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One year of COVID-19: Impacts on safe driving behavior and policy recommendations

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**Abstract**

**Introduction:** In the unprecedented year of 2020, the rapid spread of COVID-19 disrupted everyday activities worldwide, leading the majority of countries to impose lockdowns and confine citizens in order to minimize the exponential increase in cases and casualties. To date, very few studies have been concerned with the effect of the pandemic on driving behavior and road safety, and usually explore data from a limited time span. **Method:** This study presents a descriptive overview of several driving behavior indicators as well as road crash data in correlation with the strictness of response measures in Greece and the Kingdom of Saudi Arabia (KSA). A k-means clustering approach was also employed to detect meaningful patterns. **Results:** Results indicated that during the lockdown periods, speeds were increased by up to 6%, while harsh events were increased by about 35% in the two countries, compared to the period after the confinement. However, the imposition of another lockdown did not cause radical changes in Greek driving behavior during the late months of 2020. Finally, the clustering algorithm identified a “baseline,” a “restrictions,” and a “lockdown” driving behavior cluster, and it was shown that harsh braking frequency was the most distinctive factor. **Policy recommendations:** Based on these findings, policymakers should focus on the reduction and enforcement of speed limits, especially within urban areas, as well as the incorporation of active travelers in the current transport infrastructure.

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1. Introduction

In 2020, the COVID-19 pandemic dominated every aspect of life globally by infecting around 100 million individuals, leading to more than 2 million casualties (Dong et al., 2020). When the spread of COVID-19 started increasing around the world, the majority of governments imposed lockdowns as means of restricting non-essential civilian movements, while all recreational, religious, cultural, dining, and entertainment establishments were instructed to cease operations.

With typical social activities interrupted, the transportation ecosystem was disturbed as well. Recent studies have been mainly focused on the effect of COVID-19 on travel behavior (e.g., Barbieri et al., 2020; De Vos, 2020) but also on air travel operations (Hotle & Mumbower, 2021) and shared mobility (Padmanabhan et al., 2021). As can be anticipated, road traffic volumes were heavily reduced (De Vos, 2020; Vingilis et al., 2020). This decline in traffic volumes has led to higher speeds and more frequent harsh events (Katrakazas et al., 2020) while large reductions in crashes have been recorded (Aloi et al., 2020; Katrakazas et al., 2020; Saladié et al., 2020).

During the year 2020, COVID-19 response measures varied from country to country according to the fluctuation of the number of cases and patients in the available Intensive Care Units (ICUs). The harshness of the response measures has been captured by the stringency index introduced by Hale et al. (2020), which explores information on 19 indicators of COVID-19 government responses and corresponds to the strictness of government policies on the matter. Nevertheless, to date the strictness of government policy on COVID-19 response measures has not yet been correlated with driving behavior during the pandemic. Furthermore, an overall limited number of studies have been concerned with road safety and driving behavior during the pandemic, and the majority of those studies explore a limited timespan for data collection.

The aforementioned reasons form the motivation for the current paper, which aims at providing a detailed overview of how COVID-19 affected road safety indicators in Greece and the Kingdom of Saudi Arabia (KSA), while accounting for the strictness of COVID-19 countermeasures. Although this paper does not employ advanced statistical approaches to fulfil its aim, it is the first of its kind to provide a detailed overview of highly disaggregated naturalistic driving behavior data and provides result-based policy rec-
In order to fulfill this aim, a descriptive exploration of 12 months of data regarding several driving behavior indicators (i.e., average speed, speeding percentage, average driving speed, harsh accelerations/100 km, harsh brakings/100 km, total duration, total driven distance, and mobile phone usage duration/driving duration) is initially presented to understand the effect of the pandemic on driving during 2020. It is worth noting that harsh acceleration refers to a driver event where more force than normal is applied to the vehicle’s accelerator system. The term acceleration used in the manuscript does not refer to lateral acceleration (hard cornering), as the latter variable acts transversely to the direction of travel of a car. Thus, particular emphasis was given to the harsh accelerator variable as it can be an indicator of aggressive or unsafe driving behavior. The exploratory analysis is supplemented by an unsupervised pattern recognition algorithm, aiming at identifying clusters of weeks according to driving behavior and the strictness of COVID-19 response measures. Following the effect of the pandemic on driving behavior and road safety, policy recommendations are discussed in order to pave the way for post-pandemic safer roads.

The paper is structured as follows: initially, the literature with regards to driving behavior and road safety during the pandemic is reviewed. This is followed by an overview of the data needed for the exploratory analysis. The main part of this paper is dedicated to depicting the changes in driving behavior during 2020 and is followed by a section on weekly pattern identification. Finally, the results are discussed and helpful conclusions for researchers and policymakers are provided.

2. Literature review

To be able to provide an overview of the effect of COVID-19 in Greece and the KSA, the literature was reviewed for studies correlating the pandemic and driving behavior or road safety. The search took place in the databases Google Scholar and Scopus using the Boolean terms (“COVID-19” or “Pandemic” and “driving behavior” or “driving behavior” or “road safety”).

From the list of examined papers, it was observed that the majority of studies on the effect of COVID-19 on transportation were concerned with changes in travel behavior and mode choice (e.g., Bhaduri et al., 2020; De Vos, 2020; Jenelius & Cebecauer, 2020; Parady et al., 2020; Shamshiripour et al., 2020). Only 10 of the studies were concerned with the road safety effects of the pandemic and were chosen to be further reviewed for the purposes of this research. The retrieved papers can be divided into three categories: (a) the ones focusing on epidemiological models and analyzing road safety as yet another health consequence of the pandemic; (b) the ones providing descriptive evidence of the effect of the pandemic; and (c) the ones utilizing advanced statistical tools to investigate crucial indicators and explain the impact of COVID-19 on injuries, road crashes, and driving behavior.

With regards to epidemiological studies, a compensation effect between damage from epidemic deaths and road crashes-related deaths in Italy was examined (Colonna & Intini, 2020). It was demonstrated that damage from loss of human capital and health care costs could have been fulfilled if a lockdown was imposed 10 days earlier. Similarly, Lenke et al. (2020) promote syndemic (i.e., population-level clustering of social and health problems, as per Singer et al., 2017) frameworks for the evaluation of commercial driver stress, health, and safety; but their work is limited to a theoretical discussion on advantages of such frameworks and potential enhancements these may offer in safety assessment during the pandemic.

Descriptive results are presented in Saladié et al. (2020), where the reduction in road crashes in the province of Tarragona was presented by comparing the frequency of crashes and checking statistical significance using a chi-square test on weekdays and weekends as well as different road types. A large reduction in crashes (74% compared to February of 2020; 76% compared to 2019) was observed and was associated with the overall reduction of traffic volumes. Likewise, Katrakazas et al. (2020) provided descriptive evidence from Greece and the KSA with regards to COVID-19 and driving behavior. It was observed that when a lockdown was imposed, a slight increase by 6–11% in average driving speed was observed, while harsh accelerations and brakings per 100 km were more frequent by up to 12% when compared to normal operations. Nevertheless, the results presented in the aforementioned studies were purely descriptive, without significant statistical analyses.

To date, only a few studies have conducted statistical analyses with regards to the effect of COVID-19 on driving behavior both using simple as well as more sophisticated models. These can be further distinguished between simple modeling and hypotheses testing and time-series regression modeling of the effect of the pandemic. For instance, Prasetijo et al. (2021) used a simple linear fit speed model and underlined the importance of road design to incorporate sudden changes in traffic volumes with regards to safety. On the same principle, using crowdsourced cycling data from July 2019 to March 2020, Hong and Mcarthur (2020) employed a simple linear regression model, but mixed results with regards to the safety of cyclists are presented.

A more sophisticated approach is presented in Qureshi et al. (2020), where a two-sample t-test was utilized to identify differences in road crashes before and after a lockdown in the United States, as well as ARIMA modeling for autocorrelation and trend analysis was implemented. The reduction of road crashes compared to non-serious or injuries was found significant, but more complex analyses would shed light on the influencing factors. Stavrinos et al. (2020), using multi-level modeling, demonstrated that after the appearance of COVID-19 driving days per week decreased by 37%, while vehicle miles driven dropped by 35. Similar results were presented by Roe et al. (2020) using within-subjects general linear models on a sample of elderly drivers. It was demonstrated that driving days as well as frequency of speeding were reduced. Finally, a full time-series modeling approach was employed by Inada et al. (2020). Using a seasonal ARIMA model and data from January to May 2020, the authors concluded that the lockdown was the crucial factor for speed-related traffic violations, which consequently led to an increase of fatal road crashes. It was further revealed that speeding increased by 52% in March 2020 compared to March 2019.

Moreover, Sekadakis et al. (2021) analyzed the impact of COVID-19 on the total number of road safety figures using time-series forecasting in Greece. It was found that road collisions, fatalities, and slightly injuries were decreased, mainly due to the remarkable decrease of traffic volumes. Similarly, Seasonal AutoRegressive Integrated Moving Average (SARIMA) and XGBoost algorithms were implemented in order to identify the impact of the COVID-19 on driving performance (Katrakazas et al., 2021). Results revealed that average speed increased by 2.27 km/h on average compared to the forecasted evolution, while harsh brakings per distance (i.e. 100 km) increased to almost 1.51 on average. Interestingly, road crashes in Greece were reduced by 48% during the months of COVID-19 in comparison to the non-COVID-19 period. Another study was conducted aiming to provide a comparative overview of the impact of COVID-19 on traffic safety behavior (Michelaraki et al., 2021). It was revealed that speeding percentage, average speed, and harsh accelerations or brakings increased dur-
ing the lockdown period. Lastly, a reduction in traffic volumes (i.e., people driving and walking) was also observed.

From the aforementioned literature findings, it is evident that no study has yet presented an overview of naturalistic driving data throughout 2020, and the impact of the strictness of response measures as well as machine learning approaches are yet to be utilized to investigate patterns correlating the pandemic with driving behavior. As a result, the current paper is an attempt to fill this particular research gap.

3. Data overview

To present a descriptive overview of the impact of the pandemic within 2020, four types of data are utilized both for Greece and the KSA:

- COVID-19 data on cases and casualties
- Governmental response measures
- Naturalistic driving data captured from novel smartphone apps by OSeven Telematics
- Traffic exposure data

These data are further overviewed in the following sections. It should be noted that Greece and the KSA were chosen compared to others, since only these countries had the appropriate sample size for further investigation. In particular, trip data were collected from a specific subset of the population of Greece and the KSA (i.e., users of OSeven mobile phone application) and additional information (e.g., gender, age, educational level) was not provided due to the anonymity of the drivers. No examination or analysis based on any demographic or personal characteristics of the examined sample was possible due to standing Greek and European data protection legislation (GDPR). As a consequence, this study retains a scope of macroscopic examination of driver behavior, considering the trips produced by the drivers collectively.

3.1. COVID-19 cases and casualties

Data on COVID-19 confirmed cases and casualties were retrieved from the corresponding ministries of health and were cross-checked with press releases and popular websites (e.g., Worldometer, 2020). The evolution of COVID-19 cases and casualties in the two countries are presented in Fig. A1 in the Appendix.

3.2. COVID-19 response measures

Regarding COVID-19 response measures apart from governmental press releases, the government response tracker for COVID-19, put together by the University of Oxford (Hale et al., 2020) was reviewed in order to obtain a homogenized set of validated response measures for Greece and the KSA. Table A1 gives an overview of the response measures milestones for the two countries, while Fig. A2 provides a timeline of the evolution of the response measures stringency index (i.e., the strictness of the measures), as shown in the Appendix.

With respect to Greece, the first lockdown of non-essential movements refers to the period between 23/03/2020 and 04/05/2020. Then, after a 42-day lockdown, Greece began to gradually lift restrictions on movement and restart business activities. The second lockdown of restrictions refers to the period between 07/11/2020 and 31/12/2020, when Greece put in place new measures on movements. Thus, the 6-month framework, between 04/05/20 and 07/11/20, refers to the period between the first and the second lockdown. KSA announced a lockdown of non-essential movements along with the suspension of all domestic and international travel on March 26. After the aforementioned restrictions took place, the number of daily confirmed cases shrunk dramatically and by June 21, all curfews were lifted. By the end of 2020, the KSA was seeing more daily recoveries than cases.

3.3. Naturalistic driving behavior data

For the purpose of the current research, OSeven has provided trip data from its database for Greece and the KSA for a 12-month timeframe from 01/01/2020 to 31/12/2020. The provided dataset corresponds to the same set of random users so that the data before and after the COVID-19 crisis are fully comparable. It should be noted that OSeven Telematics (oseven.io) uses a smartphone application and a platform in order to explore data from smartphone sensors (e.g., GPS, accelerometer, and gyroscope data). State-of-the-art technology and algorithms, reliable metrics, and novel gamification schemes are used in order to help drivers understand their weak points and improve themselves. For each trip, a vast quantity of data were collected and communicated through Wi-Fi or cellular network, and valuable critical information such as features, highlights, and driving scores was generated in order to assess the driver’s profile and performance. Data were then transferred to the OSeven backend infrastructure, where it was analyzed with filtering, signal processing, machine learning algorithms, and safety/eco rating models. The final outcome of the analysis is risk-related driving events such as speeding, mobile use, harsh accelerations, and harsh braking, as well as safety/and eco scores.

A standard procedure is followed every time a new trip is retrieved by the application: the application collects in real-time the data from the sensors of the mobile phone and then data processing takes place. All the variables in the analyzed data were derived from a combination of machine learning methods (data fusion, clustering & classification). Since OSeven has strict data sharing policies, further information cannot be provided at the moment. Nevertheless, additional details for data extraction regarding the OSeven application can be found in Papadimitriou et al. (2019) and Kontaxi et al. (2021).

It should be clearly mentioned that the OSeven platform is able to detect different driving patterns as well as recognize whether the user is a driver or a passenger. Undoubtedly, drivers have their own driving patterns, strongly affected by their personality and daily routine and the recorded driving behavior is totally different when they are passengers instead of drivers. To that end, OSeven developed a set of machine learning algorithms that can reliably determine if the user is the driver or a passenger, taking into consideration all the above parameters. It is worth noting that this specific driver/passenger recognition achieves over 92% accuracy. However, in case of false alarms, users are able to confirm through the app if there were drivers or passengers. For instance, if a person who had the app on their phone was a passenger, driving data from another driver during the specific trip were not collected by the app and thus, these data were not included in the analyses. This is also explicitly stated in the OSeven terms of use, and the drivers understand that their smartphone becomes a driving recording device when driving, thus becoming more mindful of it and limiting false recording.

The OSeven application has been utilized for road safety research, as described in several studies (Stavrakaki et al., 2019; Tselenitis et al., 2019; Yannis et al., 2017). A similar approach is followed in the present paper. A large amount of data were recorded using the aforementioned state-of-the-art platform, as described in recent research utilized this specific scheme (Papadimitriou et al., 2019). For instance, harsh events (i.e., harsh accelerations and harsh braking) are calculated via machine learning algorithms and data fusion. There is not a rule-based approach, using as input...
the values of the accelerometer or values from additional sensors (e.g., GPS, orientation, gyroscope). In addition, the outputs of the OSeven algorithms have been evaluated both in the published studies and used by major insurance companies in several countries (e.g., Greece, UK, Brazil, Qatar); this serves as evidence with regards the acceptance of the proposed algorithms implemented. It is worth mentioning that OSeven follows strict information security procedures and privacy policies, which comply with the General Data Protection Regulation (GDPR) and related European Union directives. Therefore, all data have been provided by OSeven in a completely anonymized format and no geolocation information for the trips (apart from the related country) have been included in the dataset. A similar dataset was utilized in previous analysis by the authors (Katrakazas et al., 2020; 2021). Privacy policy statements cover the type of data that are collected, the reason they were collected, the time that they are stored, and the measures that they have been taken to protect them based on encryption standards for data in transit and at rest. OSeven technology has already been accepted and approved by several national authorities and compliance officers of multinational brands and it complies with the national regulation in EU and around the world. What is more, details on the data collected, the purpose of the collection as well as information on the storage and retention of data, are explicitly stated in compliance with the GDPR. In addition, OSeven is also audited for ISO 27001 by TÜV Hellas. The ISO certification verifies the focus on meeting the highest security and privacy standards by auditing and constantly improving their policies, systems and procedures. Thus, customers can be reassured that their data is treated within OSeven Platform with integrity and confidentiality. It should be also mentioned that OSeven is dedicated into maintaining high-security standards in the design, implementation and delivery of its services and products and this is an iterative approach subject to annual assessment. It becomes evident that OSeven is compliant with international and European privacy and security standards. As it was previously mentioned, the data that have been used are fully anonymized and their recording has been approved by users of the app through the terms and conditions of the company. Moreover, since data from the OSeven platform are high-level and aggregated, it was assumed that they do not violate ethical concerns, since their use has already been approved for use in several peer-reviewed publications (e.g., Papadimitriou et al., 2019; Yannis et al., 2017; Tselentis et al., 2019; Stavrakaki et al., 2019; Kontaxi et al., 2021). Overall, the authors state that the current study complied with the Declaration of Helsinki’s ethical principles because no one was harmed, physically or emotionally, during the driving measurements, and because all of the drivers participated voluntarily. The OSeven application is open-access and has no impact on drivers when driving. The OSeven application aims to improve eco-driving and road safety while tracking and evaluating the driver’s performance. The director of the Department of Transportation Planning and Engineering of the School of Civil Engineering at the National Technical University of Athens also gave his approval to the ethics rules. The driving indicators included in the analysis are presented in Table 1.

Table 2 presents the descriptive statistics (i.e., median, standard deviation, max, min, interquartile range-IQR) with regards to the entire database in both countries. The subset of trips provided by OSeven for the aforementioned time framework included approximately 268,549 trips in Greece and 448,736 trips in the KSA. It was revealed that driving performance indicators (i.e., speed percentage, harsh brakings per 100 km, total/driving duration) for the KSA appeared to have higher values compared to the corresponding parameters for Greece. In order to have an initial depiction of changes happening to these indicators during the evolution of the COVID-19 pandemic, Table 3 provides descriptive statistics for the lockdown periods in both countries. It is evident that during the lockdown periods, the total number of trips was much lower compared to the period under normal circumstances. With regards to Greece, it was demonstrated that during the first lockdown period, values for the majority of available indicators were higher compared to the

Table 1

| Indicator                        | Unit | Description                                      |
|---------------------------------|------|-------------------------------------------------|
| Total duration                  | sec  | Total trip duration                             |
| Total distance                  | km   | Total trip distance                             |
| Harsh accelerations/100 km      |      | Number of harsh accelerations per distance (i.e. 100 km) |
| Harsh brakings/100 km           |      | Number of harsh brakings per distance (i.e. 100 km) |
| Speeding duration               | sec  | Total duration of speeding in a trip            |
| Average speed                   | km/h | Average speed over the speed limit              |
| Average driving speed           | km/h | Average speed during driving with stops been excluded from the duration of the trip |
| Mobile phone usage duration     | sec  | Total duration of mobile usage                  |
| Speeding percentage             | %    | Ratio of speeding duration in a trip per total duration of driving |
| Mobile phone usage duration /driving duration | % | Ratio of total duration of mobile usage per total duration of driving |
second lockdown period. This is due to the fact that drivers observing empty roads were willing to undertake more risks and appeared to have worse driving behavior in comparison to the second wave of the COVID-19 pandemic. Furthermore, it should be noted that during the lockdown period in the KSA, an overall increase in average speeding, average total/driving speed, and harsh events per distance was observed compared to the entire database.

3.4. Traffic exposure data

In order to be able to provide a holistic overview of the COVID-19 impact, exposure data were also extracted. As usually traffic data acquisition from national authorities requires additional time, it was chosen to use the Apple mobility report data as a proxy of traffic exposure in the study areas. Similar data have been utilized in previous work with regards to driving behavior and COVID-19 (Katrakazas et al., 2020). The aggregated data collected from Apple showed the mobility trends for major cities and several countries or regions. The information was generated by counting the number of requests made to Apple for directions. Data availability in a particular city, country, or region was subject to a number of factors, including minimum thresholds for direction requests made to Apple for directions. Data availability in a particular city, country, or region was subject to a number of factors, including minimum thresholds for direction requests made per day.

3.4.1. Driving traffic volumes

The COVID-19 outbreak as well as government responses of each country had a much more volatile effect on travel patterns. To begin with, during the first lockdown period of COVID-19, a great reduction in the volume of people driving was identified in Greece. However, during the second lockdown period, driving traffic volumes were much higher, roughly by 91% than the first one. Actually, during the first lockdown, traffic virtually disappeared, but ahead of a second one, there was a noticeable rise in people traveling by road. Interestingly, Greece performed high congestion levels throughout the summer. Traffic started to pick up significantly during August 2020 when the peak-time congestion on Greek roads hit a 400% increase, compared to the first lockdown. According to the available data for November-December 2020, driving traffic volumes decreased and a 62% reduction was identified compared to the period between the first and the second lockdown. Figs. 1 and 2 illustrate the volume of driving sessions of Apple users from January 2020 to December 2020 along with the number of COVID-19 cases in Greece and the KSA, respectively.

4. Methodology

In order to provide a yearly overview of the impact of COVID-19, the aforementioned data are presented descriptively in order to identify critical changes throughout 2020. Comparisons were made with regards to the lockdown periods as well as periods with restrictions between the lockdown states, and explanatory figures are provided to depict the status of driving behavior and road safety indicators in relation to COVID-19 cases.

In order to identify patterns with regards to driving behavior indicators and the strictness of response measures (stringency index), clustering was utilized on weekly aggregated OSeven trip data. Within the present study, clustering is a useful technique in order to divide the trip sample into several distinct categories. The evaluation of the cluster centroids describing these categories can provide insights as to whether driving behavior differs system-
aticaly on a macroscopic scale during the periods of shifting measures due to the pandemic. A well-known and straightforward technique is k-Means clustering, an algorithm used to divide datasets into clusters of similar magnitudes.

The k-means algorithm searches for a specific number of clusters \( k \) in a given dataset. The algorithm first initiates by randomly selecting centroids in the data. Each data-point is then assigned to the nearest centroid, forming the requested \( k \) clusters. Centroids are re-computed for the formed clusters, and thus their location changes. Calculations are then performed to re-assign each data-point to their new centroid. Afterwards, iterative calculations are conducted until no reassignments are made and thus the centroids have stabilized. The popularity of k-means algorithms presented in the past (e.g., Hartigan & Wong, 1979) has led to several customized approaches in the literature (e.g., Kanungo et al., 2002; Likas et al., 2003). K-means has been used widely for clustering purposes in several transport/road safety studies as well (e.g., Yannis et al., 2007; Mantouka et al., 2019).

5. Descriptive overview of the COVID-19 impact on driving behavior

5.1. Trip characteristics

In this section, the impacts of COVID-19 on trip characteristics and, more specifically, on total trip duration and distance are discussed.

5.1.1. Total duration

From Fig. 3, it is evident that total duration during the periods of lockdown is similar (i.e., a 1% reduction in total duration was observed in Greece during the second lockdown compared to the first one). When the restrictions on movement and business activities were gradually lifted, total duration increased by 22%, compared to the first lockdown period. At the same time, total duration dropped again roughly by 19% during the second lockdown compared to the period between the first and second lock-
down. In the KSA, after the end of the lockdown, more vehicles on city streets were observed; thus, a 10% rise in total duration was identified. Overall, the total number of driving trips in the KSA was significantly reduced due to the lockdown period, as depicted in Fig. 4.

5.1.2. Total distance driven per trip

In accordance with the total distance driven, the COVID-19 pandemic also had a direct effect on active drivers on the roads. Specifically, the second wave of COVID-19 pandemic led to a 10% reduction in total distance driven in Greece, compared to the first one. After the end of the first lockdown period, Greek drivers started to increase weekly mileage, reaching an 18% increase in total distance monitored in March and April compared to the period between the first and the second lockdown (i.e., from May to early-November 2020). Total driving distance per week dropped again by around 23% in November and December after the second lockdown compared to the period from May to early November. Similarly, the total distance driven per trip was also reduced during the lockdown period in the KSA. After the end of the lockdown period, a 13% increase in miles driven was observed when comparing data from March to June (i.e., COVID-19 lockdown period) with data from the end of June to December (i.e., after the end of lockdown of non-essential movements). Figs. 5 and 6 illustrate the changes in the total distance driven per trip in Greece and the KSA, respectively.

5.2. Driving behavior

5.2.1. Average driving speed

It is worth mentioning that during the first and second lockdown periods, an overall increase in average driving speed was identified compared to the period between the first and the second lockdown (i.e., from May to early-November 2020). When a decrease in driving traffic volumes was observed, drivers tended to increase their average driving speed. In particular, after the end of the first lockdown period, Greek drivers started to gradually increase their average driving speed, while a 5% drop in average driving speed monitored in March and April was identified compared to the period between the first and second lockdown (i.e., from May to early-November 2020). Additionally, the second wave of COVID-19 pandemic led to a 5% decrease in average driving speed in Greece, compared to the first one. Interestingly, average driving speed had not changed in November and December (i.e., after the second lockdown had been announced) compared to the period before (i.e., between the first and the second lockdown from May to early-November). Regarding the KSA, no change in average driving speed was identified, when comparing data from March to June (i.e., COVID-19 lockdown period) with data from end-June to December (i.e., after the end of lockdown of non-essential movement). Figs. 7 and 8 illustrate the changes in the average driving speed in Greece and the KSA, respectively.

5.2.2. Average speeding

As shown in Figs. 9 and 10, both in Greece and the KSA, average speeding was reduced due to the lockdown restrictions. In particular, during the second lockdown period, a negligible 1% reduction in average speeding was identified in Greece compared to the first one. Additionally, when Greece began to gradually lift restrictions on movement and restart business activities, average speeding decreased by 1% compared to the first lockdown period (i.e., March and April 2020), while there was no change in the average speeding during the second lockdown period compared to the period between the first and the second lockdown. Regarding the KSA, after the end of the lockdown period, a 9% decrease in average speeding was observed.

5.2.3. Speeding percentage

The second wave of COVID-19 pandemic led to a 2% reduction in the ratio of speeding duration/driving duration in Greece, compared to the first one. After the end of the first lockdown period, a 9% drop in speeding percentage compared to the period between the first and the second lockdown was identified. Furthermore, the ratio of speeding duration/driving duration was increased by around 8% in November and December after the second lockdown had been announced compared to the period before (i.e., between the first and the second lockdown from May to early-November). Interestingly, the speeding percentage was also reduced after the end of the lockdown period in the KSA. In particular, a 23% drop was observed when comparing data from March to June (i.e., COVID-19 lockdown period) with data from end-June to December (i.e., after the end of lockdown of non-essential movements). Figs. 11 and 12 illustrate the changes in the ratio of speeding duration/driving duration in Greece and the KSA, respectively.

5.2.4. Harsh accelerations per 100 km

With regards to harsh accelerations per 100 km, during the first phase of the lockdown and especially in April 2020, these were
increased compared to February (i.e., before the appearance of COVID-19 pandemic), as shown in Fig. 13. It should be noticed that during the second lockdown period, a 17% decrease in harsh accelerations per 100 km was identified in Greece compared to the first one. When the restrictions on movement and business activities were gradually lifted, harsh acceleration events per distance again
Fig. 7. Average driving speed per week along with the evolution of COVID-19 cases in Greece (Source: OSeven, Data Processing: NTUA).

Fig. 8. Average driving speed per week along with the evolution of COVID-19 cases in the KSA (Source: OSeven, Data Processing: NTUA).

Fig. 9. Average speeding per week along with the evolution of COVID-19 cases in Greece (Source: OSeven, Data Processing: NTUA).
dropped by 18% compared to the first lockdown period. Interestingly, a negligible 2% increase in harsh accelerations per 100 km was observed during the second lockdown compared to the period between the first and the second lockdown. With regards to the KSA, it was revealed that drivers accelerated harshly during the months of COVID-19. Overall, after the end of the lockdown period,
a 34% decrease in harsh accelerations per 100 km and less harsh accelerations per distance were observed, which indicates that drivers improved their driving behavior after the COVID-19 pandemic, as depicted in Fig. 14.

5.2.5. Harsh brakings per 100 km

Similar to harsh acceleration patterns, harsh brakings per 100 km were decreased during the second lockdown period compared to the first one. Additionally, when Greece began to gradually lift restrictions on movement and restart business activities, harsh brakings per distance dropped by 33% compared to the first lockdown period (i.e., March and April 2020), while there was a 10% increase in harsh brakings per 100 km during the second lockdown period compared to the period between the first and the second lockdown. With regards to the KSA, after the end of the lockdown period, a 23% reduction in harsh brakings per distance was identified. Figs. 15 and 16 depict the changes in harsh brakings per 100 km in Greece and the KSA, respectively.

5.2.6. Mobile phone usage duration/driving duration

With regards to mobile phone use, a general increase in the ratio of mobile phone usage duration per driving duration during the lockdown periods, compared to the period between the first and the second lockdown in Greece and the KSA, respectively, is presented in Fig. A3 in the Appendix. In more detail, the second wave of COVID-19 pandemic led to a 6% decrease in the ratio of mobile phone usage duration per driving duration in Greece, compared to the first one. After the end of the first lockdown period, a 9% reduction in the ratio of mobile phone usage duration per driving duration was identified compared to the period between the first and the second lockdown. Interestingly, mobile phone usage duration per driving duration increased by 4% in November and December after the second lockdown had been announced compared to the period between the first and the second (i.e., from May to early-November 2020). Similarly, the ratio of mobile phone usage duration per driving duration was also raised during the lockdown period in the KSA. Afterwards, a 5% increase was observed when comparing data from March to June (i.e., COVID-19 lockdown period) with data from end-June to December (i.e., after the end of lockdown of non-essential movement).

5.3. Road crashes

A more comprehensive picture of the effects of COVID-19 pandemic on road safety can be drawn from the high-quality data on the total number of road crashes. Fig. 17 illustrates the difference
in the total number of road crashes from January to December 2020 in Greece. Specifically, during the second lockdown period, a 46% increase in the total number of road crashes was observed compared to the first one. After the end of the first lockdown period, driving volumes were gradually increased and a 116% rise in the total number of road crashes was identified in the period between the first and the second lockdown compared to the first lockdown period. Interestingly, a 32% reduction in road crashes was observed in November-December 2020 (i.e., during the second lockdown) compared to the period before (i.e., between the first and the second lockdown from May to early-November 2020). Lastly, it should be noted that monthly data for road crashes are available only for Greece, while there is no evidence for road crashes in the KSA during 2020.

5.4. Overview

Table 4 summarizes the changes in exposure, driving behavior, road crashes, and response measures strictness during and after the lockdown periods for each country. It should be clarified that the first lockdown period in Greece refers to the period from April to May 2020, the second lockdown period refers to the period from early-November to December 2020, while the period between the first and the second lockdown refers to the period from May to early-November 2020. With regards to KSA, the first lockdown period (i.e., from end-March to June 2020) is compared to the post-lockdown period (i.e., from June to December 2020).

The total number of trips and traffic volumes in Greece reduced by 70% for people driving, respectively, during the first lockdown compared to the period before the appearance of COVID-19 pandemic. However, increased driving volumes, roughly by 100%, during the second COVID-19 lockdown compared to the first one. Exposure indicators (i.e., distance traveled, total duration, and driving duration) were also decreased during the first lockdown period compared to the period before. Similarly, the aforementioned indicators were also reduced during the second COVID-19 lockdown compared to the period before. A dramatic increase in total/driving duration and total distance during the second lockdown period compared to the period between the first and the second lockdown was also identified.

In Greece, during the first lockdown period, driving behavior indicators (i.e., average speeds, speeding percentage, harsh accelerations/brakings per 100 km, mobile phone usage duration/driving duration) increased to a great extent compared to the period

![Fig. 15. Harsh brakings/100 km per week along with the evolution of COVID-19 cases in Greece (Source: OSeven, Data Processing: NTUA).](image1)

![Fig. 16. Harsh brakings/100 km per week along with the evolution of COVID-19 cases in the KSA (Source: OSeven, Data Processing: NTUA).](image2)
before. For instance, during the first lockdown, average speed, speeding percentage, and mobile phone usage duration/driving duration increased by 10%, 22%, and 21%, respectively, compared to the period before and 1% (second lockdown) compared to the pre-pandemic period. This indicates that with fewer vehicles on city streets, slightly more drivers are blowing the speed limit. After the end of lockdown periods, a significant drop in speeding percentage was identified. Harsh accelerations/100 km and harsh brakings/100 km increased by 5% and 11% during the first lockdown compared to the period before. Interestingly, during the second lockdown, harsh events reduced by up to 17%.

It is worth mentioning that during the first lockdown period in Greece, an overall 50% reduction in road traffic crashes was observed compared to the period before the appearance of COVID-19 pandemic. In addition, during the second lockdown period, a 26% decrease in the total number of road traffic crashes was identified compared to the period between.

With regards to the KSA, similar patterns to Greece were also observed for both exposure and driving behavior indicators. A 36% and 27% reduction of people driving was identified during the lockdown period compared to the period before. After the lockdown, people driving adapted immediately to baseline frequencies and traffic volumes increased. In addition, a 2% spike in average speed was identified during the lockdown period compared to the period before. The speeding percentage increased by 17%, while the number of harsh accelerations and brakings per 100 km

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**Table 4**

Changes in traffic volumes, driving behavior and road safety during and after the COVID-19 lockdown period in Greece and the KSA.

|                        | Greece | KSA |
|------------------------|--------|-----|
| **Exposure**           |        |     |
| Total duration         | -18%   | -21%|
| Total distance         | -11%   | -14%|
| Driving traffic volumes| -70%   | -36%|
| **Driving behavior**   |        |     |
| Average driving speed  | 7%     | 2%  |
| Average speed          | 1%     |     |
| Speeding percentage    | 22%    |     |
| Harsh accelerations/100km | 5% | 2%  |
| Harsh brakings/100km   | 11%    | 11% |
| Mobile phone usage duration/driving duration | 21% | 7% |
| **Road Crashes**       |        |     |
| Crashes                | -49%   | -26%|
| Stringency index       | NA     | NA  |

*Road crashes data for the KSA are not available.*
increased by 11% and 7%, respectively. Lastly, it should be noted that monthly data for road traffic crashes were not available for KSA.

6. Pattern identification according to driving characteristics and stringency index

This section presents the results of cluster analysis conducted on weekly aggregated data for Greece and the KSA. The process of selection of the final number of clusters is initially explained, followed by the presentation and interpretation of the centroid values.

In the current study, the elbow method is followed, which defines clusters by minimizing the total intra-cluster variation, expressed by the Within Cluster Sum of Squares (WCSS) (Kodinariya & Makwana, 2013). For the purpose of choosing the optimal number of clusters, the elbow method using WCSS was applied as shown in Fig. 18 for Greece (left) and the KSA (right). These figures depict the optimal number of clusters (i.e., the k value to be applied for the examined data set. The optimal value is extracted by the “elbow” or “knee” of the depicted curve (Kodinariya & Makwana, 2013). Consequently, the optimal number of clusters is three for both countries. In addition, the average silhouette method was tested in order to validate the outcomes of the elbow method. The average silhouette score for three clusters was equal to 0.47 in the Greek dataset and 0.58 in the KSA dataset, denoting acceptable k-means algorithm fits.

The added value of the k-means clustering approach is the confirmation of systematic differences in the data. In other words, after applying this unsupervised method, it is observed that the weeks can be consistently organized in distinct categories with different centroid values. Centroid differences are observed across all driver performance metrics and for the Stringency Index as well. Therefore, this machine learning algorithm provides added validation of the differences already perceived by descriptive statistics for the examined data.

6.1. Greece

For Greece, the clustering results of weekly aggregated data for 2020 are shown on Table 5. The practical meaning of each category is to provide a grouping for similar week types of 2020. In the clustering analysis, seven variables (i.e., total duration, total distance, harsh brakings/100 km, driving volume, driving speed, speeding percentage, and stringency index of lockdown) were included. The presented values of the variables were the mean value of each centroid along with the corresponding standard deviation enclosed in parentheses.

Based on centroid values, the weekly data of 2020 can be classified into the following three distinct categories:

- **Cluster 1 – ‘Baseline’:** Comprises 29 weeks with a centroid stringency index of 36.99. These can be considered as the “baseline” weeks, before the existence of lockdown measures (January and February) and time periods with the loosest restrictions (June, the second half of September and October). The baseline cluster is depicted in green in Fig. 19.

- **Cluster 2 – ‘Restrictions’:** Comprises 10 weeks with a centroid stringency index of 54.33. This group of weeks belongs to the summer of 2020 (specifically in July, August and half of September) when modest restriction measures were in place. As restrictive measures were not as strict or extensive as a full lockdown, this category is distinct from the lockdown category. These months formed a separate category probably due to the increased stringency index compared to June and October. At that time, all the examined variables (driving behavior and driving volume indicators) present peaks according to the descriptive statistics. The descriptive average stringency index of these two months is 55, which is quite close to the stringency index presented by the clustering analysis. The restrictions cluster is depicted in red in Fig. 19.

- **Cluster 3 – ‘Lockdown’:** Comprises 14 weeks with a centroid stringency index of 82.13. This group of weeks represents the periods where full lockdown measures were in place. The descriptive average stringency index for both lockdowns is 85, which is quite similar to the calculated centroid value. The lockdown cluster is depicted in blue in Fig. 19.

When examining the centroid values of these categories, the differences in driver behavior parameters become apparent. The restrictions cluster shows increased distance and trip duration from the baseline cluster, indicating that trips are longer and farther after the lockdown period. Driving volume appears to be considerably increased, probably due to two factors: (a) the anxiousness of people to travel after the lockdown period and (b) the large tourism-related traffic volumes generated during the
summer in Greece. Harsh brakings/100 km appear to be reduced from the baseline, possibly due to more careful driving or disproportionately increased travel distances. Since the temporal percentage of speeding duration seems elevated, the second explanation appears more credible.

As expected, the lockdown cluster is the one with the most limited travel, with reductions in trip duration, total distance, and driving volume. Interestingly, a peak of harsh brakings/100 km is also observed, indicating that this category comprises weeks with increased road safety risk. Drivers may have been more aggressive overall due to encountering less traffic and more available space on the roads, and taking advantage of this new situation. The ratio of speeding to driving duration appears similar to that of the restrictions cluster.

Despite these observed differences, driving speed appears mostly unaffected between clusters; this is perhaps due to the large number of trips, which leads to the absorption of fluctuations for this parameter. It is worth highlighting that in R-studio, clusters are represented by conducting an internal Principal Component Analysis (PCA) and then visualizing the results with the two most prominent components serving as x and y axis. In other words, PCA is conducted primarily in order to supply distinguishable clusters for easier visualization.

The obtained cluster categories are also illustrated in the plots of Fig. 19. In the upper part of Fig. 19, a 2-dimensional cluster plot is used to depict all the clusters and centroids of the analysis. It should be noted that week numbering starts by considering the first lockdown week as week 1, the following week as week 2, and so on, until week 53. As per standard process, cluster plot axes are described by the two most prominent PCA components of the sample (Dimension 1 and 2). In the lower part of Fig. 19, an explanatory plot with all the clusters was created in order to contrast the clustering results with the observed stringency index, plotted with a separate curve. The outcome of the clustering can be regarded as satisfactory based on the fact that both lockdowns were defined precisely enough by the k-means algorithm. Only one week (week 19; from 2020-05-03 until 2020-05-10) appears to have been erroneously classified.

For the purpose of confirming the clustering analysis, a linear discriminant analysis (LDA) was conducted with a train/test dataset ratio of 80%/20%. Results indicated correct classification in 100% of the test dataset cases for Greece.

6.2. KSA

Regarding the KSA, the clustering centroids of weekly aggregated data for 2020 are presented in Table 6, with standard deviations reported in parentheses. The process and interpretation of the centroids follows the same logic as the one followed for Greece:

- Cluster 1 – ’Baseline’: Comprises 12 weeks with a centroid stringency index of 13.59. These can be considered as the “baseline” weeks, referring to the time period before the enforcement of lockdown measures (January, February, and three weeks of March). The baseline cluster is depicted in green in Fig. 20.
- Cluster 2 – ’Restrictions’: Comprises 30 weeks with a centroid stringency index of 59.89. This group of weeks refers to the time period after the end of lockdown restrictions, when certain looser restrictions remained with an average stringency index. The restrictions cluster is depicted in red in Fig. 20.
- Cluster 3 – ’Lockdown’: Comprises 11 weeks with a centroid stringency index of 88.92. These can be considered as the weeks with full lockdown measures in effect. The lockdown cluster is depicted in blue in Fig. 20.

As previously stated, the examination of clusters reveals the differences in driver behavior parameters. The ‘restrictions’ cluster shows decreased distance and trip duration from the baseline cluster, indicating that trips are shorter in distance and duration after the lockdown period, indicating a different reaction compared to Greece. Driving volume appears to be considerably increased, pos-

| Number | Category   | Total Duration | Total Distance | Harsh Brakings /100 km | Driving Volume | Driving Speed | Speeding percentage | Stringency Index |
|--------|------------|----------------|----------------|------------------------|----------------|---------------|--------------------|------------------|
| 1      | Baseline   | 989.23 (38.35) | 11.77 (0.90)   | 16.71 (1.40)           | 97.59 (43.74) | 42.25 (1.83)  | 5.36% (0.72%)      | 36.99 (27.02)    |
| 2      | Restrictions| 1052.78 (30.84)| 13.93 (0.94)   | 13.42 (0.75)           | 195.43 (26.07) | 43.61 (1.17)  | 6.36% (1.01%)      | 54.13 (5.01)     |
| 3      | Lockdown   | 825.72 (46.92) | 10.04 (0.94)   | 18.23 (1.74)           | 44.47 (15.26) | 43.68 (2.69)  | 6.29% (0.79%)      | 82.13 (3.00)     |

Fig. 19. (a) Cluster plot and (b) Annual distribution of cluster categories and stringency index (Greece).
possibly due to the same reasons for Greece, anxiousness of people to travel and tourism during these months. Harsh brakings/100 km appear to be once again reduced from the baseline. Since the temporal percentage of speeding duration appears close to the baseline, and total distance is reduced, innate more careful driving of drivers is a likely explanation.

As expected, once again the lockdown cluster is the one with the most limited travel, with the largest reductions in trip duration, total distance, and driving volume. Interestingly, a peak of harsh brakings/100 km is also observed, indicating that this category comprises weeks with increased road safety risk. Once again, drivers may have been more aggressive and taking advantage of emptier roads. The ratio of speeding to driving duration appears to be the highest between clusters. Consistently with Greece, driving speed appears mostly unaffected between clusters; this is perhaps due to the large number of trips, which leads to the absorption of fluctuations for this parameter.

The obtained cluster categories are also illustrated in the upper and lower plots of Fig. 20. The quality of the clustering can be considered adequate, as the lockdown period was defined sufficiently by the clustering analysis. Contrary to Greece, the KSA clusters were separated into three continuous time periods (before, during, and after the lockdown); it should be noted, however, that there were five erroneously grouped weeks this time. For both countries, the sample size utilized as input for the k-means algorithm, comprising of the 52 weeks of 2020, can be considered marginally adequate. While there is no precise definition in the literature, values of $2^n$ are cited as appropriate (Formann, 1984), with $n$ being the number of included variables. With the present data, five variables would be the maximum permissible, requiring $2^5 = 32$ data points. Since it was not possible to obtain more weekly average data within the framework of this study, the k-means algorithm was fitted for five and six variables only in addition to the previous analyses. The clustering results and categories were not affected. The cohesion as well as the reasonable centroid value interpretations of three clusters across two different countries allowed for the seven variable variants to be retained as the selected analyses.

The linear discriminant analysis (i.e., LDA) on the KSA clustering indicated correct classification in 90% of the test dataset cases for the KSA.

### 7. Discussion on the impact of the pandemic on road safety

The paper presents evidence of the impact of COVID-19 and constitutes a first attempt to understand the relationship between the strictness of corresponding response measures and the effect on driving behavior and crash frequency. The paper builds upon previous work (Katrakazas et al., 2020), which provided an overview of the effect on driving behavior and road safety during the first wave of the pandemic. The overview is completed with the current paper, which for the first time describes the effect of the pandemic using data from the entire 2020 year.

With “normal” everyday life disrupted, it was evident that driving behavior would be significantly affected. The first wave of the pandemic took governments and citizens by surprise, but at present, one year into the pandemic, signs of adjustment to the new reality are becoming apparent. For example, data showed that when lockdown states were lifted, a dramatic change in traffic by up to 400% in Greece was observed. In the KSA the corresponding change rose to 82%, an increase which is still considerably high. Following the same pattern, traffic volumes were substantially increased when comparing the first and second lockdowns. This finding is interesting when put into the perspective of the stringency of response measures and COVID-19 cases and casualties, since the lockdown periods (i.e., the first and second lockdown in Greece as well as the single lockdown in the KSA) are characterized by strict measures and a high number of COVID-19 cases and casualties. As a result, it can be tentatively assumed that drivers adjusted to these new conditions and behaved as if no restrictions were applied.

### Table 6

| Number | Category   | Total Duration | Total Distance | Harsh Brakings /100 km | Driving Volume | Driving Speed | Speeding percentage | Stringency Index |
|--------|------------|----------------|----------------|------------------------|----------------|---------------|--------------------|------------------|
| 1      | Baseline   | 1382.19 (49.66)| 20.49 (0.98)  | 20.94 (1.74)           | 68.71 (41.91) | 52.76 (2.53) | 7.24% (0.45%)      | 13.59 (18.36)   |
| 2      | Restrictions| 1164.09 (38.72)| 18.44 (0.79)  | 18.48 (0.9)            | 94.67 (10.27) | 53.83 (1.20) | 6.96% (0.86%)      | 59.89 (9.63)    |
| 3      | Lockdown   | 1052.90 (41.48)| 16.22 (0.88)  | 24.20 (1.08)           | 48.25 (10.63) | 53.90 (1.07) | 9.07% (0.69%)      | 88.92 (9.63)    |

![Fig. 20. (a) Cluster plot and (b) Annual distribution of cluster categories and stringency index (KSA).](image-url)
For Greece, driving after the shock of the first lockdown, all driving behavior indicators pointed towards safer attitudes. Harsh accelerations and brakings were reduced by up to 33% after lifting the response measures, while speeding and mobile phone use per driving duration were reduced by up to 9%. This positive outcome with regards to driving behavior, however, lasted until the imposition of the second lockdown in Greece, where it was demonstrated that drivers speeded more in relation with the average driving duration and also increased their harsh acceleration, harsh braking, and mobile phone usage frequency. On the contrary, in the KSA all driving indicators except mobile phone use, demonstrated a reduction after the end of the lockdown and thus hinted toward safer driving.

Unfortunately, the positive attitudes of Greek drivers immediately after the first lockdown and until the imposition of a second one, were not reflected in the frequency of road crashes. For example, crashes increased in Greece after the first lockdown by 116% when comparing the period between the first and second lockdown with time spent under confinement in March and April 2020. This is in contrast with other studies regarding the effect of COVID-19 on crash frequency (Inada et al., 2020; Muley et al., 2021; Saladié et al., 2020) although previous studies used a more limited time span for their data collection. The fluctuation in crashes and injuries during the period where lockdowns are imposed or resolved is something that is expected, however, due to the rapid changes in social and behavioral patterns during the pandemic (Calderon-Anyosa & Kaufman, 2021). Nevertheless, further in-depth crash research during the pandemic in Greece is needed in order to discover contributing and causal factors that led to the crashes in question.

Taking into account the stringency index of the response measures, it was demonstrated that driving behavior can be clustered into three categories: (a) baseline, which represents the period before restrictions or lockdowns, (b) restriction, which comprises periods where response measures start to get stricter, and (c) lockdown, which represents the strictest measures taken in form of a lockdown. From Table 6, it is evident that harsh brakings are one of the most representative indicators between clusters for Greece (together with driving volume and the stringency index), as large differences between the three groups are observed. Moreover, the most interesting finding from Table 6 is that in periods where restrictions are tightened in Greece, traffic volume is significantly higher, probably due to the good weather, as the “Restrictions” cluster includes the summer months and because of a potential fear of more strict measures that might come, which led people to more outdoor activities such as shopping when it was still allowed (2020). Similarly, with regards to the KSA, distinctions between clusters can be more clearly observed for harsh brakings and driving volume as well as the ratio between speed and driving duration, probably due to the fact that during strict response measures, streets were emptier. It should also be mentioned that the stress imposed by confinement conditions around the world (Lee & You, 2020; Lemke et al., 2020; Singh & Tech, 2020) might have also affected the increase of traffic volumes after the lift of the lockdown, as well as more dangerous behavior when streets were emptier due to stay-at-home governmental instructions.

One of the added contributions of this study was the continuous monitoring of smartphone metrics, which provide naturalistic driving data in a seamless and non-intrusive manner. These metrics disclose valuable information on the safety profiles of drivers and their fluctuations during times of the pandemic. The one-year span provides an opportunity to witness the effects of different lockdown or other restriction policies as they are not instantaneous in their inception, application, enforcement, and removal. The combination of these two features is also an advantage of the study; few naturalistic experiments are conducted in newfound conditions for such a duration.

8. Policy recommendations

The COVID-19 pandemic showcased the fragility that mobility patterns face in cases of unpredicted health or societal emergencies. Policymakers in the road safety domain should act proactively in the years to come to incorporate safety lessons from the pandemic period. As it was demonstrated in this paper, driving speed was significantly increased during the periods when lockdowns were imposed, due to the heavily reduced traffic volumes for motorized traffic. Towards that end, the paradigm of reducing speed limits inside urban areas to 20 or 30 km/h, as declared by the Stockholm Declaration of the 3rd global ministerial conference on road safety (Trafikverket | Swedish Transport Administration, 2021) should be extended. With lower speeds, crash risk, severe injuries, and harsh events will be apprehended. Such policies have already been applied in Paris, Brussels, and Bilbao1 and could be extended to major metropolitan areas worldwide.

Although active traveling increased during the pandemic period, due to the avoidance of crowding and public transportation, mortality of pedestrians and cyclists was generally increased, when considering the increase in exposure (ONISR - French Road Safety Observatory, 2021). As a result, measures to incorporate or increase VRUs and active travelers in the present ‘car-dominated’

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1 https://etsc.eu/30km-h-limits-set-to-spread-in-2021/.
infrastructure are needed. For example, new recovery and resilience funds directed to road safety (both infrastructure and policy) need to be created in order to timely adapt to potential infrastructure changes for more active traveling. Finally, state-wide policies that enforce social responsibility, as well as boost smart speed and traffic safety enforcement are also encouraged. In that principle, data with regards to the pandemic (e.g., countermeasures in effect along with COVID-19 cases and casualties) could be integrated with safety data (e.g., speed limits and current traffic conditions) within mobile applications to inform drivers to proactively take care of their speed and driving behavior while driving on different urban and suburban areas.

9. Conclusions

The present research aimed at presenting descriptive evidence of the impact of COVID-19 and the corresponding response measures on driving behavior and road safety for the entire year of 2020. For the first time to date, data from two countries (i.e., Greece and the KSA) were explored and were correlated with the stringency of COVID-19 response measures. To fulfill that aim, following the presentation of the representative figures and overview tables, a clustering approach (i.e., k-Means) was utilized in order to identify patterns correlating the stringency of government measures with driving behavior indicators. By examining the statistics of the entire year, it was evident that the dissolution of imposed lockdown led to an increase in traffic volumes, but also to smoother driving behavior. This difference was found to be more prominent when the first lockdown in Greece and the KSA was lifted, where speeds were reduced by up to 6% in Greece and by 9% in the KSA.

Using the k-means clustering technique, it was revealed that 2020 can be split into three clusters of driving behavior: (a) baseline, one depicting driving behavior when no or light response measures apply, (b) restrictions, when COVID-19-related cases and casualties increase and thus stringency of measures increases, and (c) lockdown. The clustering results validated that the most significant differences in driving behavior of Greek drivers were found between the “Restrictions” and “Lockdown” phases in terms of exposure (total distance, total duration, and driving volume) as well as harsh braking frequency. On the contrary, negligible differences were found for speeds and speeding for all three clusters.

With regards to the policy implications of the findings, the relevant stakeholders should focus on the reduction of driving speeds, as these are indicated in the Stockholm declaration as well as the safe incorporation of active traveling modes in the current infrastructure by utilizing resilience funds and social responsibility measures.

Finally, additional crash research is needed to analyze the composition of traffic exposure, psychology, and COVID-19 as contributing factors for road safety during the pandemic period in Greece and other countries. Data for crashes per kilometer driven were inaccessible in the current research; hence, a future study could take the aforementioned indicator into consideration. As a result, future research should be directed toward analyzing crash frequency and the captured driving behavior indicators from a time-series perspective. Furthermore, a future study could expand the scope of the findings by classifying the distraction types (e.g., texting, calls, navigation) and providing insights into this topic. Psychological factors (e.g., fatigue, sadness) during the pandemic, socio-demographic characteristics (e.g., gender, age, educational level), as well as the overall effect on human psychology of the unknown future could also be taken into account. This direction will assist in better understanding the influence of the response measures as exogenous factors as well as the inter-relationship between the evolution of COVID-19 in terms of cases or casualties and the progression of driving behavior or road safety indicators.

Conflicts of Interest

The authors declare no conflict of interest.

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Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Christos Katrakazas, Apostolos Ziaiopoulos; data collection: Eva Michelaraki, Marios Sekadakis; analysis and interpretation of results: Christos Katrakazas, Apostolos Ziaiopoulos, Eva Michelaraki, Marios Sekadakis; draft manuscript preparation: Christos Katrakazas, Apostolos Ziaiopoulos, Eva Michelaraki, Marios Sekadakis, George Yannis. All authors reviewed the results and approved the final version of the manuscript.

Appendix A

See Table A1 and see Figs. A1–A3.

| Table A1 |
|--------------------------|--------------------------|
| **Timeline of COVID-19 response measures in Greece in Greece and KSA.** |
| **Greece** | **KSA** |
| 1st Lockdown of non-essential movements | 23/03/2020 |
| End of the 1st lockdown | 04/05/2020 |
| Closure of bars, cafes, restaurants, theatres and concert halls | 02/11/2020 |
| Travel Lockdown of non-essential movements | 07/11/2020 |
| Closure of primary schools and kindergartens | 14/11/2020 |
| Opening of shops and hairdressers | 14/12/2020 |
| **KSA** | **KSA** |
| Closure of educational institutions | 09/03/2020 |
| Lockdown of non-essential movements in Qatif | 09/03/2020 |
| Closure of shops, restaurants, coffee shops and public parks | 15/03/2020 |
| Lockdown of non-essential movements in Mecca, Medina, Riyadh | 26/03/2020 |
| End of Lockdown | 21/06/2020 |
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