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How much traffic is too much? Finding the right vehicle quota for a scenic mountain road in the Italian Alps

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ABSTRACT

An effective yet neglected option to limit the detrimental effects of car traffic in natural tourist destinations is the imposition of vehicle quotas. Defining the right quota for a road system, however, may not be straightforward because of the complex connection between the number of vehicles entering the system and traffic levels across space and over time. In this paper, we present a novel approach to tackle this issue that combines agent-based modeling and standards of quality, and we use it to define an hourly quota aimed at limiting traffic congestion and demand for parking along a scenic road in the Dolomites (Italian Alps). The model is designed and calibrated using geospatial and traffic data, and the acceptability of the quotas is further tested according to the hourly modal splits they might induce.

Our model simulations highlight that, by redistributing morning traffic inflows, the quota can almost eliminate congestion with only a negligible impact on overall traffic figures. Further, while traffic reductions of up to 35% may be needed to eliminate traffic-related issues, more reasonable reductions (i.e. 10–25%) may be enough to address most of those. From an empirical perspective, the paper shows the effectiveness of quotas in sustainable transport and tourism; from a policy and management perspective, it proposes an approach for the definition of an ideal quota. The design of a quota system, however, requires detailed implementation and communication strategies, and more advanced simulation tools to capture circulation patterns induced by such strategies.

1. Introduction

The steady growth of the tourism sector – 1.4 billion international arrivals in 2018, 5.4% more than the previous year (UNWTO, 2019) – and particularly nature-oriented tourism (Buckley, 2000; Balmford et al., 2009), is forcing more and more outdoor destinations (e.g. national parks) to deal with exceptional traffic volumes and related issues (NPS, 2014). These include widely acknowledged problems such as congestion (Steiner and Bristow, 2000), air and noise pollution (White, Aquino, Budruk, and Golub, 2011; Merchan, Diaz-Balteiro and Soliño, 2014), and conflicts with wildlife (Burson, Belant, Fortier, and Tomkiewicz, 2000; Delgado et al., 2019), but also commonly neglected externalities such as habitat fragmentation and land-use changes associated with the enhancement of road infrastructures and the creation of parking lots for an increasing number of vehicles (Bruschi et al., 2015; Orsi, 2015). All of this means a reduction in the quality of visitors' recreational experience (Hallo and Manning, 2009; Benfield, Bell, Troup, and Soderstrom, 2010) and ultimately the impairment of the very resources people are attracted to (Martin-Cejas, 2015).

Various studies have shown that the number of vehicles in natural settings can hardly be reduced by simply making alternative transportation systems (ATS) more attractive (e.g. higher frequency, lower fares), but that the goal may be achieved when interventions on ATS are coupled with measures directly aimed at discouraging the use of private transport (Holding and Kreutner, 1998; Steiner and Bristow, 2000; Orsi and Geneletti, 2015; Scuttari et al., 2018a). The most well-known of such measures is road pricing, by which visitors are charged a fee to drive their vehicles into areas that are particularly sensitive to the impacts of traffic owing to their natural and infrastructural characteristics (Steiner and Bristow, 2000). Alternatively, parking fees can be used to match the demand and supply of parking spaces, and to reduce traffic (Marsden, 2006; Chung et al., 2011). Another option is the temporary closure of a road to eliminate traffic for part of the day or the season (Holding and Kreutner, 1998).

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Table 1
Strengths, weaknesses and unintended consequences of "push" measures aimed at limiting car use in natural settings.

Measure	Strengths	Weaknesses	Unintended consequences
Road pricing	Revenues raised for infrastructure maintenance and resource protection	Public and political opposition Burden on lower income groups (regressive taxation)	No decline in car use Congestion at gates (if any)
Parking fees	Revenues raised for infrastructure maintenance and resource protection	Through traffic not affected	Congestion due to drivers unwilling to park slowing down near attractions
Road closure	All traffic-related issues eliminated Enhancement or creation of other recreational activities (e.g. cycling)	Driving for pleasure impossible Very efficient ATS required No revenues	Congestion before and after closure (on daytime implementation) Congestion at gates (if any)
Quota	Desired level of traffic	No revenues	Measure perceived as road closure (decline in visitation) Congestion at gates (if any)

Regardless of their specific strengths and weaknesses (see Section 2), however, these measures present a common drawback: their implementation does not necessarily guarantee the desired or acceptable traffic levels: they either barely discourage driving or exclude traffic altogether. In other words, a pricing scheme may end up not bringing traffic below the level that is deemed acceptable, whereas a road closure might eliminate traffic in contexts where some traffic would be totally acceptable and even necessary to guarantee a wider spectrum of recreational opportunities. A solution to this issue may come from the adoption of a quota system, namely the imposition of an upper limit on the number of vehicles that can enter a road on a given time frame (e.g. hour, day).

While quotas are already enforced in various protected areas around the world to limit visitor flows in highly sensitive environments (e.g. daily quotas on wilderness permits in Yosemite National Park, USA) (NPS, 2018), their use for controlling car traffic volumes is still very limited and related scientific literature virtually nonexistent. Yet, the definition of the right quota for a given road or road network is a very relevant research topic, also considering the potential of an adequately calibrated quota system to achieve an ideal tradeoff between access for all users and environmental protection.

The inherent difficulty of estimating the right quota is associated with the dynamic nature of a road system and therefore the lack of a direct relationship between the number of vehicles entering the road and the number of vehicles at different locations along the road and at parking lots during the day. Such complexity can be handled by simulation tools and particularly agent-based models (ABMs) owing to their ability to account for nonlinear interactions between multiple individual entities (e.g. vehicles), heterogeneity among entities and randomness (Bonabeau, 2002). ABMs have been used in various transportation studies (Dia, 2002; Espie and Auberlet, 2007; Benenson et al., 2008; Querini and Benetto, 2014; Liu et al., 2017), including in outdoor recreational settings (Takama and Preston, 2008; Orsi and Geneletti, 2016), where they have proved to offer considerable benefits for the simulation of visitor movements (e.g. possibility to account for feelings and preferences) compared to more traditional transportation modeling techniques (Bishop and Gimblett, 2000; Nicholls et al., 2017; Morelle et al., 2019).

This paper deals with the definition of a vehicle quota aimed at minimizing the adverse impacts of private motorized traffic that have been experienced over the last two decades on a scenic (and popular) mountain road circling the Sella massif in the Dolomites (Italian Alps). The approach used to identify the ideal quota(s) is novel for two reasons. Firstly, because a simple spatially-explicit ABM is specifically developed to simulate vehicle movements along the road network given rates of entrance in the network that are regulated by the quota. Secondly, because different quotas are assessed based not only on their ability to keep key traffic-related variables (i.e. congestion and demand for parking space) within acceptable levels throughout the day, but also on the acceptability of the modal splits they would induce. The study is particularly relevant because its findings have supported the design of a real quota system, which has been recently identified by local administrations as the best policy option to guarantee the protection of natural resources and recreational experiences. The contribution of the paper is therefore not only to further improve the use of ABM models in transport studies, but also to offer a concrete solution to the so-called "tourism-traffic paradox" (Scuttari et al., 2019): the implementation gap in policies aimed at mitigating tourism-related traffic.

2. A review of "push" measures for the reduction of car traffic in natural areas

Policy measures aimed at transferring people from private vehicles to ATS are commonly divided into "push" measures, which target the use of the private vehicle trying to make it less attractive, and "pull" measures, which instead target ATS, trying to make them more attractive. Among the former, four can be applied in natural areas: road pricing, parking fees, road closures, and quotas. A summary of these measures' strengths, weaknesses, and unintended consequences is reported in Table 1.

Road pricing is a charge levied on drivers for the use of a road based on the assumption that road space is a scarce resource, hence the use of it by one individual prevents another one from using it, and that an excessive demand generates costs associated with longer trip times (Pigou, 1918; Morrison, 1986). By implementing a pricing scheme on a popular/scenic road, managers of a park or an outdoor recreational area, in general, can then reduce demand and avoid congestion (Steiner and Bristow, 2000), plus they can raise revenues to be used for a variety of purposes (e.g. improvement of a shuttle bus system), including coverage of costs due to overuse of infrastructures and natural resources (Rosenthal et al., 1984). Road pricing in officially protected areas may also be applied indirectly by means of entrance fees, provided these are adequately differentiated between car users and pedestrians (or cyclists).

Unfortunately, road pricing may face a strong public and political opposition (Kendal et al., 2010), also because it implies equity issues in the form of an excessive burden on lower-income classes as well as visitors from nearby areas, for whom the road fee would represent a higher share of the total trip cost (Eckton, 2003). Moreover, the presence of gates where fees are collected may generate congestion problems at the entrance of the area the measure is intended to preserve (Eckton, 2003). On top of that, (reasonable) fees do not guarantee that traffic volumes will be maintained within acceptable levels because the demand for visits to natural attractions is relatively inelastic (Clawson and Knetsch, 1966; Shultz, Pinazzo and Cifuentes, 1998; Reynisdottir, Song and Agrusa, 2008).

Parking fees are another pricing scheme aimed at matching the supply and demand of a limited resource, namely parking space. The economic rationale behind their adoption is that free parking, by stimulating people to drive to a destination (Weinberger, 2012) and to roam around searching for a parking space (Shoup, 2006), generates a negative externality (i.e. congestion) that everybody pays for in terms of longer travel times (Inci, 2015).

Parking fees are common practice in many outdoor recreational areas, they are generally well received by visitors (Chung et al., 2011) and represent a viable option to raise funds for the maintenance of infrastructures. A major limitation of this measure is that it does not intercept through traffic, hence a road's capacity might be systematically exceeded even in the presence of expensive parking fees.

The *closure of a road* or road section on specific days (e.g. Sundays) or periods (e.g. peak season) is a relatively common practice in protected areas and other popular natural areas (Cullinane, 1997; Holding and Kreutner, 1998). It has the fundamental merit of eliminating all car traffic and related issues, and it is inherently equitable: provided some exceptions may apply (e.g. residents, disabled people), no selection is made based on income or willingness-to-pay. Among problems of closure to any motorized personal vehicle are the complete elimination of the possibility to drive for pleasure (although other recreational opportunities might be benefited by that) and impaired accessibility if adequate ATS (i.e. cheap and frequent) are not implemented. Moreover, when a road connecting two neighboring regions is closed in the central part of the day (e.g. 9–16), traffic may get congested right before and after closure as many take their chance to move from one region to the other.

Vehicle quota systems have been implemented in some overcrowded cities (e.g. Singapore) as limits on the total number of vehicles owned by the local population at a given time in an attempt to curb traffic-related issues (Koh and Lee, 1994). Quotas in outdoor recreational areas can be implemented as daily or hourly limits on the number of vehicles entering a road so that traffic and parking lot occupancy rates are always within the acceptable levels given environmental and social conditions. Similar to what happens with the release of wilderness permits in US national parks (NPS, 2018), the right to drive on a road can be granted on a first-come-first-served basis, upon previous reservation or a mix of both.

The implementation of the system may not be straightforward though and, in the absence of modern technology (e.g. online reservation, license plate scanners) and adequate road infrastructure (e.g. detours for unadmitted vehicles), the control of passes might create congestion at the gates. Finally, communication is fundamental as some drivers may interpret the limit as a closure and turn down the visit.

3. Study area

This study focuses on the area of the Sella massif in the Dolomites (Eastern Italian Alps) and particularly the scenic and extremely popular road that circles it. The road connects four passes - Passo Sella (2240 m), Passo Gardena-Gröden (2136 m), Passo Campolongo (1875 m) and Passo Pordoi (2239 m) – enabling basic trips from valley to valley and also what is often called "Sellaronda" tour, a 58 km long circular trip taken by around 14% of road travelers (Scuttari and Bassani, 2015) (Fig. 1). From a transportation perspective, the passes have multiple functions: they work as logistical connections between adjacent valleys, but also as tourist attractions in the form of panoramic terraces from which to enjoy spectacular landscapes or departure points for a variety of excursions (e.g. hikes and rock climbs during the summer season, ski tours in winter). For other active tourists (e.g. cyclists) they may be the endpoint of challenging journeys from valley floors. The technical features of the road along with the recorded volume of traffic make these multiple functions hardly coexist. For instance, the road section climbing to the Sella Pass is between 5.60 and 6.00 m wide and 7% steep (Provincial Road Office of the Autonomous Province of Bolzano, data available on demand), and it is traveled by an average 3500 motorized vehicles per day in summer months (ASTAT, 2019). For a matter of comparison, cyclists are around 600 a day in the same period (Scuttari, 2019). The tourist popularity of these places – testified by the evident link between overnight stays and traffic data (Scuttari, 2019) - has led, over the years, to significant issues (i.e. congestion, noise, parking in undesignated areas) and tough questions about how to handle visitor flows in a sustainable way.

Various traffic management strategies have been assessed in the area for 20 years now, also through the elaboration of *ad hoc* scientific studies (Pechlaner et al., 2004; Pörnbacher, 1995; Scuttari and Bassani, 2015). Nevertheless, it was only after the Dolomites have been inscribed onto the UNESCO World Heritage list (2009), that a pilot project for traffic management was finally implemented on-site to discourage the use of private vehicles and favor the use of public transport. The pilot project, called *#Dolomitesvives* ("living Dolomites"), was launched in the summer of 2017 on the roads leading to Passo Sella, and involved access restrictions for private vehicles (and improved bus service) from 9 AM to 4 PM one day a week. This specific measure was selected based on the results of a stated preference study commissioned by the Dolomites UNESCO Foundation aimed at assessing people's attitudes towards different management policies (Scuttari et al., 2019). The study had shown that a combination of road closures and improved bus service could be not just effective but also moderately well received by visitors. Other options, such as quotas or road tolls, had been deemed problematic by local administrations owing to various feasibility issues (e.g. equity of fees). Nevertheless, a higher-than-expected percentage of visitors turning down their travel to the pass in 2017 (Scuttari et al., 2018b) encouraged administrators to reconsider a previously discarded option, namely the quota system. The present study was conducted to support the design of such a system, which was then tested in July-August 2018, in the framework of the *#Dolomitesvives* initiative's second round.

4. Method

The approach to the identification of the right quota involved four steps (Fig. 2), as follows:

1) Development of an ABM to simulate the movement of vehicles along the road network;
2) Definition of objectives, indicators and standards of quality to assess the impact of different quota levels;
3) Running of multiple simulations to identify the most suitable quota level based on the previously defined indicators and standards;
4) Analysis of visitors' acceptability of the previously identified quota.

Each of the four steps is described in detail in the sections below.

4.1. The model

4.1.1. Purpose, entities and state variables

The model, which was built in NetLogo (Wilensky, 1999) and is described here following the widely accepted ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2010), aims to simulate traffic and parking lot occupancy rates throughout the day as a function of the number of vehicles allowed to enter the study area every hour from the various gates. The model was developed and calibrated considering traffic flows monitored during weekdays of July and August, that is when the measure would be implemented. Although the model simulates traffic along the entire road circling the Sella massif, accuracy is only guaranteed on road sections leading to the Sella and Gardena-Gröden passes as these entirely fall within the territories of Provinces willing to implement the quota system.

Two agent types are considered – private vehicles and buses – whose state variables are reported in Table 2. Private vehicles may be cars or motorbikes and be driven by residents (i.e. people living in the administrative Provinces hosting the study area) or tourists (i.e. people living elsewhere). Mode and residence affect the behavior of this agent type (e.g. average time spent at destination, acceleration) as observed in reality. Buses represent the ATS serving the road network (cableways, though existing in the study area, are not considered in the

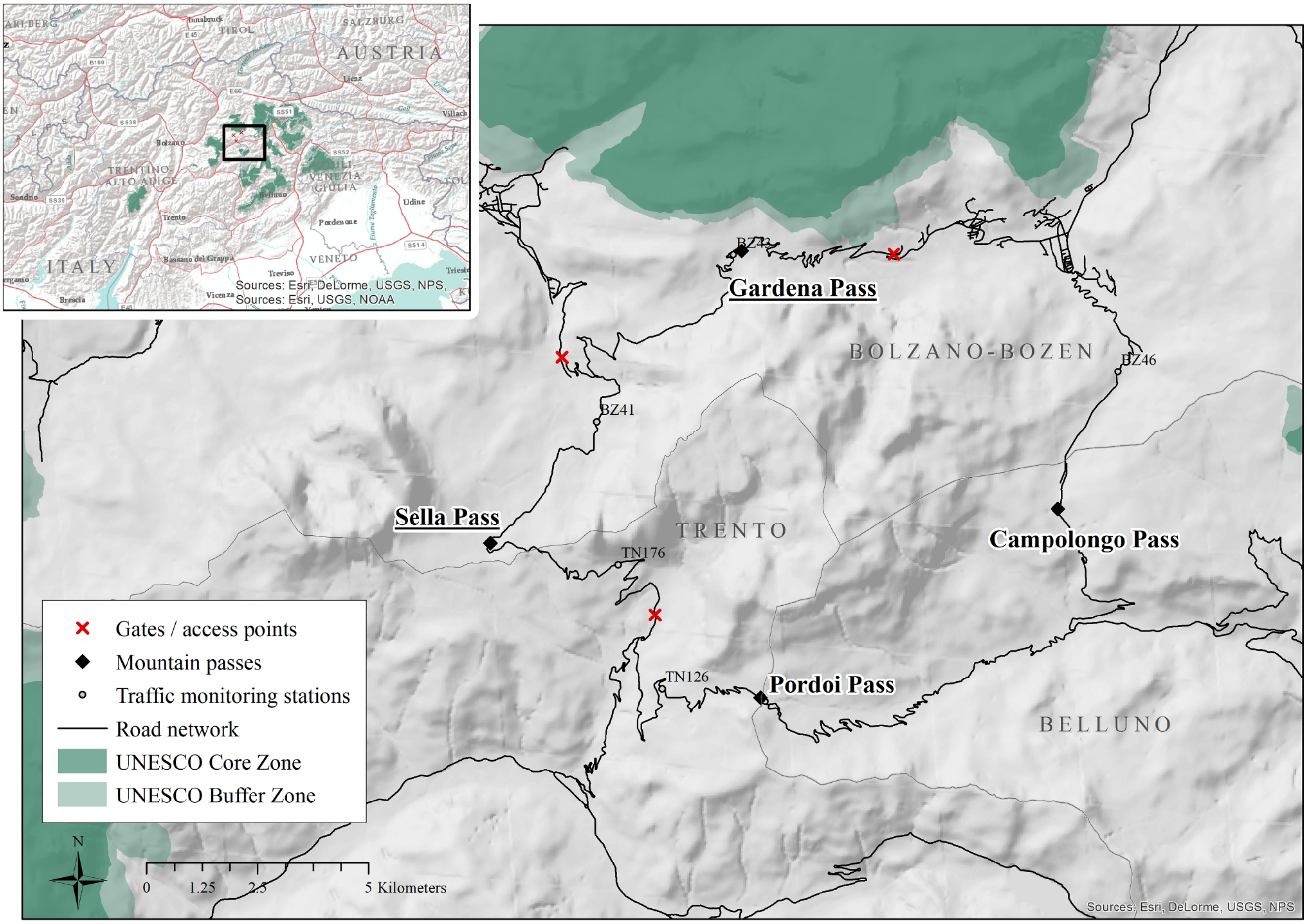

Fig. 1. The area of the Sella massif in the Eastern Italian Alps, with the famous road running around it and the four passes the road goes through: Sella, Gardena-Gröden, Campolongo and Pordoi. This study primarily focuses on road sections leading to the first two.

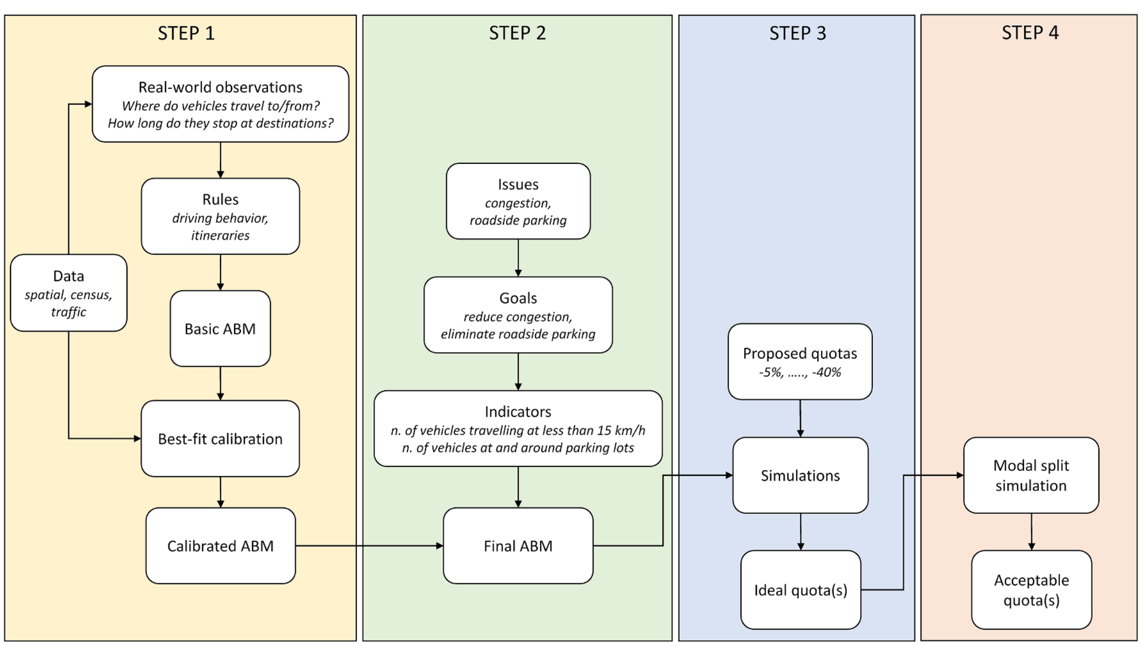

Fig. 2. Four-step process aimed at the definition of the appropriate quota: a basic ABM for the simulation of vehicle movements along the road network is developed (1); objectives, indicators and standards of quality to assess the impact of different quota levels are defined and implemented in the ABM (2); multiple simulations are run to identify the most suitable quota level according to indicators and standards (3); the visitors' acceptability of the ideal quota is assessed according to the modal split it induces (4).

Table 2
State variables assigned to the model's entities (measurement units are in parentheses, when available).

Entity	State variables	Variability
Private vehicle	Origin (i.e. gateway valley); destination (i.e. pass); mode (i.e. car or motorbike); visitor type (i.e. resident or tourist); itinerary (i.e. pass or valley on the other side of the pass); speed factor (m s^{-1}); acceleration factor (m s^{-2});	Constant (established when the agent is created)
	Speed (m s^{-1}); distance from vehicle ahead (m); distance from junctions (m); curvature of the road ahead (degrees)	Change at each time step
	Time spent at destination (s)	Constant (established when the agent reaches the parking lot)
Bus	Origin (i.e. gateway valley); destination (i.e. pass); time spent at bus stop (s)	Constant (established when the agent is created)
	Speed (m s^{-1}); distance from vehicle ahead (m); distance from bus stop (m); curvature of the road ahead (degrees)	Change at each time step
Grid cell	Presence/absence of road, parking lot or bus stop; distance to key locations (e.g. villages) (m)	Constant (established in the setup phase)
	Number of parked vehicles	Changes at each time step

model).

The environment is represented by a grid of 414 × 454 cells, each covering an area of 625 m^2 (25-m side). Cells corresponding to roads are assigned values of path distance to key locations (e.g. villages on the valley floors), whereas cells corresponding to parking lots are assigned state variables reporting the number of parked vehicles. One time step in the model represents one second in the reality and simulations are run for 12 h (43,200 time steps): from 7 AM to 7 PM (traffic beyond this slot is negligible).

4.1.2. Process overview and scheduling

The model encompasses a limited series of processes for both private vehicles and buses (Fig. 3). Private vehicles are generated at the four entrances of the study area at a rate controlled by a dedicated submodel, which also assigns vehicles a mode, visitor type and itinerary based on real-world observations. Vehicles travel to the destination (the driving behavior is handled by a submodel) and may do brief stops along the way depending on their preferences and contingent conditions (i.e. crowding). Once at the destination, they occupy a parking space for a time that is a function of their characteristics (e.g. mode) and time of arrival. When time is up, they update their destination variable (i.e. destination = origin) and travel back to their origin, where they are eventually removed from the simulation.

Buses are generated at the four entrances according to the real schedule, they are assigned a destination, to which they travel (the driving behavior is handled by a submodel), stopping at the designated bus stops. They are removed from the simulation once they have reached their destination.

The order in which an agent performs different actions is fixed (e.g. a vehicle moves to the destination, stops at the parking lot and travels back), but the order in which different agents perform a specific action (e.g. move along the road) is shuffled at each time step.

4.1.3. Design concepts

Design concepts, as defined in the ODD protocol (Grimm et al., 2010), are presented in Table 3.

4.1.4. Details

At time step $t = 0$, no agents populate the study area. They are created as the simulation runs according to vehicle arrival rates observed in the reality and the quota imposed by the user (see below). The model relies on three submodels for vehicle generation, driving and parking, as follows.

Vehicle generation. New vehicles are generated at the study area's four entrances (Fig. 4) between 7 AM and 2 PM: all traffic after 2 PM is assumed to be made up of vehicles that started their trip earlier during

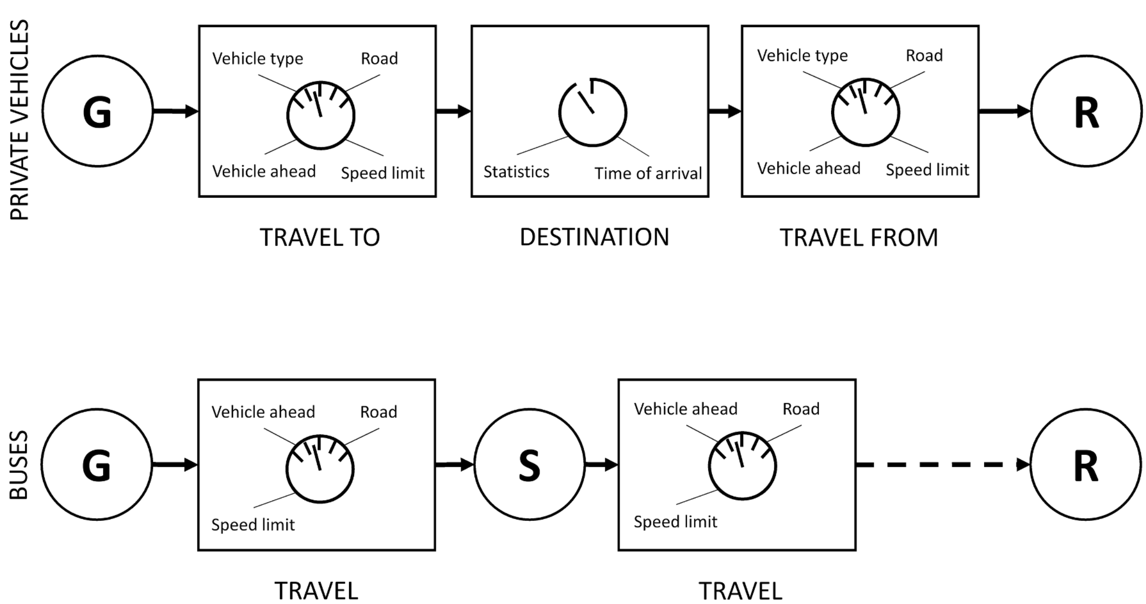

Fig. 3. Model's schedule showing actions performed by the two agent types - private vehicles and buses – from the time they are generated (G) till the time they are removed from the simulation (R). Private vehicles perform three main activities: they travel to/from the destination (speed determined by vehicle type, traffic, road curvature and speed limit) and spend time at the destination (time determined by real-world visitation statistics and time of arrival). Buses travel (speed determined by traffic, road curvature and speed limit) except when they are at a stop (S).

Table 3
Design concepts as defined in the ODD protocol (Grimm et al., 2010).

Design concept	Description
Basic principles	The study area is modeled as a closed system with four sources/sinks of vehicles corresponding to the four entrances. The overall behavior of private vehicles (e.g. where to go) does not change depending on the amount of vehicles in the system.
Emergence	Queues emerge as vehicles adapt their speed to that of the vehicle ahead. This is particularly evident at junctions and bus stops, and when traffic volumes are higher.
Adaptation	Private vehicles move towards cells that are closer to their destination, make brief stops along the way if parking space is available and define the time to spend at the destination based on time left to the end of the day.
Objectives	Agent's movement is driven by the goal of minimizing path distance (i.e. distance along the road) from destination.
Learning	Agents do not change their adaptive traits over time.
Prediction	Agents do not have predictive abilities.
Sensing	Agents can evaluate the curvature of the road ahead, perceive a vehicle (and which type of vehicle) is ahead of them, assess if roadside stopping places have free parking spaces.
Interaction	Direct interactions take place on the road, where vehicles adapt their speed to vehicles ahead, and at roadside stopping places, which vehicles enter only if there is space available.
Stochasticity	The speed and acceleration factors (i.e. initial speed and acceleration level) of private vehicles, as well as time spent at roadside stopping places are modelled stochastically according to normal distributions. Mode, visitor type and itinerary are assigned stochastically based on real-world observations.
Collectives	Cars and motorbikes are not separate collectives as they share the same state variables.
Observation	The number of vehicles at main parking lots, the average speed of vehicles, the hourly number of vehicles exiting the study area from the four entrances and the hourly number of vehicles not allowed to enter the study area are monitored throughout the simulation.

the day. When the model is run under current conditions (i.e. no quota), the hourly rate of vehicle generation reflects the arrival rate of vehicles observed in reality. When a quota is imposed (as a percentage of today's traffic volumes), vehicle generation between 7 AM and 9 AM is unaltered (the quota would be effective after 9 AM), whereas after 9 AM the total number of vehicles allowed to enter after that time (expressed as a percent reduction from current conditions) is equally distributed across the five hours between 9 AM and 2 PM.

As soon as a vehicle is generated, it is assigned a mode, visitor type and itinerary according to the characteristics and choices of real visitors. Regarding itinerary, it is assumed that visitors have only two options: they either reach a pass, spend some time there and return, or they cross the pass, reach the opposite valley, spend some time there and return (Fig. 4). The possibility of crossing two or more passes was discarded for a matter of simplicity because the monitoring of visitor trips had shown that only a very limited share of all visitors (about 16%) choose this option (Scuttari and Bassani, 2015).

Driving. During the driving phase, decision-making is limited to following the road and maintaining a safety distance from the preceding vehicle, similar to what implemented in pioneering cellular automata transportation models (Nagel and Schrekenberg, 1992) and in queueing simulation (Charypar et al., 2007). At each time step, driving vehicles move towards the adjacent road cell that is closest to their current destination. Vehicles accelerate (up to the speed limit) when they are on a straight road section or are exiting a curve (i.e. when the curvature of the road ahead is progressively declining), whereas they slow down when entering a curve (i.e. when the curvature of the road ahead is progressively increasing) or they are approaching a junction or a pass. The acceleration of each vehicle is given by the basic individual acceleration potential established at the beginning of the simulation (based on random normal distributions for private vehicles, constant for buses) and a factor inversely related to speed (i.e. acceleration decreases as speed increases). Acceleration is highest for motorbikes, followed by cars and buses. For example, at moderate speeds, motorbikes have an acceleration that is 10% higher than that of cars (i.e. every second the speed of a motorbike increases 10% more than that of a car), whereas buses have one that is 5% lower than that of cars. Deceleration is given by the summation of two factors: a fixed one and one inversely related to road curvature.

Cars and buses adapt their speed to that of the vehicle ahead (overtaking is never allowed), whereas motorbikes do so only when they are on a curve (i.e. they overtake on straight road sections). The slope does not have an impact on vehicle speed.

The submodel was calibrated by adjusting acceleration and deceleration parameters, both the fixed ones (constants) and those associated with speed and road curvature, until travel times between known points (e.g. a junction and a pass) reflected real ones as calculated on Google Maps.

Parking. Vehicles reaching their destination (i.e. passes and valley floors) park by simply moving on a parking cell adjacent to the road (the parking cell keeps track of how many cars are parked at any given moment). Neither queues nor a shortage of parking spaces are simulated because, in the reality, people park on roadsides as soon as the official parking lots are full. Once the vehicle is parked, the specific

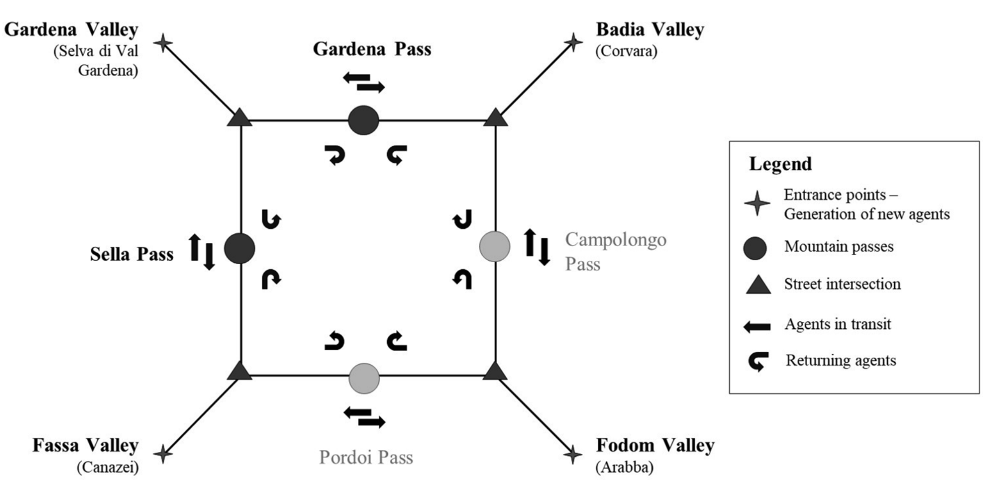

Fig. 4. Layout of the simulated road network showing origins and destinations of agents. Agents are generated at the four corners of the study area and are assigned a direction reflecting one of the two passes adjacent to the origin (e.g. agents generated in Fassa Valley can travel towards either Sella Pass or Pordoi Pass). Once at a pass, they can keep going and reach the opposite valley or stop. Although the whole study area was considered, the model is accurate on the north western part only (passes indicated with darker color), where a real quota system is under consideration by local administrations.

time spent at the destination is computed according to a random normal distribution that is a function of mode (i.e. on average, car users tend to stay longer than motorbike users) and time of arrival (i.e. people must return before the end of the day, hence length of stay computed according to the above-mentioned distribution can never exceed the difference between 6 PM and the time of arrival), based on real-world observations (i.e. average time of stay for car users is three to five hours, depending on the destination, compared to only one hour for motorbike users).

Vehicles approaching roadside stopping places make a brief stop if they have not done so already (i.e. only one stop along the way is admitted), at least one parking space is available and feel like stopping (as defined by a random probability).

4.1.5. Calibration

While the driving submodel was calibrated independently as specified above, the overall model was calibrated by adjusting the random components of time spent at destinations so that the number of vehicles exiting the area every hour (time-series calibration) from the four gates during the afternoon (i.e. 1–2 PM, 2–3 PM, etc.) and the maximum number of vehicles at the parking lots on the passes were consistent with what observed in the field. A best-fit calibration approach was selected: parameter values were sought for that minimized the sum of squares of the differences between the real and the predicted counts of vehicles exiting the area in the different time slots. Additionally, it was ensured that the maximum number of vehicles at the passes as predicted by the model did not exceed what observed in reality.

In the absence of accurate hourly information on the distribution of vehicles along the road network, qualitative analyses were also performed to make sure patterns observed in the reality (e.g. queues at junctions) were adequately simulated by the model.

4.1.6. Data

Data used to build and calibrate the model are summarized in Table 4. Spatial data were used to define the characteristics of the study area, including the exact shape of roads, the location of bus stops and the capacity of parking lots. Traffic data, from both official statistics and authors' analyses (e.g. Google Maps, video footage), were used to estimate the flows of vehicles and modal splits, and to calibrate, quantitatively and qualitatively, the model as explained in the previous section.

4.2. Definition of objectives, indicators and standards of quality

The most pressing issues associated with car traffic in the study area are traffic congestion (i.e. a considerable percentage of cars traveling at low speeds in various sections of the road network) and excessive demand for parking space (i.e. official parking capacity systematically exceeded), which determine a broad array of environmental and social problems impoverishing visitor recreational experience. Congestion leads to increased travel times and pollution, whereas the shortage of parking spaces results in the occupation (and damage) of roadside spaces, visual intrusion, and further congestion. Hence, the adopted quota should make sure that: traffic congestion affects only a minor share of vehicles at any time of the day and parking lot capacity is never exceeded during the day. The indicators selected to measure the performance of a quota concerning these objectives are:

- share (%) of vehicles traveling at speed below 15 km h^{-1} out of all vehicles traveling along the road network in a given moment;
- number of cars (not motorbikes) parked at (and around) parking lots on the passes.

The standards assumed to ascertain the actual achievement of the objectives are: 2% for the congestion goal, and 300 (Passo Sella) and

Table 4
Data used in the study with specification of their sources and whether they were used for model design or calibration.

Type of data	Data description	Source	Data usage
Spatial data			
National and provincial roads	Shapefiles of national roads (SS242, SS243, SS244, SS248) located in the region Trentino-Alto Adige and one provincial road (SR48) located in the Province of Belluno (Veneto region).	Spatial data services of the Autonomous Province of Bolzano-Bozen (APoB, 2018) and EURAC's database.	Design
Parking areas and capacities	Location of public and private parking lots within the study area (with data about their capacities) as of 2018.	Municipalities (data available on demand) and Google Maps.	Design
Bus stops	Location of all bus stops along the roads of the study area as of 2018.	Spatial data services of the Autonomous Province of Bolzano-Bozen (APoB, 2018), Google Maps and Streeview.	Design
Speed limits	Georeferenced data about speed limits and restrictions along the road network as of 2018.	Own observations.	Design
Census and traffic data			
Traffic flows on mountain pass roads (private vehicles)	Hourly inbound and outbound flows (and average speed) of light vehicles (motorcycles, cars and small vans) during working days in July and August 2016 at 5 monitoring stations (BZ 41, BZ 43, BZ 46, TN 126, TN 176) located on state roads in Trentino and South Tyrol.	Provincial Institute of Statistics (ASTAT, 2019) of the Autonomous Province of Bolzano-Bozen (ApoB) and Provincial service for road and railway works, Autonomous Province of Trento (ApoT) (data available on demand).	Design and calibration
Schedule of public transport (buses)	Official schedule of buses along roads leading to Sella and Gardena-Gröden passes on weekdays in July and August 2018.	Public transport companies of APoT and APoB (http://www.ttesercizio.it; www.sii.bz.it).	Design
O-D matrix (private vehicles)	Average daily transit traffic flows on the state road of the Sella mountain pass collected with specific cameras during July 26th to August 23rd 2017.	Provincial Service for road and railway, ApoT (Scuttari et al., 2018a, p. 22–27).	Design
Preferred transport mode	Transport mode chosen by visitors to reach the Sella pass (modal split).	Project report based on a survey conducted in 2014 (Scuttari and Bassani, 2015).	Design
Time spent at destination	Average time spent by visitors on the Sella pass in July and August 2017 (data used as a proxy for visits to the Gardena-Gröden Pass).	Project report based on a survey conducted in 2014 (Scuttari and Bassani, 2015).	Design and calibration
Travel time	Travel times between key points along the road network (e.g. junctions, passes)	Google Maps	Calibration
Traffic patterns	Occurrence of queues and congestion along the road network on an average day	Video taken by one of the authors using a motorbike and a helmet camera	Calibration

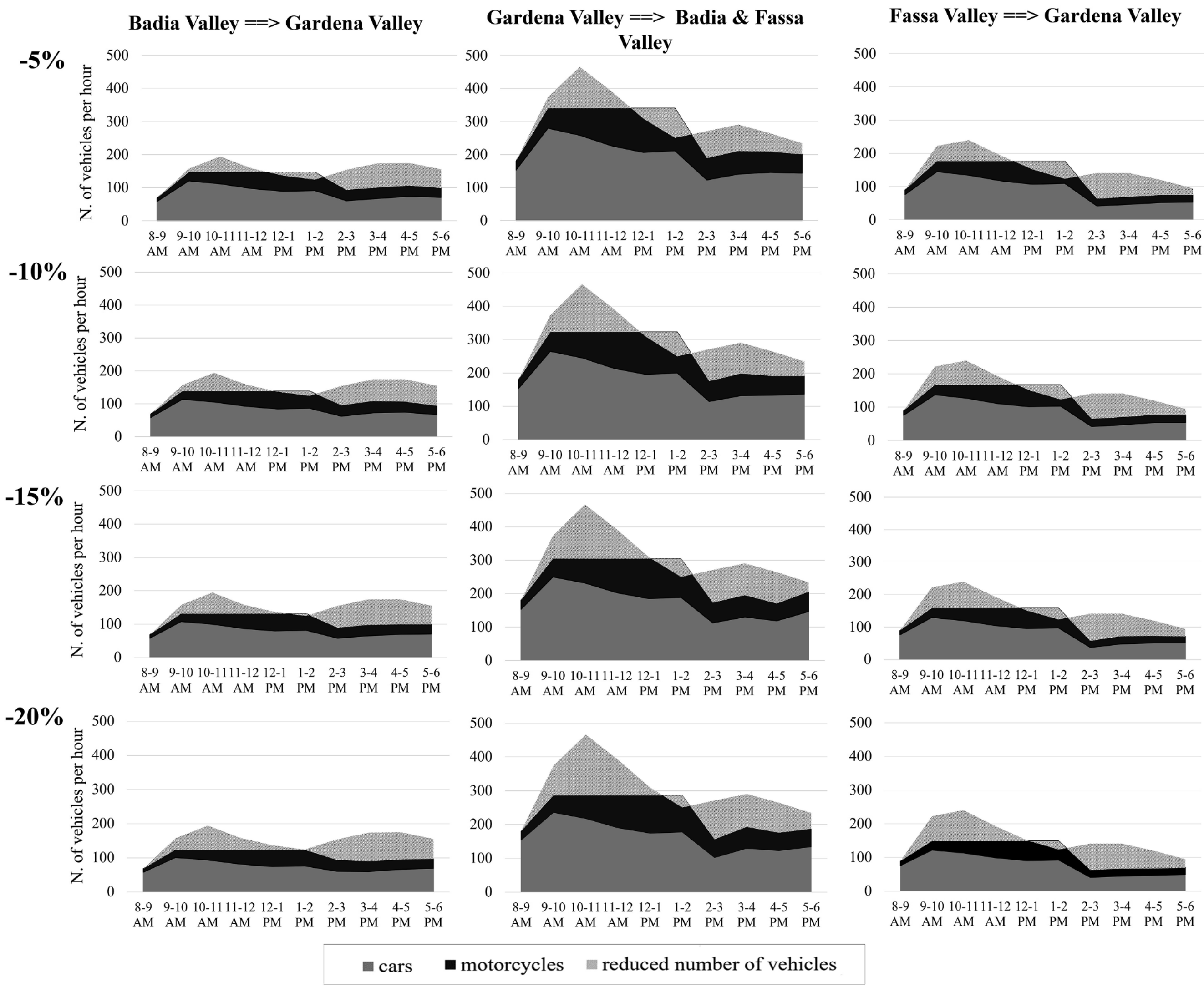

Fig. 5. a. Current and projected hourly traffic inflows at the Badia, Gardena-Gröden and Fassa entrances under quotas of −5%, −10%, −15%, and −20%. Inflows at the Badia and Fassa entrances only consider vehicles travelling to the Gardena-Gröden and Sella passes, respectively. b. Current and projected hourly traffic inflows at the Badia, Gardena-Gröden and Fassa entrances under quotas of −25%, −30%, −35%, and −40%. Inflows at the Badia and Fassa entrances only consider vehicles travelling to the Gardena-Gröden and Sella passes, respectively.

120 (Passo Gardena) for the parking goal. The former reflects the background congestion that is observed even with low traffic levels, mostly due to the presence of junctions slowing down vehicles. The latter represent the number of parking spaces currently available at the two passes.

The model was slightly modified so that it could monitor the above indicators at each time step throughout the simulation and compute hourly averages that would ultimately be used for assessing the effects of a quota.

4.3. Simulations

Eight quotas (scenarios) were considered corresponding to overall traffic reductions (after 9 AM) of 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%, respectively. While the most extreme of these scenarios might seem inappropriate from the point of view of traditional traffic management, they are consistent with the idea of curbing traffic volumes in a context characterized by very limited road space, high environmental sensitivity and high incidence of motorcycling tourism. Five replicate simulations were run for each scenario and the average of indicator scores across a scenario's replicates computed. Given the lack of hourly data on both congestion and number of parked vehicles, indicator averages for the eight scenarios were compared, on an hourly basis, to relevant values obtained from simulations run under current conditions (status quo). Ideal quota level(s) were identified as those producing outcomes that comply with the standards presented in Section 4.2 during the entire day.

4.4. Analysis of acceptability

The appropriateness and success of vehicle quotas in a recreational area lie in their ability to reduce (or eliminate) traffic-related issues through a sensible moderation of vehicle inflows, while making sure that occupants of rejected vehicles accept to shift from private vehicles to other, more sustainable, transport modes (e.g. buses, bicycles), rather than leaving the area. This possibility was tested by simulating, on an hourly basis, the modal split induced by the quota using a Nested Logit model, whose parameters had been estimated through a survey conducted in the study area in the summer of 2014 (parameter estimates are presented in the Appendix) (Scuttari et al., 2019). The model considers three alternatives – private vehicle, bus, abandon the area – and five attributes pertaining to the cost, hours of access, ease of access, use level (i.e. road traffic for the private vehicle option, crowding onboard for the bus option) of the transportation alternatives, and expected crowding at the passes. In particular, ease of access for the private vehicle option refers to the quota and is measured as the probability of being allowed to enter the road with the private vehicle.

One modal split was estimated for each of the ideal quota levels, each gateway (i.e. Badia Valley, Gardena-Gröden Valley, Fassa Valley), each of the five hours between 9 AM and 2 PM, and each of three frequencies of bus service (i.e. 30, 20, 15 min), considering no cost for the private vehicle (i.e. no road toll), a 2 euro round trip ticket for the bus (i.e. in line with current prices and the availability of discount cards), no road closures (i.e. vehicles can enter at any time up to the fulfillment of the quota), an extended bus service (i.e. 9 AM to 7 PM), medium traffic on the road and medium levels of crowding both on the buses and at the passes. As to the probability of entering the road because of the quota, a different value was considered for each of the five hours between 9 AM and 2 PM, reflecting the ratio of the number of vehicles allowed to enter on an hourly basis to the number of vehicles entering in that specific hour under normal conditions.

5. Results

The impact of quotas on the flow of vehicles entering the three valleys with direct access to the Sella and Gardena-Gröden passes is summarized in Fig. 5a and b (only traffic moving to the Gardena-Gröden Valley is considered in the first and last columns because that would be subject to restrictions). Two elements are evident. The first one, as per the design of the quota system, is the replacement of the morning peak by a constant inflow of vehicles. The number of vehicles entering the valleys between 10AM and 11AM (i.e. the busiest time slot) would decline by between 50 (−5% quota) and 100 units (−40% quota) in Badia Valley, between 120 (−5%) and 270 units (−40%) in Gardena-Gröden Valley, and between 60 (−5%) and 130 units (−40%) in Fassa Valley. The second element is the fact that, as long as the overall vehicle reduction is moderate (i.e. up to −25%), some of the traffic not allowed during the morning hours is compensated by extra traffic in the early afternoon. For traffic reduction of 5–10%, this compensation is considerable, meaning that overall traffic is mostly redistributed rather than reduced. Moreover, graphs show how quotas, while simply targeting morning traffic, might affect also afternoon traffic in terms of both volume (i.e. less vehicles) and trend (i.e. shifted peak) as this is mostly return traffic. The afternoon peak would decline by between 80 (−5%) and 100 units (−40%) in Badia Valley, between 90 (−5%) and 150 units (−40%) in Gardena-Gröden Valley, between 60 (−5%) and 80 units (−40%) in Fassa Valley, and generally shift to the 4PM-5PM and 5PM-6PM slots (Fig. 5b).

All quota levels might considerably reduce congestion problems in the morning hours, bringing the share of slow-traveling vehicles in the 10-11AM slot from 6% (status quo) to 2.5% or less (Fig. 6). While a comprehensive look at curves for the eight scenarios highlight an expected negative correlation between traffic reduction and congestion (i.e. the stronger the reduction the lesser the congestion), an hour-by-hour analysis shows stronger traffic reductions might cause slightly worse congestion problems than lighter reductions in some parts of the day (e.g. −40% quota compared to −30% and −35% quotas in the last part of the day). Even more interestingly, a comparison between the status quo and the −5% curve suggests traffic redistribution, rather than traffic reduction, is the key contribution of the quota system to easing congestion. In fact, under the −5% quota, an overall amount of vehicles slightly smaller than that of the status quo would flow smoothly during the entire day, with only minor congestion problems between 12PM and 2PM (when the quota system would let more vehicles in). The −40% scenario is the only one under which congestion would remain within the previously defined standard (2%) throughout the day, though conditions would still be acceptable with reductions of −25% to −35% (i.e. 2.16% of slow-traveling vehicles at most) (Table 5).

The implementation of the quota system could reduce parking lot occupancy rates, in a way that is proportional to overall traffic reduction, and delay the moment of maximum occupancy (from the 1-2PM slot to the 2-3PM slot at Sella Pass and from the 12-1PM slot to the 1-2PM slot at Gardena-Gröden Pass) (Fig. 7). The latter effect would be mostly associated with milder traffic reductions (−5% to −25%) as in that case traffic flows in the early afternoon would surpass those of the status quo. While even 10% traffic reductions would ensure good conditions at parking lots during most of the day, a −35% quota might be needed to make sure current parking lot capacity is never exceeded. Hence, taking into account the outcomes of the congestion analysis, the −35% quota seems that guaranteeing the full achievement of management objectives (Table 5).

Modal splits that would be induced by the −25%, −30% and −35% quotas are presented in Fig. 8. As expected, the number of vehicles abandoning the area because of the quotas would be higher in the first three hours of restriction, when the actual probability of entering the road on one's own vehicle is considerably low (i.e. a mere 50–60% between 10 and 11 AM). In this time frame, up to 65 vehicles (equivalent to about 150 people) in Gardena-Gröden Valley and about 30 vehicles (equivalent to 70 people) in both Fassa and Badia Valleys might give up their visit on an hourly basis. However, these figures may be reduced considerably by simply improving the bus service. For example, under a −35% quota, shifting from a 30-minute to a 15-minute bus frequency might reduce the number of abandoning vehicles in the 10–11 AM time slot from 65 to 47 in Gardena-Gröden Valley, from 34 to 24 in Fassa Valley and from 27 to 17 in Badia Valley. Simultaneously, the number of vehicles whose passengers would shift to the bus would increase from 280 to 350 in Gardena-Gröden Valley, from 146 to 178 in Fassa Valley and from 114 to 146 in Badia Valley. The enforcement of stricter quotas (i.e. shifting from −25% to −30% to −35%) would have a stronger effect on the number of entering vehicles (which would decline) and the number of bus riders (which would increase) than the number of abandoning vehicles (which would increase). Moreover, it is interesting to observe that the number of private vehicles "willing" to enter the road is markedly lower than the threshold imposed by the quota and that the summation of these vehicles and vehicles that would abandon the area is generally below, or slightly above (when bus frequency is 30 min), that threshold. This means that, given today's visitor preferences, clear information about the quota system and an adequate bus service could shift enough people to the bus to potentially allow all those who are determined to drive (i.e. everyone except those who would choose the bus) to do so.

6. Discussion

The contribution of this study to the transport policy literature is twofold. From an empirical perspective, it shows whether and how a quota system might address some of natural areas' traffic-related issues, hence improving environmental protection and the quality of visitor experience. From a policy and management perspective, it proposes an approach protected area and tourism managers can follow to identify the right quota for a specific context.

Our study has shown that relatively moderate traffic reductions and a redistribution of inflows can achieve great results in terms of limiting traffic-related issues. On the Sellaronda network, for example, a 10 to 25% overall traffic reduction is enough to handle most of congestion and parking problems, though a 35% reduction may be needed to comply with the standards imposed by the local context. These numbers are totally consistent with findings of similar studies – for example, Lawson et al. (2003) found that excluding around 50% of vehicles normally entering Arches National Park may be needed to achieve management objectives – and not too different from those expected from road pricing schemes in various cities (Bureau and Glachant, 2008; Börjesson et al., 2012).

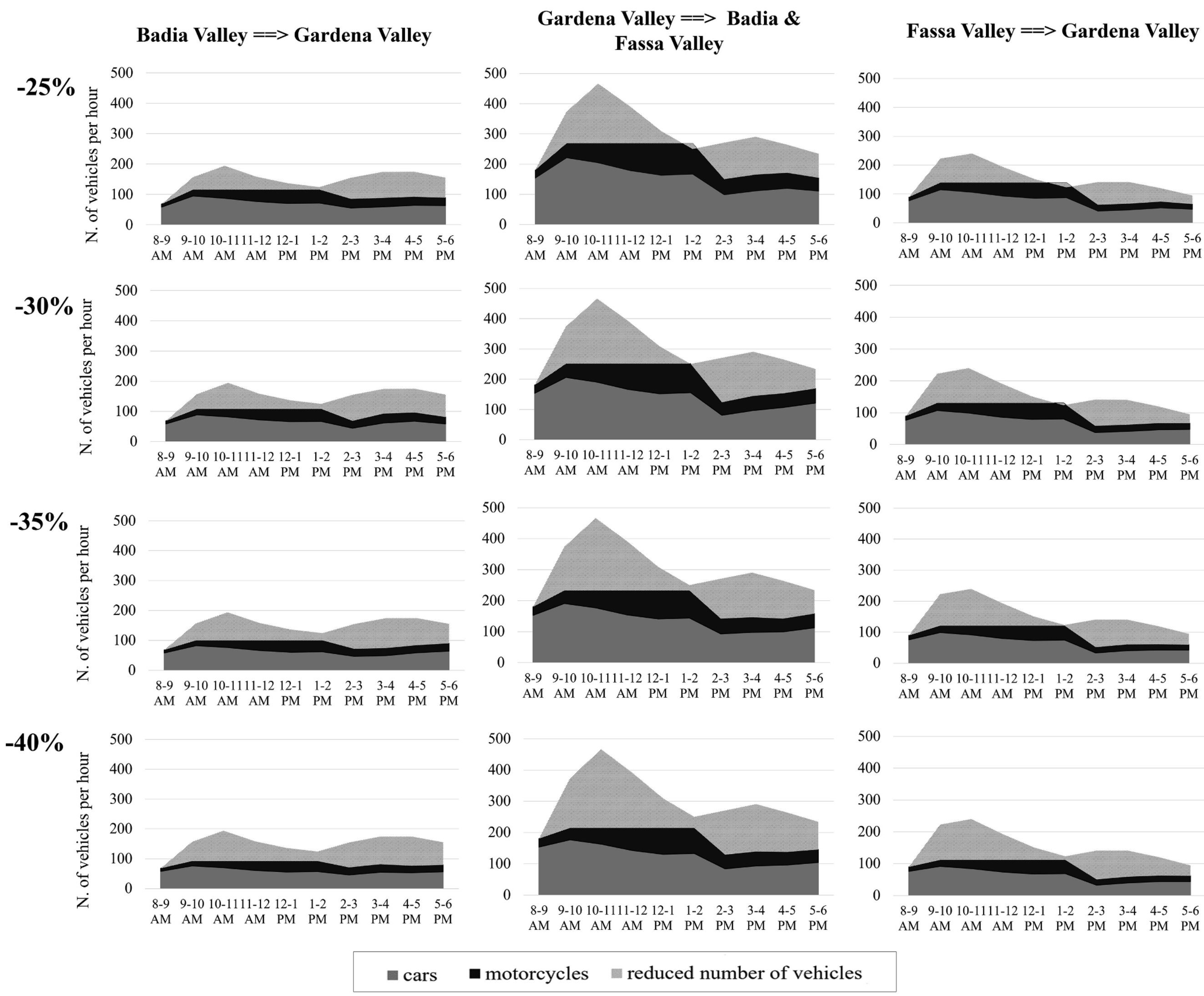

Fig. 5. (*continued*)

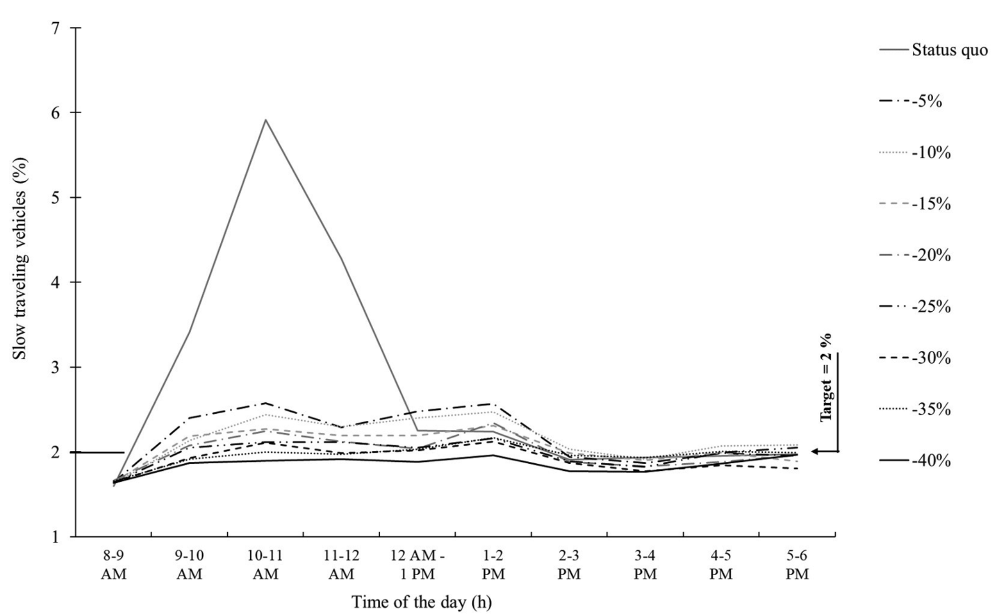

Fig. 6. Traffic congestion, measured as the share of vehicles traveling at speed below 15 km/h, between 8 AM and 6 PM under different quota levels.

Table 5
Effectiveness of the different quotas in terms of their ability to achieve (Yes) or not achieve (No) the management objectives (standards of quality).

Quota	Achievement of management objectives		
	Congestion[a]	Parking capacity (Sella)	Parking capacity (Gardena)
−5%	No	No	No
−10%	No	No	No
−15%	No	No	No
−20%	No	No	No
−25%	Yes/No	No	No
−30%	Yes/No	No	No
−35%	Yes/No	Yes	Yes
−40%	Yes	Yes	Yes

[a]While traffic reductions of −25% to −35% do not formally achieve the congestion objective, they get very close to it (2.16% slow-traveling vehicles instead of 2%) and can therefore be considered successful.

Moreover, our findings support the idea that a quota system may be designed so as to not simply reduce traffic volumes, but also redistribute traffic inflows in a way that is deeply beneficial for an area. Specifically, we observed that a hourly quota replacing the morning traffic peak with a constant inflow of vehicles may substantially eliminate traffic congestion, even when the actual reduction in overall traffic volume is negligible (−5%). This suggests managers could minimize transport-related nuisance, and possibly the impact of visitors at the destination (Lawson et al., 2009; Orsi and Geneletti, 2016), without necessarily reducing the overall number of vehicles entering a road system during the day if they only were able to regulate the hourly vehicle inflow according to the road network's capacity. While such strategy would still levy a burden on visitors as it would require some of them to anticipate or postpone their visit according to the available slots, it would allow everybody to drive through an area, possibly limiting the economic losses of businesses located along the restricted section of the road (e.g. restaurants, souvenir shops, etc.). Clearly, this would only be possible if existing traffic volumes were somewhat manageable and visitors had a certain degree of flexibility, which may not be the case in very popular destinations offering specific recreational opportunities (e.g. hikers may want to be at the trailhead relatively early).

Simulations suggest the overall traffic reduction imposed by the quota system would have different effects on congestion and parking lot occupancy. Congestion would generally decline as quotas become stricter, though reversals might be observed in some parts of the day owing to the complex interactions between vehicles and the road as well as among vehicles (Fig. 6). For example, less traffic may facilitate higher speeds in one section of the network, but these can generate a temporary slowdown in another section (see, e.g. Scuttari, 2019).

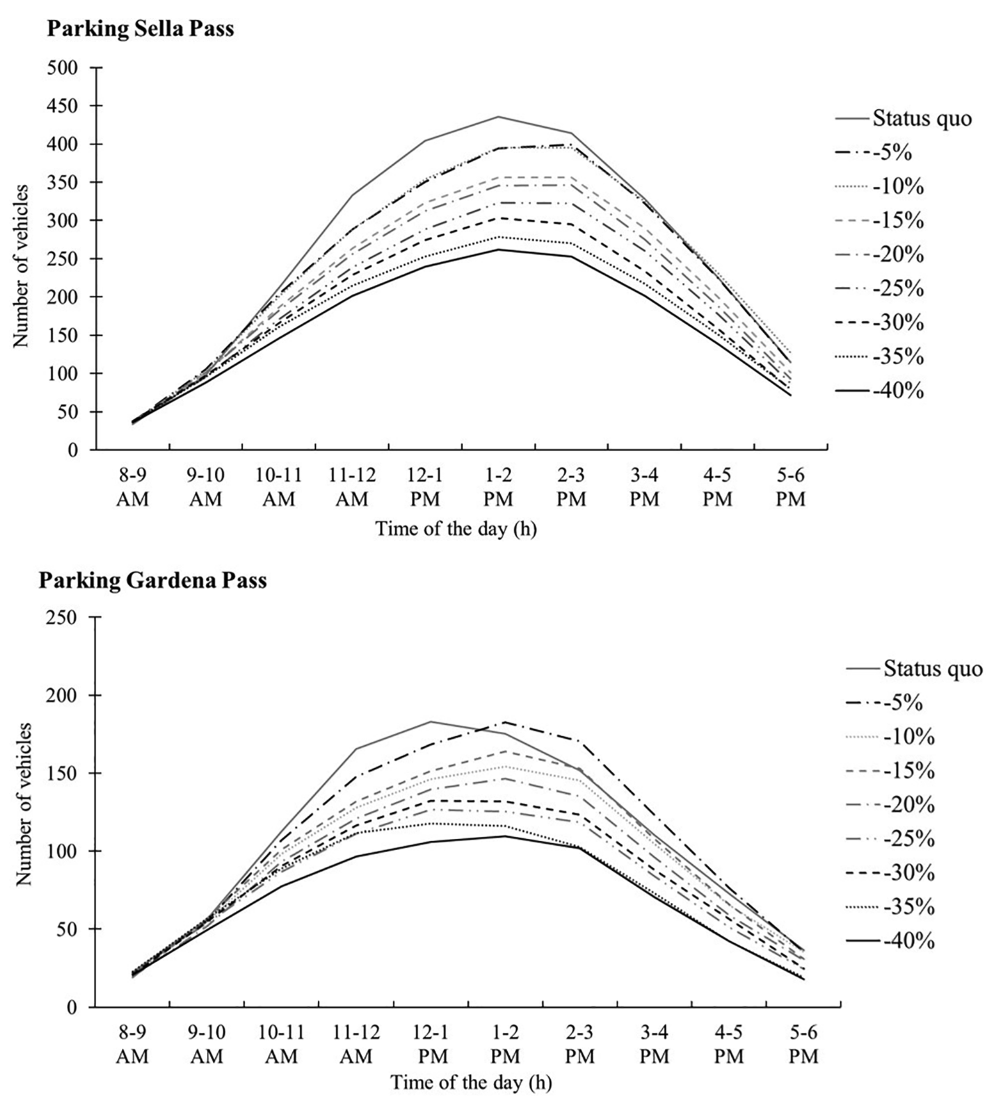

Fig. 7. Average number of cars parked at the Sella and Gardena-Gröden passes between 8 AM and 6 PM under different quota levels.

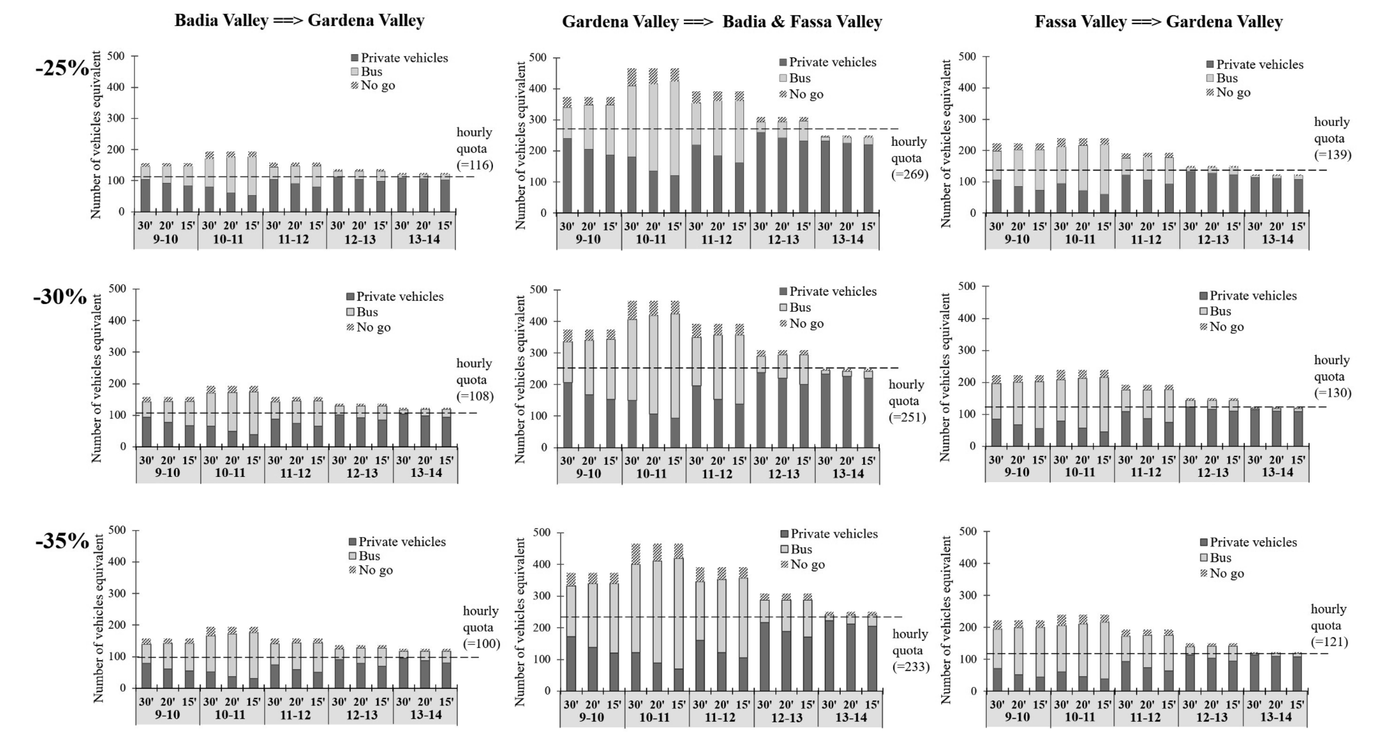

Fig. 8. Hourly modal splits induced by the −25%, −30% and −35% quotas in the period 9 AM-2 PM for different bus services (i.e. bus every 30, 20, 15 min). Modal shares are expressed in number of private vehicles equivalent (i.e. number of vehicles entering, number of vehicles whose passengers would get the bus, number of vehicles abandoning the area) and the length of the bar represents the total number of vehicles that would enter the road in a given hour under normal conditions. The horizontal line shows the number of vehicles allowed to enter every hour under a given quota.

Although both absolute congestion figures and relative differences between levels of congestion associated with different quotas may seem low, it is worth noticing that the hourly averages considered in this study capture congestion issues holding for relatively long time frames. A one percent increase in traffic congestion, for example, means that if 1,000 vehicles are travelling over an hour, 10 (i.e. a 150–200 m queue) are systematically slowed down.

The occupancy of parking spaces instead would be totally related to overall traffic volume, with stricter quota levels being associated with less parked vehicles at any time of the day (Fig. 7). This was expected as the time spent at parking lots is generally only determined by the time of arrival, not the amount of parked vehicles (unless ad hoc regulations are enforced). However, the imposition of quotas letting higher numbers of vehicles in during the late morning and early afternoon proved capable of temporally shifting the peak of parking lot occupancy (in our case, postponed by at least an hour). This may have management implications as the achievement (and exceeding) of parking capacity is generally associated with the phenomenon known as “cruising for parking” (Shoup, 2006), whose consequences (e.g. congestion, noise) may negatively affect people at the destination (e.g. tourists having lunch on the pass).

Our simulation of the modal split induced by the supposedly ideal quota provides figures that are in line with what found in other studies investigating the impact of traffic management measures in protected areas (although our abandonment rates seem more optimistic) (e.g. Steiner and Bristow, 2000; Sims et al., 2005). Moreover, it shows that a reliable and efficient bus service (i.e. cheap, frequent, on time) combined with knowledge, among visitors, of the road restriction may free up enough space on the road to accommodate all those who are firmly determined to drive (Fig. 8), therefore eliminating traffic-related issues while still guaranteeing the driving option. Moreover, the modal split analysis also highlights that effective communication about the different transport options has a major impact on the willingness to drive (White, 2007), with the supposedly most crowded hours seeing less drivers than the less crowded hours (excluding formally abandoning visitors who may eventually be allowed to enter with their vehicles).

The approach that is proposed here for assessing the effectiveness of different quota levels, based on the design of a simulation model and the evaluation of simulated outputs against multiple standards to be simultaneously met, is inspired by research in outdoor recreation management (Lawson et al., 2003; Lawson, 2006; Hallo and Manning, 2010; Orsi and Geneletti, 2016). Our study has shown that simulation modeling can indeed help describe visitor flows (e.g. traffic), monitor hard to measure variables (e.g. traffic levels and parking occupancy at each time of the day) and test the effectiveness of different management practices (e.g. quota levels) (Lawson, 2006). The decision to use an ad hoc agent-based model, rather than a common traffic simulation software package, was dictated by the consideration that restrictions imposed at the gates of the study area reverberate, through repeated interactions (between vehicles and between vehicles and the road), across time (i.e. morning to afternoon) and space (i.e. the road network) (Espie and Auberlet, 2007). The peculiar patterns characterizing the temporal evolution of congestion rates and, to a lesser extent, parking space occupancy seem to confirm the appropriateness of this decision. The decision to use an ABM, however, was also driven by the idea of developing a tool that, once properly upgraded, could account for other variables relevant to the management of protected areas, such as crowding perception or visitor satisfaction (Bishop and Gimblett, 2000).

The analysis of model’s output against standards of quality is consistent with normative theory in the field of protected area management (Manning and Krymkowski, 2010) and in line with studies assessing the ability of traffic management measures to safeguard environmental conditions (e.g. air quality) (Mitchell et al., 2005). Compared to what Hallo and Manning (2010) did in a similar study, however, we assessed the performance of different quota levels against fixed standards (e.g. availability of parking spaces) rather than visitor perception of traffic-related disturbance.

The introduction of a quota implies a considerable paradigm shift, whose effects on visitors may be hard to predict. We attempted to interpret these by simulating the potential modal split introduced by the quota as a function of visitors' stated preferences, consistent with a relatively long tradition of recreational studies predicting the likely effects of different transport policies (Shiftan et al., 2006; Pettebone et al., 2011; Orsi and Geneletti, 2014). The novelty of our approach lies in the fact that the analysis was conducted on an hourly basis as the "perceived" quota changes from hour to hour (i.e. a smaller percentage of visitors is allowed to enter in the peak hours given a constant hourly quota) and most visitors are likely unwilling to change their time of visit from a more crowded to a less crowded hour.

Beyond the theoretical effectiveness of the proposed quota, its translation into an actual quota system entails various technical obstacles. How to allocate visitors to different time slots? How to make sure no congestion occurs at gateways? How to minimize the number of visitors giving up on their visit? Communication is a pre-condition to addressing these concerns: visitors must be aware of how the system works well in advance of their arrival. Road signs, tourist information (e.g. at tourist offices and hotels) and interactive apps should all be used to make sure that only visitors who want (and have good probability of being admitted) to drive can reach the gateway with their vehicles. Legal and privacy issues related to accessibility restriction and screening of license plates should also be considered. The most promising approach to visitor allocation then seems to be a mixed one, whereby for each hourly slot a given share of entrance permits are to be reserved in advance, while another (smaller) share is distributed on a first come first served basis. Visitors can choose whether they prefer to book in advance for a given day and time slot or they just wish to show up at the gateway to get one of the available permits. They could then rely on a digital app for either advance booking or the monitoring of hourly availability (the same information would also be available at all tourist offices, hotels, etc. in the area via a web service).

While some infrastructural development may be needed to reduce circulation issues at the gateway, such a system, once properly tested, might guarantee a smooth access and limited abandonment rates, even among those visitors who show the greatest attachment to the private vehicle and its associated freedom (Hallo and Manning, 2009). Clearly, adequate transportation alternatives (e.g. shuttle buses, e-bikes) are to be provided (Holding and Kreutner, 1998; Orsi and Geneletti, 2014) to encourage visitors to leave their vehicles. Such adequacy should be established by considering people's preferences towards different transport modes (Shiftan et al., 2006; Orsi and Geneletti, 2014; Scuttari et al., 2019) and the potential unintended consequences of the selected alternatives (e.g. traffic congestion induced by an excessive number of additional buses). Finally, a feedback loop should be established between the simulation model and the real quota system, with the former providing the ideal hourly inflows and the latter showing evidence of the traffic consequences of such inflows, so that model design can be improved. The first attempt to introduce the quota system on the road to Passo Sella in the summer of 2018 showed how adopting some of these measures (e.g. improvement of alternative transportation) but not others (e.g. advanced reservation system) may lead to various issues (e.g. congestion at gateways, dissatisfaction), which are still unsolved.

The limitations of this study are primarily related to the inherent difficulty of designing a realistic and reliable ABM of traffic flows over a large area. A compromise had to be found between the ambition of describing all micro-events that may have an impact on the whole system and the need to limit complexity. This required us to make some choices. The wandering of vehicles around passes, for example, was merely simulated as a general slowdown on a few hundred meters around the passes. Similarly, the wide spectrum of specific itineraries visitors could embark on was reduced to two (i.e. to the pass and back, to the opposite valley and back): a considerable simplification, which is nonetheless expected to grasp key visitation patterns in the area.

Due to time and resource constraints, the model was developed relying mostly on available data (e.g. official traffic counts, geospatial data), while new data were only acquired when strictly needed and using "cheap" collection methods (e.g. video taken from a moving vehicle to detect traffic patterns along the entire road on an average high-season day). An ad hoc data collection campaign would have allowed us to accurately monitor traffic flows and vehicle counts at several locations across the whole study area, therefore supporting a better model calibration.

The effects of different quota levels were assessed against a very limited set of indicators (and standards). Although these capture the traffic-related concerns of the local context (i.e. congestion and parking demand), they dismiss, at least directly, other potentially relevant issues, such as noise and wildlife disturbance. The congestion indicator, providing overall information for the entire road network based on a unique speed limit (i.e. 15 km/h), was partly unable to detect localized issues and to control for the impact of road design on traffic. A better option would have encompassed separate indicators for different road sections and/or a more complex metric that accounts for local road characteristics (e.g. curvature, speed limit) (He et al., 2016). Finally, indicator scores were aggregated on an hourly basis: a decision taken to facilitate interpretation that, however, may have prevented us from detecting short-term phenomena.

7. Conclusion

As tourism pressure in natural areas continues to increase, managers and administrators may look more and more favorably at vehicle quota systems for their ability to control traffic levels and therefore mitigate related detrimental effects on natural resources and visitor recreational experience. By analyzing the case of a popular road in the Italian Alps, this study has provided a viable step-based approach to define the right quota for a given context and shown the magnitude of the effects of different quota levels on traffic. This was done through the development of a spatially-explicit ABM that offers the possibility to simulate at a very high temporal resolution the movements of vehicles along a road network like traditional traffic simulation models do, but is also flexible enough to potentially monitor environmental and recreational variables that matter in protected area management.

The design and implementation of an actual quota system, however, requires some additional steps. On a purely technical-modeling level, more advanced simulation tools are needed to accurately describe not just the movement of private vehicles, but also the effects of alternative transportation systems and circulation patterns around entrance gates. On a management level, further considerations should be made about the exact location of gateways, the design of surrounding areas (e.g. parking lots and detours for rejected vehicles) and the methods of access reservation because all of these have major impacts on circulation and ultimately the real effectiveness of the quota. Finally, the ideal quota can only be evaluated in the light of an area's tourism strategy, which shall include incentives to green mobility and the provision of a wide range of environmentally-friendly recreational opportunities.

CRediT authorship contribution statement

Francesco Orsi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Anna Scuttari:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Anja Marcher:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing, Visualization.

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Appendix. . Parameter estimates considered in the discrete choice model used to simulate modal split given different quotas. The quota-related variable, intended as the probability of being allowed to enter the road with the private vehicle, is highlighted in bold. For further information about the stated preference survey conducted to obtain these estimates, readers can refer to Scuttari et al. (2019).

Variable	β	Std. Err.
Bus intercept	5.07**	0.389
No go intercept	2.35**	0.315
Λ	0.629**	0.0482
Toll	−0.331**	0.0261
Bus fare	−0.303**	0.0238
Road open	0.776	
Road closed 11–13	0.224*	0.107
Road closed 9–17	−1**	0.117
Bus service 8–19	0.5364	
Bus service 9–17	−0.0514	0.0709
Bus service 10–18	−0.485**	0.0801
Quota	0.0513**	0.00427
Bus frequency	−0.0318**	0.00356
Little traffic	−0.01	
Medium traffic	0.147	0.0957
Intense traffic	−0.137	0.0976
No crowding on bus	−0.1493	
Medium crowding on bus	0.0123	0.0715
Intense crowding on bus	0.137	0.0717
No crowding at the Pass	−0.1464	
Medium crowding at the Pass	−0.0876	0.0547
Intense crowding at the Pass	0.234**	0.0573

* $p < 0.05$
** $p < 0.01$

References

ApoB, 2018. Geobrowser. Autonomous Province of Bolzano-Bozen. Retrieved January, 2018, from gis2.provinz.bz.it/geobrowser/.

ASTAT, 2019. Mobility and tourism database. Provincial Institute of Statistics, Autonomous Province of Bolzano-Bozen. Retrieved January, 2018, from https://astat.provincia.bz.it/it/banche-dati-comunali.asp.

Balmford, A., Beresford, J., Green, J., Naidoo, R., Walpole, M., Manica, A., 2009. A global perspective on trends in nature-based tourism. PLoS Biol. 7 (6), 1–6.

Benenson, I., Martens, K., Birfir, S., 2008. PARKAGENT: an agent-based model of parking in the city. Comput. Environ. Urban Syst. 32 (6), 431–439.

Benfield, J.A., Bell, P.A., Troup, L.J., Soderstrom, N.C., 2010. Aesthetic and affective effects of vocal and traffic noise on natural landscape assessment. J. Environ. Psychol. 30 (1), 103–111.

Bishop, I.D., Gimblett, H.R., 2000. Management of recreational areas: GIS, autonomous agents, and virtual reality. Environ. Plan. B: Plan. Des. 27 (3), 423–435.

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. PNAS 99 (3), 7280–7287.

Börjesson, M., Eliasson, J., Hugosson, M.B., Brundell-Freij, K., 2012. The Stockholm congestion charges-5 years on. Effects, acceptability and lessons learnt. Transp. Policy 20, 1–12.

Bruschi, D., Astiaso Garcia, D., Gugliermetti, F., Cumo, F., 2015. Characterizing the fragmentation level of Italian National Parks due to transportation infrastructures. Transp. Res. Part D: Transp. Environ. 36, 18–28.

Buckley, R., 2000. Tourism in the most fragile environments. Tourism Recreation Res. 25 (1), 35–40.

Bureau, B., Glachant, M., 2008. Distributional effects of road pricing: assessment of nine scenarios for Paris. Transp. Res. Part A: Policy Practice 42 (7), 994–1007.

Burson, S.L., Belant, J.L., Fortier, K.A., Tomkiewicz, W.C., 2000. The effect of vehicle traffic on wildlife in Denali National Park. Artic 53, 146–151.

Charypar, D., Nagel, K., Axhausen, K.W., 2007. An event-driven queue-based micro-simulation of traffic flow. Transp. Res. Rec. 2003, 35–40.

Chung, J.Y., Kyle, G.T., Petrick, J.F., Absher, J.D., 2011. Fairness of price, user fee policy and willingness to pay among visitors to a national forest. Tourism Manage. 32 (5), 1038–1046.

Clawson, M., Knetsch, J.L., 1966. Economics of Outdoor Recreation. Johns Hopkins Press, London.

Cullinane, S., 1997. Traffic management in Britain's national parks. Transp. Rev. 17 (3), 267–279.

Delgado, J.D., Duran Humia, J., Rodriguez Pereiras, A., Rosal, A., del Valle Palenzuela, M., Morelli, F., Arroyo Hernandez, N.L., Rodriguez Sanchez, J., 2019. The spatial distribution of animal casualties within a road corridor: implications for roadkill monitoring in the southern Iberian rangelands. Transp. Res. Part D: Transport Environ. 67, 119–130.

Dia, H., 2002. An agent-based approach to modelling driver route choice behavior under the influence of real-time information. Transport. Res. Part C: Emerging Technol. 10 (5–6), 331–349.

Eckton, G.D.C., 2003. Road-user charging and the Lake District National Park. J. Transp. Geogr. 11 (4), 307–317.

Espie, S., Auberlet, J.M., 2007. ARCHISIM: a behavioural multi-actor traffic simulation model for the study of a traffic system including ITS aspects. Int. J. ITS Res. 5, 7–16.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Model. 221, 2760–2768.

Hallo, J.C., Manning, R.E., 2009. Transportation and recreation: a case study of visitors driving for pleasure at Acadia National Park. J. Transp. Geogr. 17 (6), 491–499.

Hallo, J.C., Manning, R.E., 2010. Analysis of the social carrying capacity of a National Park scenic road. Int. J. Sustain. Transp. 4 (2), 75–94.

He, F., Yan, X., Liu, Y., Ma, L., 2016. A traffic congestion assessment method for urban road networks based on speed performance index. Proc. Eng. 137, 425–433.

Holding, D.M., Kreutner, M., 1998. Achieving a balance between "carrots" and "sticks" for traffic in National Parks: the Bayerischer Wald project. Transp. Policy 5 (3), 175–183.

Inci, E., 2015. A review of the economics of parking. Econ. Transp. 4 (1–2), 50–63.

Kendal, J., Ison, S.G., Enoch, M.P., 2010. UK National Parks: a role for road-pricing? Int. J. Sustain. Transp. 5 (1), 25–42.

Koh, W.T.H., Lee, D.K.C., 1994. The vehicle quota system in Singapore: an assessment. Transp. Res. Part A: Policy Pract. 28 (1), 31–47.

Lawson, S., 2006. Computer simulation as a tool for planning and management of visitor use in protected natural areas. J. Sustain. Tour. 14 (6), 600–617.

Lawson, S.R., Manning, R.E., Valliere, W.A., Wang, B., 2003. Proactive monitoring and adaptive management of social carrying capacity in Arches National Park: an application of computer simulation modeling. J. Environ. Manage. 68 (3), 305–313.

Lawson, S., Newman, P., Choi, J., Pettebone, D., Meldrum, B., 2009. Integrated transportation and user capacity research in Yosemite National Park: the numbers game. Transp. Res. Rec. 219, 83–91.

Liu, J., Kockelman, K.M., Boesch, P.M., Ciari, F., 2017. Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based simulation. Transportation 44, 1261–1278.

Manning, R.E., Krymkowski, D.H., 2010. Standards of quality for parks and protected areas: applying normative theory and methods in U.S. National Parks. Int. J. Sociol. 40 (3), 11–29.

Marsden, G., 2006. The evidence base for parking policies – a review. Transp. Policy 13 (6), 447–457.

Martin-Cejas, R.R., 2015. The environmental impact caused by road access to Timanfaya Natural Park on Lanzarote Island. Transp. Res. Part D: Transp. Environ. 41, 457–466.
Merchan, C.I., Diaz-Balteiro, L., Soliño, M., 2014. Noise pollution in national parks : soundscape and economic valuation. Landscape Urban Plann. 123, 1–9.
Mitchell, G., Namdeo, A., Milne, D., 2005. The air quality impact of cordon and distance based road user charging: an empirical study of Leeds, UK. Atmos. Environ. 39 (33), 6231–6242.
Morelle, K., Buchecker, M., Kienast, F., Tobias, S., 2019. Nearby outdoor recreation modelling: an agent-based approach. Urban For. Urban Greening 40, 286–298.
Morrison, S.A., 1986. A survey of road pricing. Transp. Res. Part A: General 20 (2), 87–97.
Nagel, K., Schrekenberg, M., 1992. A celleular automaton model for freeway traffic. J. Phys. 12, 2221–2229.
Nicholls, S., Amelung, B., Student, J., 2017. Agent-based modeling: a powerful tool for tourism researchers. J. Travel Res. 56 (1), 3–15.
NPS, 2014. Congestion Management Toolkit. Department of the Interior, National Park Service, U.S.
NPS, 2018. https:/www.nps.gov/yose, National Park Service.
Orsi, F., 2015. Sustainability requisites of transportation in natural and protected areas. In: Orsi, F. (Ed.), Sustainable Transportation in Natural and Protected Areas. Routledge, London and New York, pp. 11–27.
Orsi, F., Geneletti, D., 2014. Assessing the effects of access policies on travel mode choices in an Alpine tourist destination. J. Transp. Geogr. 39, 21–35.
Orsi, F., Geneletti, D., 2015. Estimating the effects of 'carrot and stick' measures on travel mode choices: results of a survey conducted in the Dolomites (Italy). In: Orsi, F. (Ed.), Sustainable Transportation in Natural and Protected Areas. Routledge, London and New York, pp. 150–167.
Orsi, F., Geneletti, D., 2016. Transportation as a protected area management tool: An agent-based model to assess the effect of travel mode choices on hiker movements. Comput. Environ. Urban Syst. 60, 12–22.
Pechlaner, H., Laesser, C., Raich, F., Bischof, L., 2004. Verkehrsentlastung Dolomitenpässe: Project report. Bolzano.
Pettebone, D., Newman, P., Lawson, S.R., Hunt, L., Monz, C., Zwiefka, J., 2011. Estimating visitors' travel mode choices along the Bear Lake Road in Rocky Mountain National Park. J. Transp. Geogr. 19 (6), 1210–1221.
Pigou, A.C., 1918. The Economics of Welfare. MacMillan, London.
Pörnbacher, H., 1995. Verkehrsbefragung im Dolomitengebiet: Project report.
Querini, F., Benetto, E., 2014. Agent-based modelling for assessing hybrid and electric cars deployment policies in Luxembourg and Lorraine. Transp. Res. A: Policy Practice 70, 149–161.
Reynisdottir, M., Song, H., Agrusa, J., 2008. Willingness to pay entrance fees to natural attractions: an Icelandic case study. Tour. Manage. 29 (6), 1076–1083.
Rosenthal, D.H., Loomis, J.B., Peterson, G.L., 1984. Pricing for efficiency and revenue in public recreation areas. J. Leisure Res. 16 (3), 195–208.
Scuttari, A., 2019. Cycling and Motorcycling Tourism : An Analysis of Physical, Sensory, Social, and Emotional Features of Journey Experiences. Springer nature Switzerland, Cham.
Scuttari, A., Bassani, R., 2015. I passi dolomitici. Analisi del traffico e dei suoi impatti e proposta di misure di gestione. Eurac Research, Bolzano-Bozen, final project report.
Scuttari, A., Orsi, F., Bassani, R., 2019. Assessing the tourism-traffic paradox in mountain destinations. a stated preference survey on the Dolomites' passes (Italy). J. Sustain. Tour. 27 (2), 241–257.
Scuttari, A., Marcher, A., Vanzi, G., 2018a, #Dolomitesvives. Vivere un'esperienza naturale sulle Dolomiti. Monitoring qualitativo. Eurac Research, Bolzano-Bozen, final project report.
Scuttari, A., Vanzi, G., Marcher, A., 2018b, Best Practice #Dolomitesvives: monitoraggio qualitativo. Un'esperienza di mobilità sostenibile sulle Dolomiti. – In: Pechlander, H., Angelini, P., Scuttari, A., eds., 2018, Destination Greenitaly – Modelli di governance turistica dalle Alpi al Mediterraneo. Crescita e sviluppo sostenibile 5 – Aracne Editrice, Canterano, p. 207-208.
Shiftan, Y., Vary, D., Geyer, D., 2006. Demand for park shuttle services – a stated-preference approach. J. Transp. Geogr. 14 (1), 52–59.
Shoup, D.C., 2006. Cruising for parking. Transp. Policy 13, 479–486.
Shultz, S., Pinazzo, J., Cifuentes, M., 1998. Opportunities and limitations of contingent valuation surveys to determine national park entrance fees: evidence from Costa Rica. Environ. Dev. Econ. 3 (1), 131–149.
Sims, C.B., Hodges, D.G., Fly, J.M., Stephens, B., 2005. Modeling visitor acceptance of a shuttle system in the Great Smoky Mountains National Park. J. Park Recreation Admin. 23 (3), 25–44.
Steiner, T.J., Bristow, A.L., 2000. Road pricing in National Parks: a case study in the Yorkshire Dales National Park. Transp. Policy 7 (2), 93–103.
Takama, T., Preston, J., 2008. Forecasting the effects of road user charge by stochastic agent-based modelling. Transp. Res. A: Policy Pract. 42 (4), 738–749.
UNWTO, 2019. International Tourism Highlights, 2019 ed. World Tourism Organization, Madrid.
Weinberger, R., 2012. Death by a thousand curb-cuts: evidence on the effect of minimum parking requirements on the choice to drive. Transp. Policy 20, 93–102.
White, D.D., 2007. An interpretive study of Yosemite National Park visitors' perspectives toward alternative transportation in Yosemite Valley. Environ. Manage. 39, 50.
White, D.D., Aquino, J.F., Budruk, M., Golub, A., 2011. Visitors' experiences of traditional and alternative transportation in Yosemite National Park. J. Park Recreation Admin. 29 (1), 38–57.
Wilensky, U., 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.