and transportation engineering for measuring perceived travel time.
- **Empirical contribution:** It provides experimental evidence that chronoception-informed traffic light designs (shorter cycles, three-phase signals, and countdown timers) can significantly increase acceptance of ramp metering without compromising system performance.
- **Practical contribution:** It reframes fairness in ITSs not only as an equitable distribution of objective travel times but as the alignment between perceived and factual benefits.

Together, these contributions establish chronoceptive design as a promising pathway toward publicly more accepted, fair, and psychologically attuned traffic-control systems.

The remainder of this work is organised as follows: Section 2 reviews the previous literature on time perception in general, travel time perception in particular, and public acceptance and compliance related to ITS systems. Section 3 develops the proposed chronoceptive traffic-control design approach and outlines the case study and the virtual experience stated preference experiments. Section 4 presents the results that are thereafter discussed in Section 5. The work concludes with a summary in Section 6.

2. Related Works

This section reviews related works to lay a foundation for the proposed chronoceptive design methodology. First, related works on time perception from the psychology literature are reviewed to highlight known cognitive biases and human factors to control for when designing experiments. Second, related works on travel time perception from the transportation literature are reviewed to pinpoint domain-specific aspects and to situate this work in the context of existing experiments. Third, ITSs, related public opposition, and user compliance issues are discussed to highlight and motivate the need for more dedicated, chronoceptive control designs that take human perception biases into account. Fourth, we discuss user acceptance and compliance beyond chronoception, highlighting factors such as the role of social communication, the social gradient of complaints, self-determination theory, internalisation and complaints. Finally, we summarize and identify the research gap that the present study addresses.

2.1. Time Perception

Chronoception refers to the psychological process of time perception and can significantly differ from objective, physical time [22]. Chronoception is observed to be affected by emotional states [32–34], age [35,36], familiarity with a situation [37], variation in stimuli [38], and perceived importance [39]. Well-known cognitive biases include scalar expectancy, magnitude coding, Vierordt's law (central tendency bias), telescoping effect, chronostasis, time dilation, emotional salience bias, and temporal compression. Scalar expectancy refers to the growing standard deviation of errors in perceived time with larger observed durations [38,40]. Magnitude coding relates the magnitudes of physical stimuli, such as brightness or loudness, to response rates and brain activity of sensory neurons, resulting in biases in chronoception [21]. Vierordt's law describes a bias towards the centre, where shorter durations are overestimated, and longer durations are underestimated [27]. The telescoping effect states that people perceive recent events as more distant, and past events as more recent than they actually are [26,41]. Chronostasis is a time illusion that makes us feel like time has briefly stopped [23]. Time dilation (also called the Kappa-effect) is an illusion where the time between a series of events seems longer or shorter than it really is, depending on how far apart the events are in space, sound, or touch [24,42]. The emotional salience bias describes the influence of emotions such as boredom, fear, and awe on time perception [32–34,43].

2.2. Travel Time Perception and Related Experiments

Perceptions of travelling are determined by physical distances, spatial geography, socio-economic factors, (walking) accessibility, and predominantly time [31]. A growing branch of the literature is concerned with the perception of travel time in road transportation and how this affects mode and route choice [44,45]. Regarding public transportation, trams [31], metros [46–48], and buses [49] have been investigated. Regarding individual transportation, prior works examined cycling [50], ride hailing [48,51], and driving [13,19,20,28–30,52–54].

A major finding of these works is that different types of time are perceived differently. Significant differences can be found for waiting times and in-vehicle times in the context of public transport, where waiting times are perceived longer and more negative. For driving, a discrepancy in the perception of time in motion (even in congested regimes) and that of waiting (at signalised intersections or ramp meters) could be identified [19,28], where longer waiting times were perceived over-proportionally longer and negative, despite decreasing overall travel time. Longer waiting times were observed to be correlated with higher violation rates of signals as well. Furthermore, not only travel times but also travel time reliability [55] and habitual effects [31] play a significant role in time perception, time valuation, and decision making.

Extensive research has been conducted on travel time perception and user acceptance, especially in the context of ramp metering [19,20] and signalised intersection management [28,30]. These studies found that waiting time is perceived as more onerous than freeway travel time (even in congested regimes as long as in motion) and indicate that perceived travel time better explains user preference and acceptance for traffic-control measures than actual travel time does. In particular, human drivers have little tolerance for longer waiting times. Additionally, drivers prefer to split their total waiting time across multiple stops rather than one, as they perceive this as a situation in which they are making more progress. In addition to that, a quadratic rather than linear relationship between perceived and actual travel time was identified. A possible explanation to these findings is that waiting and idleness are perceived longer than real time, as these cause psychological stress which accumulates during the waiting process. Anxiety and stress are natural reactions to the waiting process, due to the sense of waste and uncertainty when waiting to start again once the light turns green and not to miss out on the opportunity to finally drive again [56]. Another explanation is that of the delayed gratification bias, where humans fail to prefer a delayed but greater benefit over an immediate but smaller benefit [19,57]. As a result, previous works recommend the dedicated design of ITSs that minimises (subjective) total perceived travel time rather than (objective) total travel time, in order to improve satisfaction, to gain user acceptance, and to mitigate public opposition [20,28,30].

2.3. Intelligent Transportation Systems, Public Opposition and Compliance

ITS technologies in the form of signalised intersection management, ramp metering, and variable-speed-limit control are demonstrated in theory and practice to yield significant improvements in reducing congestion, delays and travel times. Despite the factual benefits of these technologies, two human factors impede their successful implementation: (i) significant public opposition that has formed against their implementation and (ii) user acceptance and compliance issues that lead to their sabotage.

In the context of variable-speed-limit control, [13] found significant public dissatisfaction and opposition in the case of St. Louis, Missouri. Across the United States, variable speed limits typically meet stiff resistance from highway users and the legal community during implementation [58]. The introduction of ramp metering caused public opposition in Miami [59], Detroit [16], and Portland [60]; in the twin cities Minneapolis and St. Paul, support for ramp metering declined rapidly after its introduction, to a point where it was deactivated following public demand to reassess its impact on commuters [61]. This public opposition delays and impedes successful implementation through policy processes.

Besides public opposition, similar issues with user acceptance and compliance can be found. Variable-speed-limit control only works if a critical mass of users actually complies. An investigation of the I-494 Work Zone in Minnesota (USA) observed compliance rates ranging between 20% and 60% [62]. A study on Istanbul's freeways (Turkey) identified compliance rates between 50% and 75% [63]. Research on the Whitemud Drive in Edmonton (Canada) highlights the importance of driver compliance for substantial benefits [64]. Important measures to increase compliance include stronger law enforcement to create driver awareness and public communication to build trust in the benefits of variable speed limits [17,62,64]. In the context of ramp metering, compliance rates of 50–90% [17,65–67] have been identified, where queue-jumping impedes the proper functioning of ramp metering [67]. Important measures to increase compliance include the usage of three-headed signals (red, yellow, and green) instead of two-headed signals (red and green), warning signs in advance to the ramp metering signals, and stronger law enforcement [17,66,67]. In the context of signalised intersection management, red-light running not only creates disturbances in traffic flows but more severely causes safety incidents and increases the risk of traffic accidents. Important causes of this violation and non-compliant behaviour include perceived, unreasonably long waiting times, risk misperception, impatience and time pressure (urgency) [68–71]. Measures to overcome these causes include law enforcement but interestingly also traffic light countdown timers, as drivers that know exactly how much time remains before the light changes are observed to decrease red-light running and abrupt stops and to improve start-up behaviour due to anticipation [72–74].

Long et al. [13] specifically studied user rejection and dissatisfaction during deployment of new ITS technologies from a change management and socio-technical system perspective. As benefits are often based more on perception than facts, perception can adversely bias implementation. As a consequence, systematic and stakeholder-differentiated communication campaigns are highly recommended during implementation to achieve "buy-in" of all users and improve acceptance.

2.4. User Acceptance and Compliance Beyond Chronoception—Benefactors over Beneficiaries

While this study primarily explored user acceptance through the lens of chronoception, it is essential to recognise that acceptance of ITSs does not depend solely on perceived efficiency or time gains on average but also on the distribution of these perceived benefits across users. Ramp metering, for instance, inevitably produces both beneficiaries—drivers who experience smoother highway flow—and benefactors—those who incur additional waiting time to enable that improvement. Even when the system's total performance increases, unequal benefit distribution can trigger perceptions of unfairness that outweigh the collective gain, highlighting the importance of fairness in this context [9,10].

Social and psychological research suggests that disadvantaged users tend to perceive losses more acutely and express dissatisfaction more readily than beneficiaries express satisfaction. In transportation contexts, this asymmetry amplifies public opposition: complaints about perceived disadvantage are vocal and visible, while silent satisfaction among those who benefit remains largely invisible in the political discourse. Consequently, decision makers often face disproportionate resistance to control measures that are objectively beneficial at the system level. This is frequently described in the previous sociological (the first two effects) and psychological (the last two effects) literature:

- **Role of Social Communication:** Complaining serves not only as an emotional outlet but also as a communicative strategy within social hierarchies. Individuals with less power or status are more likely to voice complaints as a way to signal distress, seek validation, or mobilise social support when direct influence is limited. Complaints thus function as a means of negotiating attention, empathy, or corrective action from others. In contrast, those in advantaged positions may refrain from complaining to maintain social harmony, protect authority, or avoid perceptions of vulnerability. These dynamics highlight the dual social role of complaints—as both expressions of need and instruments of relational regulation [75–77].
- **Social Gradient of Complaints:** The social gradient of complaints refers to the systematic increase in psychological and somatic complaints as social status decreases. Lower-status individuals tend to report more stress, pain, and mental distress due to higher cumulative stress, fewer coping resources, and limited social support. Conversely, those in higher positions may under-report complaints to preserve social desirability and control. This gradient has been observed across age groups and contexts, including health, education, and work settings [78,79].

- **Self-Determination Theory:** Drawing on self-determination theory, complaints can be understood as behavioural expressions of unmet basic psychological needs—autonomy, competence, and relatedness. Individuals from lower social strata often experience environments that restrict personal control, limit perceived competence, and weaken social belonging. Such need deprivation increases frustration and emotional strain, which may manifest through verbal complaints as an attempt to restore agency or seek recognition. In contrast, socially advantaged individuals typically operate within more supportive contexts that nurture these needs, thus reducing the motivational pressure to externalise dissatisfaction. SDT therefore provides a useful framework to interpret complaint behaviours as indicators of psychosocial need frustration within unequal social structures [80–82].
- **Internalisation and Complaints:** The process of internalisation further differentiates how individuals interpret and respond to disadvantage. Those who attribute their lower status to personal failure are more likely to internalise negative outcomes, resulting in chronic frustration and feelings of inadequacy that heighten the tendency to complain. Their complaints thus reflect internal conflicts between perceived self-responsibility and structural constraints. Conversely, higher-status individuals often internalise positive outcomes as self-earned and may downplay or withhold complaints to maintain coherence with positive self-concept and social image. This asymmetry in internalisation patterns contributes to the social gradient of complaints, linking subjective status perceptions with differential expressions of distress and voice in social systems [83,84].

These four effects and the uneven distribution of benefits create a biased view in political discussions against the implementation of traffic-control strategies [13,16,58–61]. These dynamics imply that perceived fairness in ITS design cannot be achieved through efficiency alone. Chronoceptive design contributes by mitigating one dimension of this imbalance—subjective time distortion—but fairness must also be assessed in distributional terms. Future ITS development should therefore evaluate who gains and who loses, both in objective and perceived terms, and explore design or policy levers that compensate disadvantaged groups. This may include adaptive control strategies that account for user heterogeneity, differentiated communication that highlights reciprocal benefits, or participatory approaches that integrate user perception into policy design.

In summary, while chronoceptive design aligns system control with individual experience, fairness in intelligent transportation ultimately depends on balancing the spatial and social distribution of both factual and perceived benefits. Understanding this distributional layer is key to preventing fairness from backfiring and to ensuring the sustainable acceptance of future traffic-control technologies.

2.5. Motivation of This Work

Taken together, the reviewed literature reveals a tension between objective optimisation and subjective user experience. Traffic engineering studies demonstrate that ITS measures such as ramp metering can improve network performance but also show that such measures often face resistance when users perceive them as restrictive or unfair. Travel-time perception studies explain part of this resistance by showing that waiting, stopping, uncertainty, and lack of perceived progress are evaluated differently from in-motion travel time. Human factors and human–computer interaction (HCI) perspectives [85,86] further suggest that acceptance of automated or semi-automated systems depends not only on functional performance but also on how users perceive control, transparency, feedback, and agency during interaction with the system.

However, these insights have rarely been synthesised into operational traffic-control design principles. Prior studies identify the problem of perceived delay and unfairness but provide limited empirical evidence on how specific interface-level modifications to traffic-control signals can alter user perception and acceptance. This study addresses this gap by translating chronoceptive and human-centred design insights into concrete ramp metering signal designs and evaluating their effects through controlled virtual experience stated preference experiments.

3. Methods

This section starts with a description of the chronoceptive traffic-control design approach. Next, we showcase the design approach in the context of ramp metering. Finally, the virtual experience stated preference experiments used to assess user acceptance of the proposed designs are outlined.

3.1. Chronoceptive Traffic-Control Design

The interplay of technology (ITS) and the human factor (biased chronoception) leads to conflicts and barriers for the successful implementation of traffic-control measures. The manifestation of this issue is visualised in the waiting time perception process in Figure 1.

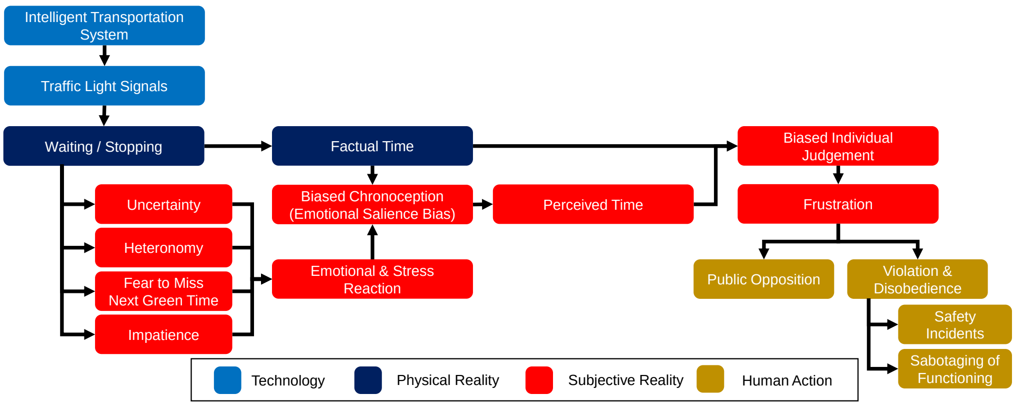

Figure 1. Chronoceptive barriers to intelligent transportation systems. Intelligent transportation systems use traffic light signals to reduce congestion. Traffic lights lead to stopping and waiting time of vehicles. Drivers experience an emotional stress reaction that leads to biased chronoception. The perceived time leads to biased individual judgment and finally to human action against the technology.

To address and overcome these chronoceptive barriers, one needs to address the subjective reality of drivers, starting from the biased individual judgment. Hence, to address the failure of humans to perceive the objective benefits of ITSs, one must design ITSs that generate factual benefits and perceived benefits at the same time, which is a challenging task due to the individual, highly unpredictable, and biased time perception process. We propose two approaches to this challenge, (i) indirect, chronoception-informed control design and (ii) direct, emotion-informed control design, as summarised in Figure 2.

First, one could optimise traffic control to account for known cognitive biases related to chronoception and thus indirectly affect the emotional stress reaction. Previous works highlight three important aspects of this approach:

- Waiting time (stopping) is highly unfavoured over time in motion (even if slow due to congestion) [19,20].
- Shorter waiting times are preferred over longer waiting times [20,28].
- Frequent stop-and-go is preferred over a long stand-still (meaning that distribution of waiting times across multiple stops is desirable) [28,30].

Shorter waiting times at the cost of more frequent stops create a feeling of progress, indirectly reduce uncertainty (as longer waiting times are perceived to be over-proportionally longer), and mitigate negative feelings such as impatience, leading to lower perceived waiting times. In the context of signalling, this implies multiple traffic lights behind each other or shorter cycle times [28]. An example for this can be found in the perimeter control of the city of Zurich, where multiple intersections delay inflowing traffic in the 1st control layer around the industry area north of Wiedikon and the Zurich main station [87].

Second, one could add elements to signals to directly affect the emotional stress reaction of drivers. Previous works highlighted the benefits of warning signs in advance to signals (in the case of ramp metering), three-headed signals, and countdown timers [17,72–74]. These technical measures could reduce uncertainty, impatience and the fear to miss the next green time and waste time and therefore lower stress and increase acceptance. Moreover, one could argue that information provision might increase autonomy and thus reduce the feeling of heteronomy.

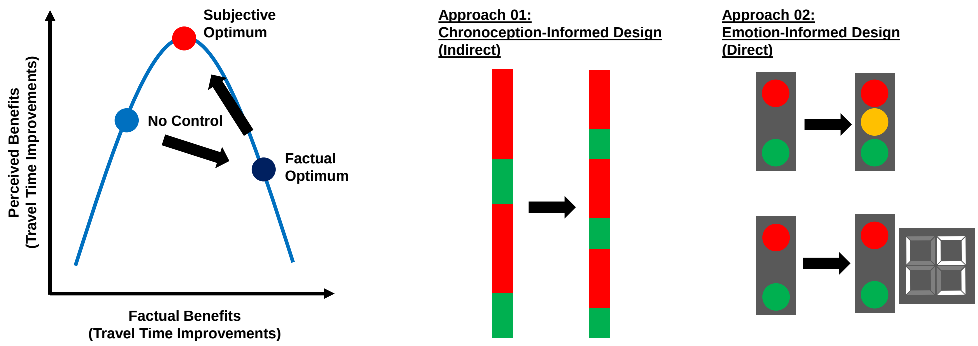

Figure 2. Chronoceptive Approach to Signal Design. Many intelligent transportation systems that provide factual benefits by optimally managing traffic (black dot) are perceived to have fewer benefits (red dot) when compared with the no-control scenario (blue dot). Two chronoceptive design approaches for signal design are proposed in this work: (i) shortening cycle durations and increasing the number of stops can increase perceived benefits and (ii) using three-headed lights and countdown timers can help to overcome stress reactions. These design changes can help improve perceived benefits and support successful implementation.

3.2. Case Study: Chronoceptive Ramp Metering Design

Within this work, we exemplify the proposed chronoceptive traffic-control design approach using ramp metering with *ALINEA* as an example for the case study [88] of the Ronda de Dalt freeway in Barcelona (Spain), as shown in Figure 3.

Ramp metering regulates and maintains congestion-free flow conditions on the mainlines, by using signals at the on-ramps ($o_i \in \mathcal{O}$) that limit and control the inflow of traffic [5]. Each metered on-ramp o_i is equipped with a traffic light that follows a signal cycle of duration t_c, from which the metering rate $r_i \in [0, 1]$ represents the share of green duration of t_c. When the traffic lights turn green, vehicles waiting on the on-ramp can continue to drive onto the highway, and merge with the mainline traffic in the merging area. There are sensors (loop detectors) that can measure traffic flow characteristics on the mainline, namely, flow q_t, average vehicle speed v_t, and occupancy c_t, at regular, discrete time intervals t and physical queue lengths at on-ramps l_t. Some ramp metering algorithms use upstream detectors, which are located in the merging areas, while others use downstream detectors, which are located downstream, after the merging area. Here, we consider an upstream sensor-informed ramp metering strategy, as this can also account for congestion in merging areas, detect congestion faster where it emerges, and hence enable the implementation of more proactive control measures. The control problem of ramp metering is to adjust ramp metering rates r_i dynamically according to the traffic conditions on the highway to achieve certain goals, such as homogenisation of traffic flow, mitigation of congestion, or increase in transportation efficiency (often measured in total travel time).

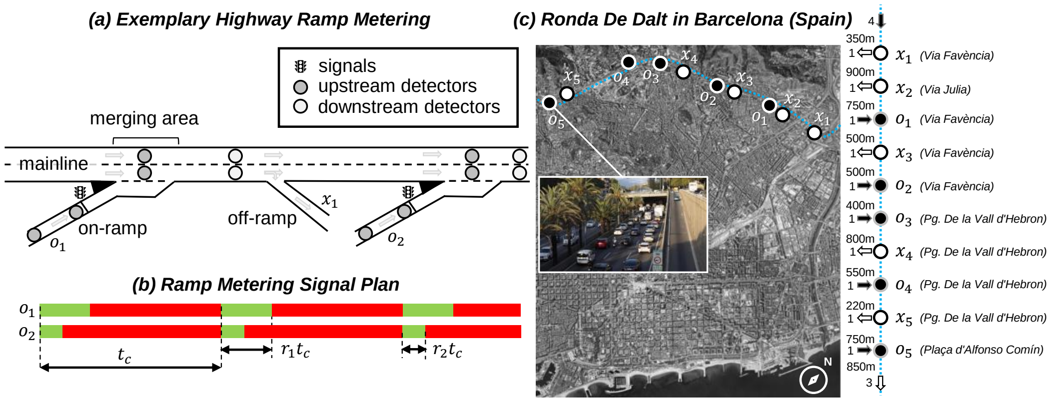

Figure 3. Case study: ramp metering in Barcelona. (**a**) Ramp metering uses upstream and/or downstream sensors and signals at the on-ramps to regulate inflow to the highway, achieving better traffic conditions. (**b**) The signal plan of ramp metering shows the major control variable, which is the share of green time r of the overall cycle duration t_c. (**c**) The highway ring-road of Ronda de Dalt in Barcelona (Spain) is an important highway that plays a multifunctional role in urban, metropolitan, and regional traffic. The considered motorway section for the case study spans a total length of 6.5 km, five on-ramps and five off-ramps, and up to four lanes on the mainline through the northern part of Barcelona.

One of the most widely deployed ramp metering strategies is *ALINEA* [89], which is distinguished by its simplicity, robustness, and effectiveness in handling freeway congestion [90]. *ALINEA*'s target is to keep the downstream mainline occupancy c_t at a critical value $\hat{c}$, using a simple P-control law, which can be denoted as follows:

$$q_t^R = q_{t-1}^R + K_R(\hat{c} - c_t) \tag{1}$$

where q_t^R represents the on-ramp flow (vehicle flow, in veh/h) for the local ramp meter in the next interval and is calculated from the previous interval's flow and the deviation of occupancy c_t from a desired, critical occupancy $\hat{c}$. K_R represents the gain parameter, and steers how aggressively the algorithm adjusts metering rates in response to changes in traffic conditions. Values of $K_R = 70$ veh/h, $\hat{c} = 20\%$, and $t_c = 60$ s were observed to work well in real-world experiments [5,89] and are assumed here in the following as well. To achieve physically plausible on-ramp flows, previous applications recommend boundary conditions:

$$\bar{q}_t = \min(q_{\max}, \max(q_t, q_{\min})) \tag{2}$$

where $q_{\min}$ and $q_{\max}$ represent the minimum admissible ramp flow and the maximum flow according to the ramp's capacity. The resulting on-ramp flow q_t can be converted into metering rates r_t:

$$r_t = (\bar{q}_t \times t_v) \;/\; t_c \tag{3}$$

where t_v represents the average time for one vehicle to pass the ramp. Based on empiric observations, $t_v = 20$ s is assumed in the following.

Using a demand-calibrated microscopic traffic simulation model of the highway using SUMO allows for the analysis of traffic flow conditions on the highway and travel time distributions, and the generation of realistic, individual trips through the network for different routes and starting times. The SUMO simulation spans 3 h of traffic during morning rush hours (06:00 AM–09:00 AM, with peak at 08:00 AM), covers more than 160,000 vehicle trips, and is calibrated using Barcelona's Open Data portal BCN [91]. In order to reproduce characteristic congestion patterns on the highway, the vehicle population's behaviour is parametrised in ten equal groups of varying level of cooperation/aggressiveness, using *SL2015* for driving behaviour and [92] for lane changing.

Based on previous insights into travellers' time perception in the context of ramp metering and the proposed chronoceptive traffic-control design approach, we suggest three design improvements, which will be validated for user acceptance in this study. The three design improvements take number of heads, countdown timer, and cycle duration into account, as shown in Table 1.

Table 1. Proposed chronoceptive ramp metering designs.

Scenario	**0** **Basic**	**1** **Design 1**	**2** **Design 2**	**3** **Design 3**
Control law	ALINEA	ALINEA	ALINEA	ALINEA
Number of heads	2	3	2	2
Countdown timer	no	no	yes	no
Cycle duration t_c	60 s	60 s	60 s	45 s

3.3. Virtual Experience Stated Preference Experiments

In order to assess perceived travel times and user acceptance for different ramp metering control strategies, we conduct virtual experience stated preference experiments, followed by a stated preference questionnaire, as outlined in Figure 4. All experiments described below were conducted in accordance with the Helsinki Declaration, and written consent from the participants was collected. The videos for the experiments were rendered with the tool sumo3Dviz [93]. (sumo3Dviz is a lightweight, open-source 3D visualisation pipeline for SUMO traffic simulations. It converts standard SUMO simulation outputs, such as vehicle trajectories and signal states, into high-quality 3D renderings using a Python-based framework and can be used across different operating systems, installable as a simple pip package. https://github.com/DerKevinRiehl/sumo3Dviz (accessed on 1 July 2026).)

Previous works differ in their experimental methodology, ranging from acceptance tasks and time estimation tasks to stated and revealed preference tasks. Prior studies found that time perception differs in experimental setups and real-world contexts, making dependency on experimental conduct especially challenging for derived insights [19,21]. As a consequence, recent, relevant research works and psychological experiments on travel time perception choose the approach of virtual experience stated preferences [19,28,46,47]. These experiments allow for a controlled environment while enabling more realistic conditions.

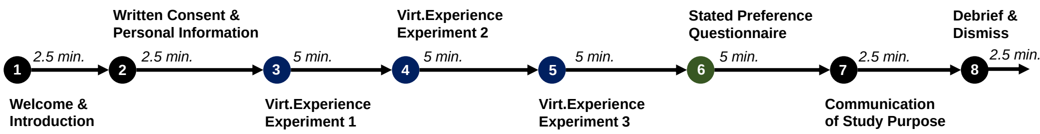

Figure 4. Virtual experience stated preference experiment conduct.

Study participation takes 30 min in total. At the beginning, personal information is collected from the participant, to account for age [29,52], gender [94], commuting behaviour and car-preference [31] biases. Moreover, each participant is assigned to one of the four proposed ramp metering designs and only sees videos with this specific design. During the three virtual experience experiments, subjectively perceived waiting time and user acceptance are assessed. To avoid fatigue and biases to temporal compression in the context of repetitive or familiar activities [22], the number of virtual experience stated preference experiments is limited to three. The three parts (repetitions) reflect three scenarios, in which the extent of the benefit (travel time reduction due to ramp metering) varies. During each repetition, participants are exposed to a video about a daily commute drive with and without ramp metering and report on their experience comparing the two different drives. After watching the two videos, the participant is requested to state (i) preference between the two scenarios, (ii) which of the two videos was perceived as faster, and (iii) how much faster (relative estimate). During the following stated preference questionnaire, perceived user acceptance in the presence of objective facts of travel time improvements is assessed. Further details on the experiment conduct can be found in Appendices A and B.

The scenarios for the different drives are derived from the aforementioned traffic simulation of the highway in Barcelona. The videos for display are generated with self-developed software. To be more realistic when generating a video of a daily commute in the morning peak hour, each video starts in a residential area and then reaches a highway on-ramp, followed by some time on the highway. An illustration of such a video can be found in Figure 5.

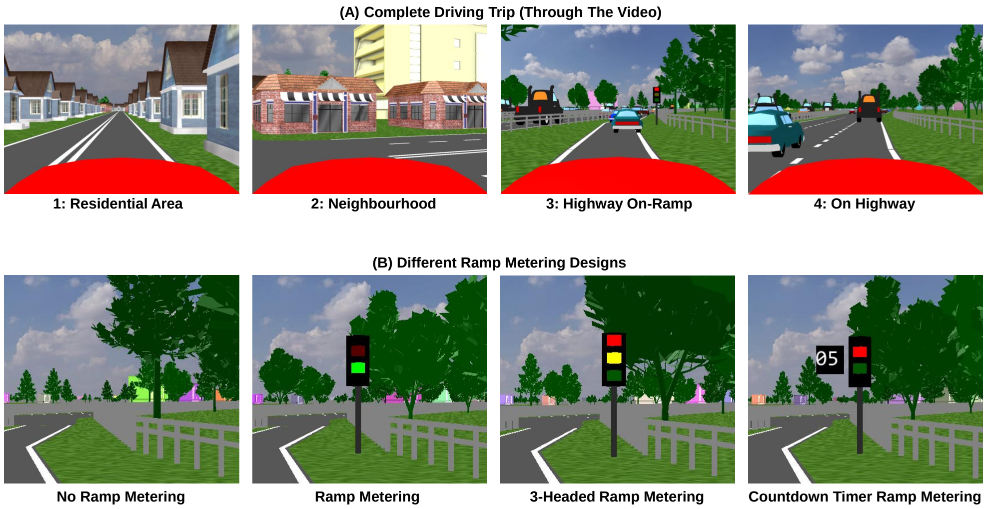

Figure 5. Visualisation used during virtual experience experiments. (**A**) The four images show different stages of a driving trip throughout the video. Each trip starts in a residential area (1) and continues into a neighbourhood closer to the highway (2); then the vehicle enters the highway on-ramp (3) and finally runs on the highway (4). (**B**) Different ramp metering designs are used during the videos shown to the participants. In case of activated ramp metering, two-headed (simple, default ramp metering), three-headed, and countdown timer-equipped ramp metering designs are used.

A video demo of the virtual experience stated preference experiments can be found on Youtube: https://www.youtube.com/watch?v=CJpNG7chmq8 (accessed on 1 July 2026). Recordings of the different traffic light designs and full-length videos that participants watched during the experiments can be found on Youtube: https://www.youtube.com/watch?v=w1gde1NYz8Q (accessed on 1 July 2026). The anonymised experiment data and code to produce the experiments can be found on GitHub: GitHub Link: https://github.com/DerKevinRiehl/chronoceptive_its (accessed on 1 July 2026).

4. Results

This section first presents the factual benefits of ramp metering with ALINEA for the case-study network from a system and user perspective. Afterwards, the outcomes of the virtual experience stated preference experiments and questionnaire are presented.

4.1. Traffic Flow Improvements with ALINEA and User Benefits

The results of the case-study microscopic simulations demonstrate the benefits of ramp metering for the highway traffic flow dynamics, as summarised in Figure 6 and

Table 2. Around 06:00 AM, when the morning peak of congestion starts, the traffic flow dynamics deteriorate significantly. The average speed on the highway drops from 60 km/h to 20 km/h, the flow is reduced from 2000 veh/h to 1500 veh/h, and the occupancy (density) rises from 3% to 25%. With the help of ramp metering, the situation can be improved significantly across the whole highway. Optimal ramp metering with ALINEA (with $t_c = 60$ s) can yield the greatest improvements, as it increases the average speed by 41% to 30 km/h and flow by 16% to 2050 veh/h and it decreases occupancy by 34% to 66%.

These improvements in highway traffic flow dynamics result in lower travel times on highways, at the cost of longer waiting times at on-ramps. As a consequence, the benefit individual drivers experience depends on their route and distance travelled along the highway, where travellers that drive longer distances on the highway benefit more than those driving shorter distances. Table 2 summarises the travel times for different routes. On average, travellers starting from on-ramp o_1 can reduce their total travel time by 32%, and those from o_2, by 24%, as travellers from o_1 join the highway earlier and thus travel longer distances on the highway when compared with those joining from o_2. The improvement in total travel time (benefit) originates from shorter travelling times on less congested highways (time after ramp), at the cost of slightly longer waiting times on on-ramps (time before ramp). For instance, travellers joining from on-ramp o_1 spend 53% less time after the ramp (on the highway) but need 15% more time before the ramp, resulting overall in 32% reduced travel time, on average.

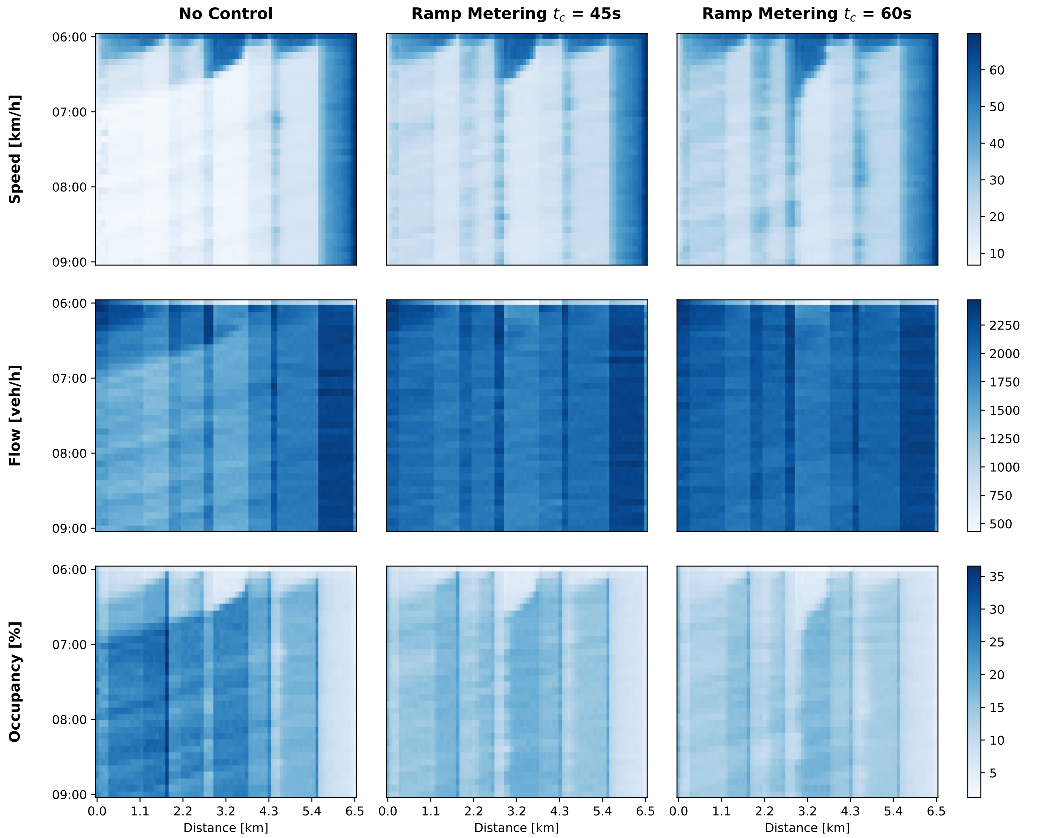

Figure 6. Traffic flow dynamic improvements on the highway during morning peak hours. Ramp metering enhances traffic flow dynamics by achieving higher speeds and flow and lower occupancy (density of vehicles). The ramp metering strategy with a cycle duration of $t_c = 60$ s yields the greatest improvements. Based on the heatmaps patterns of congestion, its back-propagation upstream over time becomes visible. Vertical lines indicate positions where on-ramps cause an inflow of additional traffic to the highway and off-ramps cause an outflow of traffic from it. The diagram was generated with 82 loop detector sensors across the highway (every 80 min) that report every 300 s (5 min).

Table 2. Driver benefits depend on the route. These numbers report the average of trips in the network for given routes during the microscopic simulation.

Cycle Duration [s] for Route			Travel Time [s]			Time Before Ramp [s]			Time After Ramp [s]			Av. Speed On Highway [km/h]		
			-	45	60	-	45	60	-	45	60	-	45	60
On-Ramp	**Off-Ramp**	**Length [m]**												
o_1	x_3	765	584	656	471	326	539	363	259	117	108	10.62	23.55	25.52
	x_4	1576	952	790	615	337	526	397	616	263	219	9.13	21.42	25.74
	x_5	3082	1390	1018	867	318	465	392	1071	553	475	9.88	19.13	22.25
	end	4566	1461	1244	1026	360	530	391	1101	714	635	11.48	19.96	23.30
o_2	x_4	564	1232	995	902	1095	926	841	137	69	61	14.61	29.16	33.01
	x_5	2070	1468	1299	1061	807	910	718	661	390	344	10.52	17.80	20.24
	end	3554	1702	1454	1363	925	887	862	776	567	501	13.38	20.62	23.41

For the virtual experience stated preference experiments, three individual trips from the population travelling from ramp o_1 to x_3 were selected, as shown in Figure 7. These three scenarios share the same benefit (total travel time reduction) but differ in their waiting time, which increases on the ramps, when comparing the no-control case with ramp metering.

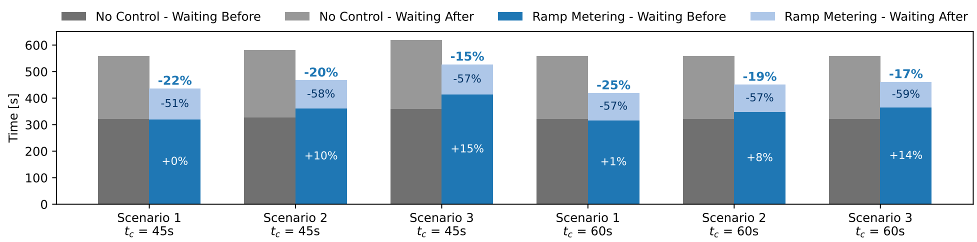

Figure 7. Traffic scenarios for the virtual experience experiments. Three scenarios (individual trips) from the population going from on-ramp o_1 to off-ramp x_3 were chosen. The three benefits offer a similar benefit of around 20% total travel time reduction and differ in different additional waiting times that the traveller needs to take into account at the on-ramp (from +0% to +10% and +15%). Similar scenarios for ALINEA ramp metering using $t_c = 45$ s and $t_c = 60$ s were chosen, to make experience comparable between two controller cycle durations.

4.2. Participant Results from Virtual Experience and Questionnaire Experiments

Over two months we recruited 101 participants for the experiments, including different ages (ranging from 21 to 66), genders, driver license ownership, attitudes towards driving, and mobility behaviours relative to the daily commute. Most of the participants were between 25 and 35 years old (~60%), were male (~65%), held a driver license (~85%), enjoyed driving (~81%), and mostly considered public transport (~57%), walking (~16%) and cycling (~15%) as their primary mode of transportation; further, they had a rather neutral attitude towards cars (average of 2.34 out of 5, where 5 is positive, and 0 is negative). A summary of the participants can be found in Figure 8.

The summary statistics of the experiments are reported in Table 3 and discussed below:

- First, the preferences in the virtual experience stated preference experiments (Table 3A) show that the traffic light design has a significant impact on user preference. The ramp metering standard design (design 1, two phases—red and green—with a 60 s cycle) achieves 79.17% preference for the controlled scenario, while chronoceptive designs achieve higher preferences up to 91.30%. The indirect, chronoception-informed design proposes a metering with a 45 s cycle (design 4) and achieves 91.30% preference. The direct, emotion-informed design proposes a metering with a yellow phase (design 2), which achieves 82.76%, and a countdown timer (design 3), which achieves 88.00%. On average 85.15% of all participants preferred the metered scenario, where no significant differences across the rounds of the experiments can be observed. Interestingly, whether the metered scenario was shown first or not significantly influenced participants' reported preferences. When shown first, metered scenarios were always preferred (100%), while these were preferred only in 70.57% of cases (on average for all designs) when shown second.

- Second, we analyse the participants' time perception in Table 3B. Participants perceived the metered scenario to be faster in 89.11% of all cases on average, which indicates that participant's preference (85.15%) is not solely based on a shorter travel time but is also based on other factors, such as the here-discussed psychological, emotional, and chronoceptive factors. No significant differences between perception and traffic light design can be observed here. Again, when shown first, metered scenarios were always perceived to be faster, while these were only perceived to be faster in 78.82% cases when shown second. On average, participants reported a time difference of 27.66% between metered and uncontrolled scenarios. Especially for traffic light designs 2 and 4, the perceived difference was higher. No differences in the perceived difference when the metered scenario was shown first or not are visible. The participants' time difference estimation error was the highest for traffic light design 1 (13.48%, meaning that they underestimated the time difference) and the lowest for design 4 (−5.45%, meaning that they overestimated the time difference). Over the rounds of the experiments, the estimation error slightly grows from −0.82% to 2.09%.
- Third, we analyse the participants' preferences in the questionnaire part of the experiments—when confronted solely with numbers and bar charts—in Table 3C. Differences between traffic light designs are visible, even though numbers in the diagrams are similar; a possible explanation for these differences is stronger awareness due to the videos watched in the previous parts of the experiments. Interestingly, showing ramp metering first (i.e., the left scenario in the diagram) this time leads to a smaller preference (81.81%) when compared with it being shown second (85.06%). Over the rounds of the experiments, shrinking acceptance for the faster, metered scenario can be observed, starting from 89.11% in round 1 to 77.22% in round 3. When confronted solely with numbers, preference of the metered, faster solution is even lower (83.50%) when compared with the preferences stated in Part A (where videos are shown) of the table (85.15%).

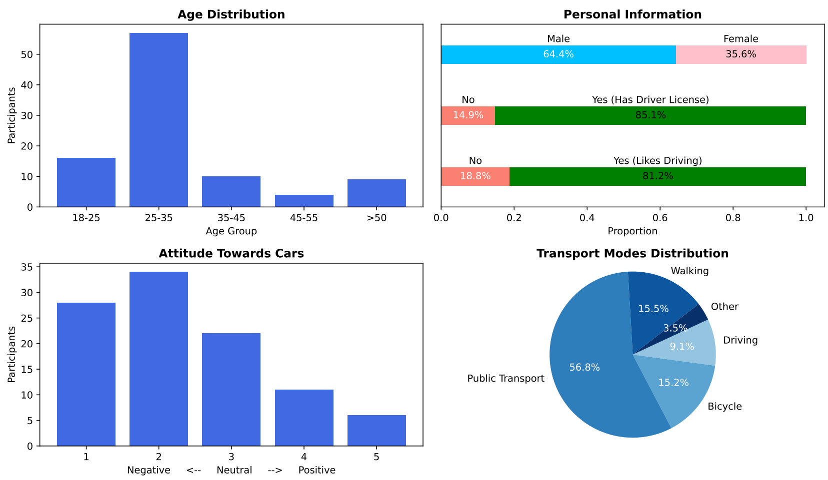

Figure 8. Experiment participant overview. A total of 101 participants were recruited for the experiments. Most of them were between 25 and 35 years old; were male; possessed a driver license; enjoyed driving; mostly considered public transport, walking and cycling as modes of transportation; and had a rather neutral attitude towards cars.

Table 3. Experimental results—summary statistics. This table shows the results of the virtual experience stated preference (VESP) experiments and the questionnaire. (A) shows the user preference for the metered solution based on the virtual experience experiments (watching videos). (B) assesses the chronoception during the experiments in terms of how many users perceived the metered solution to be faster, the perceived time difference, and the relative time perception error (difference between perceived time and actual time). (C) shows the user preference for the metered solution based on the questionnaire (where participants were shown bar charts). The numbers are reported for all experiments, complemented with breakdowns by round, traffic light design, and whether the metered solution was shown first.

(A) VESP Preference						
		By Rounds			All Rounds	
Experiment Subset Details	**N**	**1**	**2**	**3**	**N**	**Average**
[**Share That Considered Traffic Lights Better**]						
All	101	85.15%	83.16%	87.13%	303	85.15%
TL Design 1—(Standard)	24	79.17%	79.17%	79.17%	72	79.17%
TL Design 2—(Yellow Phase)	29	72.41%	86.21%	89.67%	87	82.76%
TL Design 3—(Countdown Timer)	25	96.00%	80.00%	88.00%	75	88.00%
TL Design 4—(45 s Cycle)	23	95.65%	86.96%	91.30%	69	91.30%
Showed TL First	101	100.00%	100.00%	100.00%	148	100.00%
Showed TL Second	101	73.21%	63.04%	75.47%	155	70.57%
(B) VESP Chronoception						
		By Rounds			All Rounds	
Experiment Subset Details	**N**	**1**	**2**	**3**	**N**	**Average**
[**Share That Considered Traffic Lights Faster**]						
All	101	91.09%	86.14%	90.09%	303	89.11%
TL Design 1—(Standard)	24	95.83%	87.50%	91.67%	72	91.67%
TL Design 2—(Yellow Phase)	29	75.90%	79.31%	82.76%	87	79.32%
TL Design 3—(Countdown Timer)	25	96.00%	92.00%	96.00%	75	94.67%
TL Design 4—(45 s Cycle)	23	100.00%	86.96%	91.30%	69	92.75%
Showed TL First	101	100.00%	100.00%	100.00%	148	100.00%
Showed TL Second	101	83.93%	69.56%	81.13%	155	78.21%
[**Perceived Time Difference**]						
All	98	28.19%	28.63%	26.17%	294	27.66%
TL Design 1—(Standard)	24	25.08%	27.00%	20.79%	72	24.29%
TL Design 2—(Yellow Phase)	27	29.77%	31.56%	29.55%	81	30.29%
TL Design 3—(Countdown Timer)	24	27.17%	27.38%	25.75%	72	26.77%
TL Design 4—(45 s Cycle)	23	30.65%	28.22%	28.26%	69	29.04%
Showed TL First	98	25.33%	33.29%	26.04%	144	28.22%
Showed TL Second	98	29.03%	25.04%	30.17%	150	28.08%
[**Estimation Error**]						
All	98	−0.82%	1.04%	2.09%	294	0.77%
TL Design 1—(Standard)	24	9.65%	14.76%	16.03%	72	13.48%
TL Design 2—(Yellow Phase)	27	−4.28%	−4.65%	−3.27%	81	−4.07%
TL Design 3—(Countdown Timer)	24	−0.54%	−0.15%	−0.91%	72	−0.53%
TL Design 4—(45 s Cycle)	23	−7.98%	−5.37%	−2.99%	69	−5.45%
Showed TL First	98	7.74%	2.07%	−4.89%	144	1.64%
Showed TL Second	98	−7.80%	−0.28%	8.03%	150	−0.02%
(C) Questionnaire Preference						
		By Rounds			All Rounds	
Experiment Subset Details	**N**	**1**	**2**	**3**	**N**	**Average**
[**Share That Considered Traffic Lights Better**]						
All	101	89.11%	84.16%	77.22%	303	83.50%
TL Design 1—(Standard)	24	87.50%	87.50%	83.33%	72	86.11%
TL Design 2—(Yellow Phase)	29	89.66%	79.31%	79.31%	87	82.76%
TL Design 3—(Countdown Timer)	25	84.00%	80.00%	68.00%	75	77.33%
TL Design 4—(45s Cycle)	23	95.65%	91.30%	78.26%	69	88.40%
Showed TL First	101	88.88%	83.63%	72.92%	148	81.81%
Showed TL Second	101	89.28%	84.78%	81.11%	155	85.06%

Furthermore, we employed four regression models to assess the statistical significance of the effect of participant characteristics, ramp metering traffic light design, and experimental setup on (i) whether participants preferred faster travels, (ii) whether they prefer ramp metering solutions over uncontrolled scenarios, (iii) whether they perceive metered scenarios as faster, and (iv) their chronoception estimation error. The results of this exercise are reported in Table 4 and discussed below:

- Model (1) assesses whether participants preferred the faster scenario in the questionnaire part of the experiments—when confronted with bar charts and numbers only. The model has no issues of multicollinearity as the variance inflation factors (VIFs) are close to 1.0 and shows a high explanatory power of 7.36% pseudo R^2, which is statistically significant according to the deviance test for logistic regression models at 1% niveau. The coefficients of the independent variables indicate that gender and attitude towards cars have a significant influence on whether the faster (=metered) scenario is preferred. Female participants and participants with a more negative attitude towards car driving preferred the slower scenario.
- Model (2) assesses whether participants preferred the ramp metering scenario in the virtual experience part of the experiments—when confronted with videos. The model has no issues of multicollinearity and shows a very high explanatory power of 33.08% pseudo R^2, which is statistically significant at 1% niveau. The coefficients of the independent variables indicate that gender, having a driver license, and the chronoceptive traffic light design (different from the standard setup) have a significant influence on whether the ramp metering scenario is preferred. Female gender and having a driver license have a negative impact on the preference for the ramp metering solution. Chronoceptive traffic light design contributes to a higher preference for the metered scenario.
- Model (3) assesses whether participants perceived the ramp metering scenario as faster when compared with the uncontrolled scenario (in the virtual experience part of the experiments). The model has no multicollinearity issues and shows a high explanatory power of 27.62% pseudo R^2, which is statistically significant at 1% niveau. The coefficients of the independent variables indicate that gender has a significant influence on whether the metered scenario is perceived to be faster when compared with the uncontrolled scenario. Female participants less often perceived the metered scenario as faster.
- Model (4) assesses the participants' time difference perception error between two shown scenarios (ramp metering vs uncontrolled). The coefficient for chronoceptive traffic light design is negative, suggesting a possible association with lower estimation error. However, the model shows only a weak explanatory power of 5.71% multiple R^2, and the overall F-test is not statistically significant. Therefore, Model (4) should be interpreted as exploratory rather than confirmatory, and the present data do not provide robust evidence that chronoceptive design systematically explains estimation accuracy.

The regression results should be interpreted in light of their explanatory power. For the logistic regression models, the reported pseudo R^2 values are likelihood-ratio based measures and should not be interpreted like OLS R^2. Models (2) and (3) show a comparatively strong fit for binary stated preference outcomes, whereas Model (1) has more limited explanatory power. By contrast, the OLS model for estimation error explains only a small share of the variance and its overall F-test is not statistically significant. We therefore treat the estimation error model as exploratory and refrain from drawing strong conclusions from individual coefficients in this model. The estimation error model has only weak explanatory power and should therefore be interpreted cautiously. While the coefficient signs suggest that chronoceptive design may be associated with lower estimation error, the overall model fit is weak, and the F-test is not statistically significant. Consequently, the present data do not provide robust evidence that chronoceptive design systematically ex-

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plains estimation accuracy. Instead, the stronger empirical evidence concerns participants' stated preferences and perceived faster alternatives.

Table 4. Regression analysis results. This table shows the regression analysis results with an additional column for variance inflation factor (VIF) values for each independent variable. Models (1)–(3) are logistic regressions explaining a binary dependent variable, while (4) is an ordinary least squares (OLS) model explaining a continuous dependent variable. The variable "Chron. TL Design" is a binary variable, representing whether a chronoceptive design for the traffic lights was used (1, i.e., shorter cycle duration, three heads, or countdown timer) or not (0, i.e., standard traffic lights). For each independent variable, VIFs are reported from model (1); numbers are similar for the other models and therefore not reported. For each model and independent variable, the coefficient and the z-statistics (for logistic regression) or t-statistics (for OLS regression) are reported in parentheses. For each model, statistical tests to assess quality (R^2) and significance (deviance and F-tests) are also reported. Statistical significance levels based on p-values are denoted as follows: *** implies $p \leq 0.001$, ** implies $p \leq 0.01$, * implies $p \leq 0.05$, and . implies $p \leq 0.1$.

		Questionnaire	Virtual Experiment		
Dependent Var.:		**Prefers Faster**	**Prefers TL**	**Meter Perceived as Faster**	**Estimation Error**
Model:		**(1)**	**(2)**	**(3)**	**(4)**
Independent Var.:	**VIF**				
(Intercept)	–	3.384 (3.281) **	1.984 (1.659)	2.503 (1.864) .	0.605 (0.055)
Age	1.164	0.014 (0.691)	−0.007 (−0.368)	0.016 (0.678)	−0.009 (−0.040)
Gender	1.067	−0.880 (−2.364) *	−0.804 (−2.012) *	−1.224 (−2.620) **	6.949 (1.618)
Has Driver License	1.212	0.758 (1.509)	−1.518 (−1.874) .	−1.162 (−1.384)	6.545 (1.050)
Likes Driving	1.117	−0.106 (−0.216)	−0.441 (−0.799)	0.042 (0.069)	2.239 (0.429)
Car Attitude	1.112	−0.399 (−2.469) *	0.025 (0.147)	0.105 (0.513)	2.239 (−0.155)
Chron. TL Design	1.093	−0.092 (−0.527)	0.339 (2.752) *	0.032 (0.145)	−16.293 (−3.332) ***
Showed TL First	1.013	–	18.667 (0.021)	19.122 (0.013)	2.175 (0.538)
Round	1.003	−0.441 (−1.946)	0.157 (0.687)	−0.165 (−0.624)	1.484 (0.601)
Regression Model		Logistic	Logistic	Logistic	OLS
Degrees of Freedom		274	273	273	273
Pseudo R^2		7.36%	33.08%	27.62%	
AIC		222.55	181.42	150.07	
Deviance Test		206.55 **	163.42 **	132.07 **	
Multiple R^2					5.71%
Adjusted R^2					2.95%
F-Test					1.655 (p = 0.1095)

Because each participant completed three virtual experience rounds, we tested the robustness of the regression results to alternative specifications that account for repeated observations within participants. Specifically, we re-estimated the models using round fixed effects, participant-clustered standard errors, and participant-level random intercepts. These alternative specifications did not change the substantive interpretation of the results; therefore, the more compact specification is reported in the main text, with robustness checks provided in Appendix C, Table A1.

5. Discussion

5.1. Chronoceptive Traffic Light Design Improves User Acceptance of Intelligent Traffic Control

Based on the empirical results in Tables 3 and 4, significant evidence has been found that chronoceptive traffic light design for ramp metering improves user acceptance and preference for the solution. Specifically, reducing cycle times could improve user acceptance by 12.13% (even though it reduces efficiency slightly), followed by countdown timer implementation (8.83% improvement) and three-headed traffic lights (3.59% improvement). As a consequence, we conclude that the chronoception-informed design (indirect approach) has the strongest potential for improvement when compared with the emotion-informed design (direct approach).

Moreover, there is a clear difference between perceived time improvements and preferences. Beyond the scope of stated preferences, the verbal feedback from participants after the experiments—especially those who took a longer amount of time to chat with us—were often reporting that they preferred the uncontrolled situations, despite recognising a travel time reduction. This reflects and supports what we observe empirically in Table 3 when comparing the (relatively lower) share of participants that preferred traffic lights and the (relatively higher) share that recognised that traffic lights were faster. These results are in line with previous works on travel time perceptions, such as [72–74].

5.2. Generally High Acceptance for Controlled Scenario Due to Sample Bias

When compared with previous works that report compliance rates between 50 and 90% [62,64], our results are at the higher end of the range (89.11%). The sample composition limits the external validity of the absolute acceptance rates. Because the sample is young, university-affiliated, and relatively car-independent, the observed acceptance levels should not be interpreted as representative of the broader driving population. Table 4 highlights that gender, holding a driver license, and also the attitude towards driving (pro-cars in general) had an effect on acceptance. Importantly, the present data do not allow for a quantitative projection of whether acceptance would be higher or lower among regular car commuters. The more robust interpretation is therefore comparative rather than absolute: within this controlled sample, the chronoceptive signal designs were evaluated more positively than the standard design. Future studies should replicate the experiment with larger and more representative samples and examine whether the relative design ranking persists across regular commuters, professional drivers, and different socio-demographic groups.

5.3. Higher Preference for What Was Shown First

While we can observe a strong difference in the user preference for the scenario that was shown first vs. that which was shown second (Table 3), no statistical significance was identified (Table 4). Still, the phenomenon of participants choosing the first out of two introduced options is commonly known as primacy or order effect in the psychological literature and has been observed in contexts such as memory [95], decision making [96], and voting [97].

5.4. Experimental Fatigue Was Not an Issue

The results in Table 3 show that the estimation error slightly increased, and questionnaire stated preferences for the controlled scenario decreased from round to round, while it had no influence on stated preferences from the virtual experience experiments. However, when controlling for various other variables (Table 4, the rounds did not play a statistically significant role in explaining chronoception or user acceptance. We therefore conclude that the experimental design was suitable to support the claims made in this study and did not overstrain the attention span of participants.

5.5. Gender Might Also Determine User Preferences

The observed gender coefficient should be interpreted cautiously. Although the regression results indicate an association between gender and some acceptance/perception outcomes, the present experiments were not designed or powered to identify robust gender differences in chronoception. The prior literature on gender and time perception is mixed, with reported effects depending on task type, duration range, emotional salience, and experimental context [94,98,99]. This heterogeneity is relevant here because participants did not experience an actual commute but evaluated animated driving videos in a controlled laboratory setting. The observed direction may therefore reflect the specific combination of stated preference task, video-based exposure, sample composition, and transport habits rather than a general gender difference in time perception.

Accordingly, we treat the gender result as exploratory. Future research should use gender-balanced samples, larger group sizes, and experimental designs that explicitly test interactions of gender, driving experience, stress, and waiting time perception. Such work would be needed before drawing substantive conclusions about gender-specific chronoceptive responses to ramp metering [100].

5.6. Research Limitations

This study and its conducted experiments were limited by several aspects that are discussed in the following:

- **Sample Size and Statistical Power:** The experiments included 101 participants, divided across four ramp metering design groups. This implies that each design condition was evaluated by a relatively small number of participants. Although each participant completed multiple virtual experience rounds, the effective number of independent participants per design remains limited. This is particularly relevant for the logistic regression models, which include several explanatory variables relative to the sample size. As a result, coefficient estimates, especially for participant-level covariates and subgroup effects, should be interpreted cautiously. The regression results are therefore best understood as indicative evidence of systematic patterns rather than as definitive population-level estimates. Future studies should replicate the experiments with larger samples to increase statistical power, reduce the risk of overfitting, and allow for more reliable estimation of heterogeneous effects across user groups.
- **Sample Representativeness:** The participant sample is not fully representative of the broader driving population targeted by ramp metering and other ITS control measures. Participants were recruited in a university environment and were predominantly young, male, and relatively car-independent. Many participants reported public transport, walking, or cycling as their usual commuting mode rather than regular car commuting. Although most participants held a driver license and many reported liking driving, their everyday exposure to ramp metering, congestion, and commute-related time pressure may differ from that of frequent car commuters. This limits the external validity of the acceptance estimates. In particular, absolute acceptance rates should not be interpreted as directly representative of the general driver population. Future research should include larger and more demographically balanced samples, with targeted recruitment of regular car commuters, professional drivers, and users who frequently experience congested motorway conditions.
- **Video Realism and Interface Fidelity:** The simplified animation quality of the video content and the small screen size may have affected participants' judgments and introduced measurement noise. While the video-based approach allowed for consistent exposure across participants and avoided confounding factors present in real traffic, it necessarily simplified visual detail, vehicle interaction, speed perception, and the embodied feeling of waiting. Future studies should improve stimulus realism through higher-fidelity simulation, interactive driving tasks, or immersive technologies such as virtual reality. Such approaches could help determine whether the effects observed here persist when participants experience a stronger sense of presence, agency, and time pressure.

- **Ecological Validity of the Virtual Experience:** The virtual experience stated preference experiments provided a controlled and replicable environment, but it cannot fully reproduce the emotional, physical, and contextual conditions of a real commute. Participants viewed animated driving videos on a laptop screen in a laboratory setting rather than actively driving in traffic or experiencing real consequences of delay, uncertainty, urgency, or loss of control. Therefore, the experiments may not elicit the same level of stress, impatience, or emotional engagement as actual waiting at a ramp meter during a congested commute. This limitation is particularly relevant because chronoception is expected to be influenced by stress and emotional salience. The results should therefore be interpreted as responses to a controlled virtual representation of ramp metering, not as direct measurements of real-world driver behaviour. Future work should validate these findings using more immersive driving simulators, virtual reality environments, field experiments, or naturalistic driving studies, ideally combined with physiological indicators such as heart rate variability, galvanic skin response, or gaze behaviour.
- **Geographical and Cultural Transferability:** The traffic scenarios were derived from a calibrated microscopic simulation of the Ronda de Dalt freeway in Barcelona, whereas the human experiments were conducted with participants recruited in and around ETH Zürich, Switzerland. Driving cultures, traffic expectations, compliance norms, and familiarity with ramp metering systems may differ between Swiss participants and the actual driver population in Barcelona. Consequently, the experiments test perceptual responses to Barcelona-based traffic scenarios under controlled conditions, but they do not establish that the same acceptance levels would occur among Barcelona drivers in real traffic. Future research should repeat the experiments with local driver populations and compare results across countries, cities, and traffic cultures to assess whether chronoceptive design effects are robust across different behavioural and institutional contexts.

6. Conclusions

This work set out to examine how human time perception—chronoception—shapes user acceptance of ITSs and how design modifications can reconcile perceived fairness with objective efficiency. Through virtual experience stated preference experiments involving 101 participants, we evaluated how different ramp metering signal configurations influence perceived waiting times and stated acceptance.

The empirical findings show that within the experimental setting, chronoceptive signal designs were associated with improved user attitudes toward ramp metering. In particular, shorter signal cycles produced the largest acceptance gains (+12%), followed by countdown timers (+8%) and three-phase signals (+4%). These effects occurred even when objective travel times remained constant or were slightly longer, suggesting that participants responded not only to objective efficiency but also to perceived progress and waiting time experience. The results therefore highlight important distinctions between actual travel-time changes, perceived benefits, and user preferences, which may not always align.

The results underline a fundamental paradox in modern traffic management: policies that optimise system performance may be rejected if users perceive them as unfair or inefficient. Chronoceptive design provides a human-centred framework to bridge this gap. By explicitly considering psychological time distortions and emotional stress reactions in control logic and interface design, ITSs can enhance not only compliance but also perceived fairness. This study thus contributes to a growing body of evidence that public acceptance of automation and control measures depends as much on how benefits are experienced as on how large they are.

Future research should build on these findings in several directions. First, larger-scale and demographically more diverse samples are needed to validate chronoceptive effects across cultures, age groups, and driver types. Second, longitudinal studies could explore adaptation effects—whether repeated exposure to control measures recalibrates time perception and restores acceptance over time. Third, integrating physiological indicators such as heart rate variability, galvanic skin response, or gaze behaviour could reveal underlying stress mechanisms and support bio-informed ITS design. Fourth, fairness-oriented research should investigate the distribution of perceived benefits: who feels advantaged or disadvantaged by control measures and how this affects social equity and political support. Fifth, chronoceptive design principles could be operationalised directly in control algorithms by coupling behavioural models with optimisation routines that minimise perceived rather than objective travel time. Sixth, this research could be extended to other domains such as variable-speed-limit control, signal coordination, or perimeter control, where perceived delay and loss of autonomy similarly affect acceptance and compliance.

Overall, this work demonstrates that traffic systems designed around the human experience of time—not only its physical measurement—can achieve greater acceptance, fairness, and effectiveness. Chronoceptive design thus marks a step toward truly human-centred ITSs.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki. The Ethics Committee of ETH Zurich reviewed the survey study and confirmed on 1 August 2025 that no formal ethical approval was required. No project identification code was assigned by the ethics committee.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study. Participants were informed about the purpose of the research, how their data would be used, that their anonymity was assured, and of any risks involved in participation. No identifiable participant information, images, videos, or personal details are included in this article nor the data published alongside it.

Data Availability Statement: The anonymised experiment data and code to produce the experiment can be found on GitHub: GitHub Link: https://github.com/DerKevinRiehl/chronoceptive_its (accessed on 1 July 2026). A video demo of the virtual experience stated preference experiments can be found on Youtube: https://www.youtube.com/watch?v=CJpNG7chmq8 (accessed on 1 July 2026). Recordings of the different traffic light designs and full-length videos that participants watched during the experiments can be found on Youtube: https://www.youtube.com/watch?v=w1gde1NYz8Q (accessed on 1 July 2026).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Experiment Preparation

We recruited 101 participants on the university campus and in the city over two months. Inside a compute room, we prepared 30 experimental stations, which allowed for many participants in parallel and data collection in a short amount of time. Each participant was placed in front of a laptop (Lenovo Thinkpad X1) with an AICCP screen of full-HD resolution (1920 × 1080), 14 inches in size, 350 cd/m^2 brightness, 1700:1 contrast ratio, and 60 Hz refresh rate. The user controlled the experiment with a keyboard and a mouse in a quiet environment.

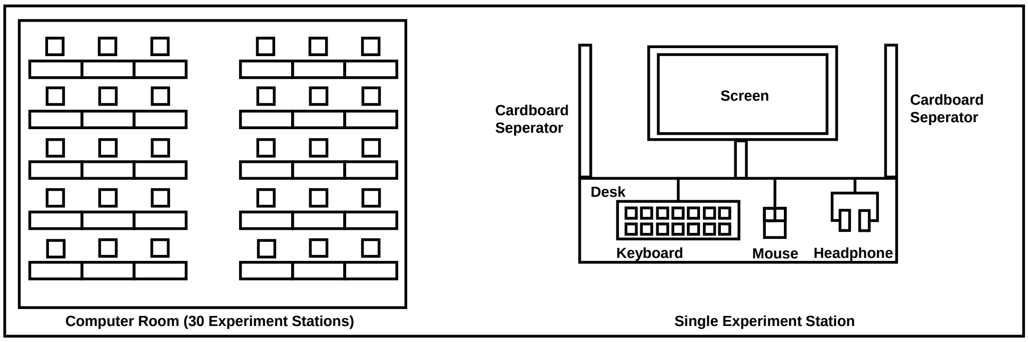

Figure A1. Experimental room preparation.

Appendix B. Experiment Conduct Details

Appendix B.1. Experimental Step 1: Welcome & Introduction

In this part of the experiment, we welcome the participant and present an introduction to the study (as shown below). Questions of the participants are answered in advance.

The introduction by purpose does not mention the full purpose of the study, which is travel time perception or user acceptance of travelling on highways, so as not to bias the outcome of the experiments. The actual purpose and context of the study are revealed after the study.

This experiment aims to investigate satisfaction & perception of driving on highways as a passenger in a car. The total experiment will take around 30 minutes, and will take place in a computer room.
You will join three experiment parts, and a questionnaire at the end. In each experiment part, you will sit in front of a computer screen, and watch two videos of a drive on a highway during a morning commute from your home to work. After watching the videos, you will answer two questions. After all three parts, there will be a short questionnaire with further questions. In order to answer the questions, you will be able to use the mouse and keyboard in front of you, and you will be wearing headphones. At the end of the experiment you will be provided with more, written information material about all details.
The experiment will take place in a computer room. Please do not talk during the experiment, as other participants are running their experiments as well. In case you have a question, please raise your hand. To avoid disturbance with metal devices during the experiment, we kindly ask you to put personal items such as smartphones and watches into a box, that we will give you back after the experiment.

Appendix B.2. Experimental Step 2: Written Consent & Personal Information

We hand out the *Written Consent & Personal Information* form and let the participant read and sign it.

Consent & Personal Information Form

Personal Information

1. Name:

2. Age:

3. Gender:

[ ] Female [ ] Male [ ] Other

4. Do you have a driver license?:

[ ] Yes [ ] No

5. Do you generally and personally like & enjoy driving by car (either as passenger or driving)?:

[ ] Yes [ ] No

6. During your commute to work or university, which mode of transportation do you usually use?:

[ ] Driving By Car [ ] Public Transport [ ] Bicycle [ ] Walking [ ] Other

7. What is your opinion on driving by car? Rate the following statement:

"Driving by car should be reduced to a necessary minimum."

(Strongly Agree) [ ] 1 [ ] 2 [ ] 3 [ ] 4 [ ] 5 (Strongly Disagree)

Consent Declaration

Herewith, I consent in participating in the experiment, and the usage of my declared data in this form and during the experiments for research purposes. Moreover, I consent the publication of the provided data in anonymised form (without name). This consent can be revoked at the end of the experiment, if undesired.

Date: **Signature:**

Appendix B.3. Experimental Step 3–5: Virtual Experience 1–3

In this part of the experiment, we provide the participant with virtual experiences of driving in ramp metering controlled scenarios. Using a questionnaire for stated preferences, we aim to assess the perceived travel time and user acceptance of ramp metering. The conduct of the virtual experience stated preference experiments is shown in Figure A2. The details are outlined below:

- The participant sits down at the computer, puts on headphones, and gets familiar with keyboard and mouse.
- The participant enters the participant number.
- One of four ramp metering designs is chosen randomly.
- The order of the three video pairs (representing three different routes with different extents of ramp metering) is randomly assigned.
- The following steps are repeated for three times (for the three parts of the experiments):
    - For each of the pairs, the order of the videos (with or without ramp metering) is randomly assigned.
    - The participant sees the first video (with or without ramp metering) and then the second video (with or without ramp metering).
    - Afterwards the user needs to answer a questionnaire about the two videos just seen.

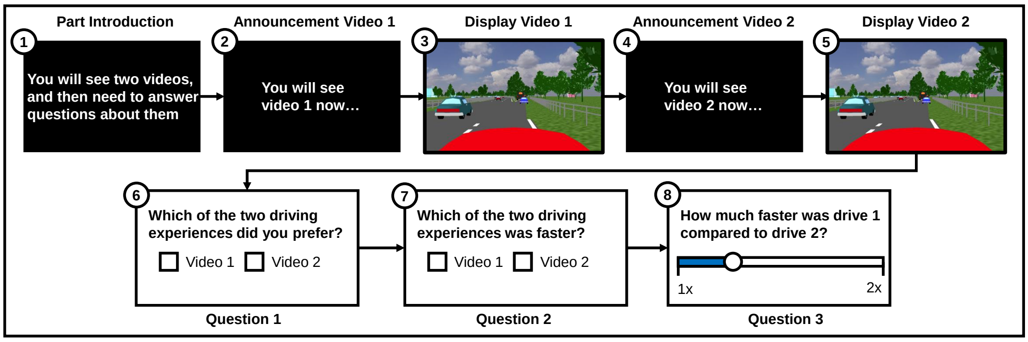

Figure A2. Virtual experience stated preference experiment.

Appendix B.4. Experimental Step 6: Stated Preference Questionnaire

In this part of the experiment, we provide the participant with numbers that represent the factual benefits of ramp metering for the virtual experiments that the participant watched in the previous steps. Using a questionnaire for stated preferences, we aim to assess whether the participant prefers ramp metering if provided with factual rather than perceived travel time reductions and benefits of ramp metering. There are three questionnaires for the three different routes that the participant watched. Option 1 represents the scenario with no ramp metering, Option 2 represents the scenario with ramp metering and a shorter cycle duration of 45 s, and Option 3 represents the scenario with ramp metering at a longer cycle duration of 60 s (which achieves the largest total travel time reduction but also the longest waiting time).

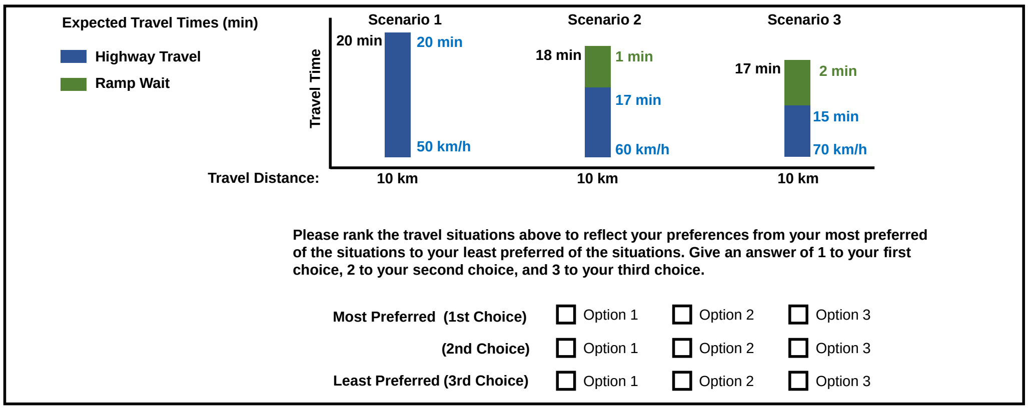

Figure A3. Stated preference questionnaire experiment.

Appendix B.5. Experimental Step 7: Communication of Study Purpose

In this part of the experiment, we provide the participant with the background information, actual purpose of the study, and expected outcomes from our experiment. For this purpose, a printed handout with the following explanations and Figure 3 are read out and provided to the participant.

Background: Congestion on Highways & Ramp Metering As A Solution
Highway traffic can be congested, especially during peak hour of a daily commute to work or university. This has many negative effects on the society, such as wasted life time, additional emissions, reduced life quality and satisfaction, and impact on health.
Ramp metering is a intelligent transportation technology, that can help to reduce congestion. It uses sensors on the highway to detect how congested the mainline is, and regulates the inflow of additional cars onto the highway using traffic light signals at the on-ramps (entrances) to the highway.
Even though ramp metering can significantly reduce overall travel time, drivers usually dislike this solution and neglect the benefits of this approach. This solution is so unpopular, that in many countries it does not even get to the stage of implementation, and that in some countries and cities there were even demonstrations and a shutdown due to political pressure of public opposition. Previous studies showed, that the waiting time in front of the traffic light is perceived longer than the travel time gains on the highway due to lower congestion levels.
Goals & Design Of Experiment
In this study we aim to explore how drivers perceive travel time on highways, and what drives the acceptance of ramp metering. For this purpose we use a virtual experience stated preference experiment. The videos were generated for traffic scenarios on a highway in Barcelona, Spain (Ronda de Dalt) during the morning commute traffic from 06:00 AM–09:00 AM. The questionnaire was used to obtain the objective preference of users (based on numbers and factual benefits), while the virtual experience stated preference experiment was used to obtain the subjective preference of users (based on perception).
Research Goal 1: Travel Time Perception On Highway & User Acceptance Of Ramp Metering
During each part of the experiment, you were provided with two videos, showing a daily commute with and without ramp metering. Afterwards, you were asked to state which you preferred, as well as how much longer one over the other took. These statements help us to better understand how well solutions are perceived, and how accurately travel time reductions (benefits) of ramp metering are perceived by human drivers.
It might be surprising to you, but the scenario with the traffic light (ramp meter) at the highway entrance was actually always shorter.
Research Goal 2: Dedicated Design To Enhance User Acceptance
During the experiment, we show participants four different versions of the six videos, where you only saw one version. In version one, a two-headed traffic light (with only red and green light) was shown. In version two, a three-headed traffic light (with red, yellow, and green light) was shown. In version three, a countdown timer was shown, to give you information how long you still need to wait until you can drive again. In version four, a ramp metering with 45 s instead of 60 s cycle duration was shown, which leads to more frequent start and stop on the ramp. Previous studies showed that these changes can help to enhance the user acceptance of ramp metering.
Moreover, during the experiment you saw videos for three different routes. These different routes differed in the extent of travel time reduction using ramp metering. In each part of the experiment, the reduction of travel time was only 0%, 10%, 15%, respectively.

Appendix B.6. Experimental Step 8: Debrief & Dismiss

In this part of the experiment, we debrief and dismiss the participant. We return personal items, such as smartphones or watches. We give the participant the chance to clarify remaining questions and also offer the possibility to revoke the consent granted at the beginning, if desired by the participant.

We thank you for participating in this experiment and your support for our research study. We hope you enjoyed it and wish you all the best for any future drives on highways.

Appendix C. Additional Analysis

Table A1. Robustness checks with participant-clustered standard errors and round fixed effects. Coefficients are shown with robust z-statistics for logistic models and robust t-statistics for the OLS model in parentheses. Significance levels: *** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, and $p \leq 0.1$. The coefficient for *Showed TL First* in the logistic models should be interpreted only as evidence of a strong order effect because the variable perfectly predicts positive responses when the traffic-light video was shown first.

	Questionnaire	Virtual Experiment		
Dependent Var.:	**Prefers Faster**	**Prefers TL**	**TL Perceived as Faster**	**Estimation Error**
Model:	**(1)**	**(2)**	**(3)**	**(4)**
Independent Var.:				
(Intercept)	2.762 (2.213) *	2.796 (2.023) *	3.060 (2.316) *	1.882 (0.181)
Age	0.014 (0.497)	−0.009 (−0.381)	0.029 (0.985)	−0.009 (−0.045)
Gender	−0.882 (−1.501)	−0.877 (−1.837)	−1.481 (−2.674) **	6.947 (1.076)
Has Driver License	0.750 (0.906)	−1.599 (−1.805)	−1.326 (−1.226)	6.542 (0.822)
Likes Driving	−0.122 (−0.151)	−0.288 (−0.487)	0.188 (0.271)	2.236 (0.379)
Car Attitude	−0.390 (−1.996) *	0.005 (0.023)	0.110 (0.435)	−0.279 (−0.159)
Chron. TL Design	−0.169 (−0.268)	0.625 (1.593) *	−0.872 (−1.349)	−16.288 (−2.301) *
Showed TL First	–	24.843 (81.052) ***	24.300 (66.809) ***	2.099 (0.791)
Round 2	−0.234 (−0.803)	−0.654 (−1.466)	−0.863 (−1.829)	2.241 (0.811)
Round 3	−0.846 (−2.492) *	0.342 (0.840)	−0.472 (−0.863)	2.968 (1.124)
Regression Model	Logistic	Logistic	Logistic	OLS
Observations	282	282	282	282
Participants	94	94	94	94
Round fixed effects	Yes	Yes	Yes	Yes
Participant-clustered SEs	Yes	Yes	Yes	Yes
Pseudo/multiple R^2	0.074	0.340	0.300	0.057

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