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A data fusion approach for providing valid annual passenger transport statistics during the COVID-19 pandemic

Anton Galich[1*], Christine Eisenmann[2] and Katja Köhler[3]

Abstract
The global outbreak of the COVID19 pandemic dramatically changed people's life's and their travel behavior in 2020. Consequently, capturing these changes accurately and providing valid annual transport statistics constitutes a tremendous challenge all over the world. Against this background and the lack of a single comprehensive source of data revealing the ground truth, we present a data fusion approach to provide valid annual transportation statistics for Germany during the COVID19 pandemic. Therefore, we adapted our existing model approach at generating annual, national statistics for Germany on passenger transport. Unlike in the existing model, we do not model the whole year as one, but divide the year into pandemic stages in order to model passenger transport demand as adequately as possible within each stage. Three travel surveys capturing the altered travel behavior in the different stages of the pandemic were used in order to adapt our passenger kilometers travelled (PKT) model, which bases on a cross-sectional national household travel survey which in many countries serves as the data basis for providing annual transportation statistics.

The main results show a decline in the overall number of trips in 2020 in Germany of around a quarter and around a third less kilometers travelled compared to 2019. These changes in travel behavior differ considerably between different modes of transport, trip purpose and the different stages of the pandemic in 2020. The results produced were validated on the basis of other studies and further sources of data such as floating car data and automated count stations for bicycle traffic and ensure reliable passenger transport statistics in the years of the COVID19 pandemic.

Keywords Data fusion, National passenger transport statistics, COVID19, Travel behavior

*Correspondence:
Anton Galich
anton.galich@dlr.de
[1]Department of Mobility Spaces, German Aerospace Center, Institute of Transport Research, Rudower Chaussee 7, 12489 Berlin, Germany
[2]Chair of Infrastructure and Mobility Planning, Brandenburg University of Technology (BTU), Konrad-Wachmann-Allee 4, 03046 Cottbus, Germany
[3]Department of Means of Transport, German Aerospace Center, Institute of Transport Research, Rudower Chaussee 7, 12489 Berlin, Germany

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1 Introduction

In 2020, people's travel behavior worldwide changed abruptly to an unprecedented extent. Due to the COVID19-pandemic governments of various countries introduced nationwide lockdowns and closed their borders to slow down the further spread of the virus. In addition, many people took further measures by themselves and restricted their movements and social contacts in order to reduce the likelihood of infection. All of this resulted in radical changes in mobility in terms of the number of trips conducted, the kilometers travelled, the means of transport used, etc.

Transportation researchers all over the globe attempted to capture the pandemic's impact on mobility as quickly as possible by analyzing various sources of data such as smart card data [1], mobile phone data [2, 3], investigated GPS-based location data from mobile applications [4–6], online surveys [7–14], telephone interviews [15], Google's popular time graph data [16], congestion index and subway ridership data [17], floating car data or count station data (see [18] or [19] for a more comprehensive overview of the data sources used). Consequently, a rich pool of literature containing analyses of the pandemic's impact on mobility and travel behavior in different countries emerged in 2020 and 2021 [20, 21]. These analyses based on surveys and big data provide very valuable insights into how and why the mobility of different population groups has changed during particular phases of the pandemic. However, they do not provide annual quantifications and statistics of mobility indicators for entire countries which constitutes an enormous challenge in times of extreme irregularities in travel behavior due to peaking or plummeting numbers of new infections and lockdowns or relaxations of restrictions.

Hence the unique contribution of this paper to the scholarly literature lies in presenting an approach for providing valid annual transport statistics at the national level during the pandemic. In so doing, the approach developed goes beyond most other studies in a temporal and spatial manner. Many other studies, for instances, focus on capturing changes in mobility in specific stages of the pandemic such as the first lockdown in spring 2020 [14, 22–25], the first and second wave of infections [26, 27], the first three waves of infections [28], or a lockdown period and a subsequent period of time in which restrictions were relaxed [17, 29–31]. Other studies tried to capture the effects of COVID19 on mobility during an entire year but do not distinguish between different stages of pandemic [32]. Distinguishing different stages of the pandemic, however is crucial for providing valid annual transport statistics as mobility behavior varied considerably between lockdown period and periods in which restrictions were lifted again. In addition, many studies do focus on mobility changes during the pandemic on a national level but rather on the level of metropolitan areas of a country [17, 28] or on specific cities such as Thessaloniki [14]. Those studies that do focus on analyzing changes in mobility due to COVID19 on the national level often do not attempt to develop transport statistics such as the modal split or the annual mileage but rather try capturing the altered mode preferences [23, 27, 32, 33] or changes in commuting patterns [24].

In contrast, the study at hand presents an approach for capturing changes in mobility during an entire year and for an entire country. For this purpose, data capturing the COVID19 induced changes in mobility was gathered during all relevant stages of the pandemic throughout the year 2020. Furthermore, a methodology was developed in order to merge this data and to provide valid annual transport statistics at the national level taking into account extremely varying mobility behavior throughout the year. Annual transport statistics are provided in many countries as they serve as information for political decision-making in the transport sector and also as the provide important data on the basis of which many companies develop further services. In Germany, for instances, "Transport in Figures" is an annual compendium provided by the German Federal Ministry for Digital and Transport that constitutes the central reference for transport statistics. Among others, key mobility statistics of passenger transport for the entire population of Germany with focus on trips made and kilometers travelled, split by transportation modes used and trip purposes are compiled. In normal years, a passenger kilometers travelled (PKT) model, a data fusion approach which is largely based on a cross-sectional national household travel survey (NHTS), is applied in order to produce these annual statistics [34]. However, the usual PKT model could not be used because the most recent cross-sectional NHTS for Germany is from 2017 and thus does not reflect the changes in travel behavior due to COVID19. Therefore, the methodology of the PKT model has been fundamentally modified to reflect the changes in mobility due to the COVID-19 pandemic in 2020.

This paper presents the modification of the PKT model using a sophisticated data fusion approach to capture changes in travel behavior during the COVID-19 pandemic. The main objective was to develop a method that enables a reliable annual quantification of key mobility indicators such as the modal split or the annual kilometers travelled with regard to the different stages of the pandemic (lockdown, easing of measures, etc.) throughout the year 2020. For this purpose, a cross-sectional NHTS capturing average daily travel behavior in Germany before the pandemic was adjusted on the basis of minor surveys focusing on travel behavior during specific stages of the pandemic and calibrated with sociodemographic data and secondary transport data.

The remainder of the paper is structured as follows: the METHODS chapter gives an overview of the usual PKT approach and discusses the PKT model extensions due to the COVID-19 pandemic. Moreover, the data sources for validation are introduced. The RESULTS chapter presents key figures of passenger transport in Germany in 2020 – for the different stages of the pandemic as well as for the entire year 2020 in comparison to 2019; additionally, the PKT results are validated with further data sources. The strengths and limitations of the model are documented in the DISCUSSION chapter. The CONCLUSION chapter gives a concluding summary and provides an outlook.

2 Methods

The methodological procedure used for producing reliable transportation statistics for the year 2020 in Germany is described in five subsections. First the usual approach of the PKT model is introduced. Second, it is explained how we splitted the year 2020 in different stages of the pandemic. Third, the collection of new data on travel behavior in these different stages is outlined, before, fourth, the adjustment of the usual approach for producing annual transportation statistics is illustrated. Fifth, the data sources used for validating the results produced by the adjusted approach are described.

2.1 Transport in figures: the usual approach of the PKT model

The PKT model aims at generating annual figures on passenger kilometers travelled (PKT) conforming to official to passenger transportation statistics and is part of the annual now-casting procedures applied for the German National Transport Statistics. It relies on various sources of data with the main input being the German NHTS "Mobility in Germany 2017" (MiD 2017) [35], which was conducted from May 2016 to September 2017 with 316,000 individuals. The methodology of the PKT model comprises three steps (Fig. 1), which are described in greater detail in [34].

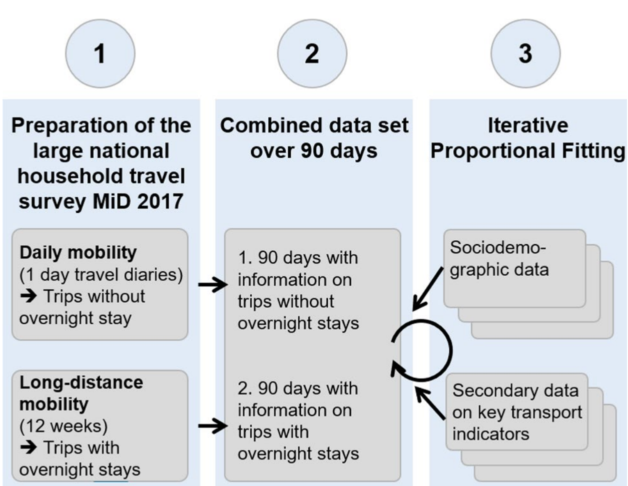

Fig. 1 Overview of the three steps of the PKT model

Step 1 includes the preparation of two original MiD 2017 data sets covering daily mobility and long-distance mobility on the basis of different temporal dimensions. In the second step these two data sets are merged together by harmonization to the same temporal dimension. For this purpose, the 24-hour-trip diaries covering daily mobility and the long-distance data set comprising journeys with overnight stays over 3-months are reweighted to a time period of 90 days. Consequently, the resulting combined data set contains socio-economic information as well as travel demand of the total population for a 90-day period. This socio-economic and travel information forms the basis of an iterative weighting procedure in Step 3 which ensures that hard-wired input statistics from various other sources of data are met.

The iterative weighting relies on annual information on socio-demographic characteristics and secondary transport parameters. Input variables for the socio-demographic weighting are official statistics of the Federal Statistical Office, the Federal Institute for Research on Building, Urban Affairs and Spatial Development and the Federal Employment Agency (e.g. resident population, employed population, unemployed population, pupils, car ownership, household size, household income, regional statistical spatial typology of place of residence). Input variables for the weighting of secondary transport parameters are official statistics of the Federal Statistical Office (e.g. trips made and kilometers travelled by public transport) as well as annual vehicle kilometer statistics from the vehicle kilometers travelled and fuel consumption model, which was also developed within Transport in Fig. [36]. This weighting procedure ensures that transport parameters for which we have precise knowledge from other official statistics are reproduced in the PKT model. This is the case for public transport trips and kilometers travelled and for the kilometers travelled by car. Other PKT key figures, in particular cycling and walking demand and transport use differentiated by trip purpose, are not calibrated to secondary statistics.

The resulting data set of the PKT model offers countless analysis options and constitutes a prime example of how insufficient survey data can be updated and upgraded harnessing the full potential of combining different data sources. Among others, the resulting data set includes information on trip purposes and the mode of transportation used on each trip. More concretely, six different transport modes are depicted in the PKT model:

1) Walk.
2) Bicycle.
3) Public transport (road).

4) Public transport (rail).
5) Motorized individual transport.
6) Airplane.

Various means of transport were categorised into the six travel modes shown. In particular, innovative mobility options are also available in cities in Germany, for example car sharing or bike sharing. However, an analysis of the MiD 2017 shows that the share of trips made using innovative mobility options was less than 1% of all trips in 2017; it can be assumed that the mode share in 2020 was of a similar size. For this reason, trips made using innovative mobility services are currently not shown separately. Instead, trips made using innovative mobility services are assigned to the respective transport modes shown. For example, bike-sharing trips are assigned to the transport mode bicycle.

Furthermore, seven different trip purposes are distinguished:

1) Work.
2) Education.
3) Business.
4) Shopping.
5) Leisure.
6) Escort.
7) Holiday.

The criterion for assigning a trip or a journey to a purpose is the activity at the destination. Exceptions to this rule are trips or journeys whose destination is one's residence. In these cases, the main activity before arriving at one's residence is decisive for the assignment of the trip purpose.

2.2 Splitting 2020 into the different stages of the pandemic

Unlike in the existing PKT model, we decided not model the whole year 2020 in one step as mobility varied massively in the course of the year 2020. Instead, we divided the year into pandemic stages with different mobility patterns in order to model passenger transport demand as adequately as possible within each stage. To identify those pandemic stages, various data sources such as floating car data, automated count stations for vehicles, bicycles, and pedestrians, official public transport statistics, mobile phone data, and web-scraping data of shared e-scooters, bicycles, and cars were considered. In particular, mobile phone data provide a good illustration of the changes in mobility in 2020 as shown in Fig. 2.

By mere eye it can be seen that the first lockdown in mid-March 2020 resulted in a sharp decline in overall mobility. From then on, people slowly began to make more movements from day to day until around the end of May 2020 the pre-pandemic level of daily movements is reached. While the summer months of 2020 are characterized by a similar level in overall mobility as the same months in 2019, the second lockdown in early November 2020 again results in a decline in overall mobility.

These changes in mobility were not only brought about by political measures such as the two lockdowns but also by people adjusting their behavior to increasing or decreasing daily cases of new infections as these numbers affected the perceived risk of contracting COVID-19. Figure 3 provides an overview of the development of the detected daily cases of new infections and the political measures undertaken to contain the further spread of the virus in 2020 in Germany.

In sum, the analyses of all these different kinds of data highlighting different forms or aspects of mobility point out that there were huge changes in travel behavior in 2020 not only in comparison to 2019 but also during different stages of the pandemic in 2020. Against this

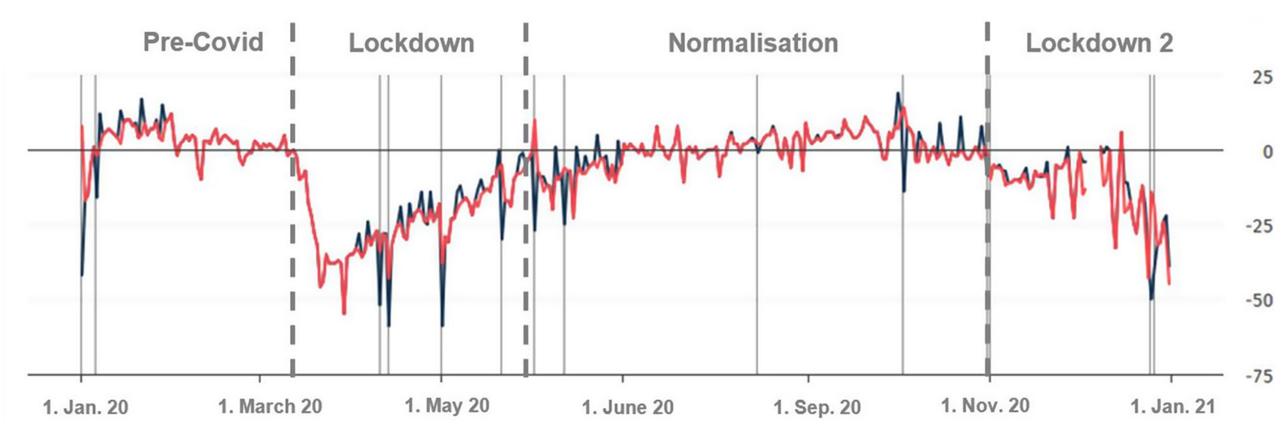

Fig. 2 Relative changes in mobility per day in Germany from 2019 (baseline zero) to 2020 (red resp. blue line) based on mobile phone data. The blue line illustrates raw data, while the red line shows changes that take public holidays into account [37]

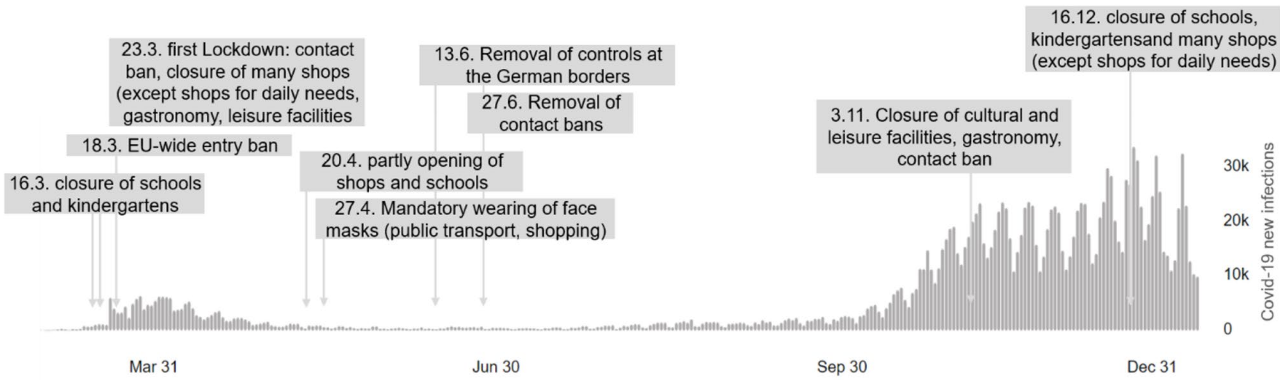

Fig. 3 Political measures and new infections (positive tests) per day in 2020 in Germany. It should be noted that the number of infections only outlines those infections that were detected by a COVID19 test. Hence the real number of infections might be much higher as many infected people might not have been tested, in particular in the first half of 2020 as testing capacities were still limited

background the year 2020 was split up into four different stages for the production of annual transportation statistics:

1) Pre-pandemic mobility: 01.01.2020–14.03.2020.
2) 1. Lockdown: 15.03.2020–31.05.2020.
3) Normalisation: 01.06.2020–31.10.2020.
4) 2. Lockdown: 01.11.2020–31.12.2020.

Each of these stages characterizes general trends in travel behavior in Germany in 2020. While the travel behavior in the first 2 ½ months of 2020 did not change much in comparison to 2019, the two lockdowns in mid-March and early November resulted in considerable declines in overall mobility. In contrast, the stage of normalisation in the summer months of 2020 is characterized by higher levels of mobility as retail shops, schools, restaurants, cinemas, and recreational venues were allowed to open again (however, it should be noted that other data sources suggest that mobile phone data may overestimate the mobility in the normalisation phase).

For the development of reliable annual transportation statistics for the year 2020 we assume that people's travel behavior differs considerably between these four different stages but is relatively homogenous within each stage. Therefore, people's daily travel behavior had to be separately adjusted in the PKT model for each of the different stages of the year 2020 after the outbreak of the pandemic in March. Only the travel behavior in the first 2 ½ months of 2020 could be treated as pre-pandemic mobility and thus directly derived from the original data set without the need of any adjustments. However, in the two lockdowns and in the stage of normalisation people's actual travel behavior differed considerably from the one outlined in the original data set and thus new sources of data were needed for the adjustment.

2.3 Data collection in the different stages of the pandemic

To adequately map travel demand in the various pandemic stages, primary data is needed on how the mobility of different population groups has changed during the pandemic phases. Mobility surveys are particularly suitable in this regard. At the DLR, altogether three online surveys capturing people's travel behavior were carried out in 2020 [10, 38]. Each of these surveys collected data on changes in travel behavior in one of the three stages after the outbreak of the pandemic in comparison to pre-pandemic times. Table 1 displays the data collection periods of the surveys as well as the number of participants and the issues covered, respectively.

The three surveys were carried out in a panel design, i.e. the 1,000 people that answered the first survey were also invited to the second and the third survey. Indeed, more than half of them also participated in the second and the third survey. In addition, further people were invited to participate in the second and the third survey in order to reach at least 1,000 participants. These additional participants were sampled according to their sex, age, and place of residence (large city, small city, rural area etc.) so that the overall number of participants of each survey represents the general population of Germany in these categories.

Besides questions on the sociodemographic background of the participants, each survey also collected information on the number of trips conducted by trip purpose in the respective last week and the mode of transportation used on these trips. This information was not only collected for the last week at the point of time of data collection but also for a usual week before the outbreak of the pandemic. Consequently, the data sets resulting from each survey contain information that allow analyzing potential changes in travel behavior between pre-pandemic times and the different stages of the pandemic in terms of the number of trips conducted

Table 1 Three panel design surveys in 2020 to capture changes in travel behavior due to the COVID-19 pandemic

	First survey	Second survey	Third survey
Data collection period	06–10 April 2020	29 June – 07 July 2020	25 November – 04 December 2020
Number of participants	1,000	1,000	2,504
Absolute number and relative share of participants that already participated in the first survey	-	566 (57%)	523 (21%)
Participants are representative of the population in Germany in terms of	Sex, age, and spatial distribution (large city, small city, rural area, etc.)		
Mobility stage covered by the survey	1. Lockdown (16 March – 31 May 2020)	Normalisation (01 June – 31 October 2020)	2. Lockdown (01 November – 31 December 2020)
Issues covered by the survey	• Sociodemographic data • Number of trips conducted by trip purpose • Mode of transport used on the trips • Travel behavior before the outbreak of the pandemic		

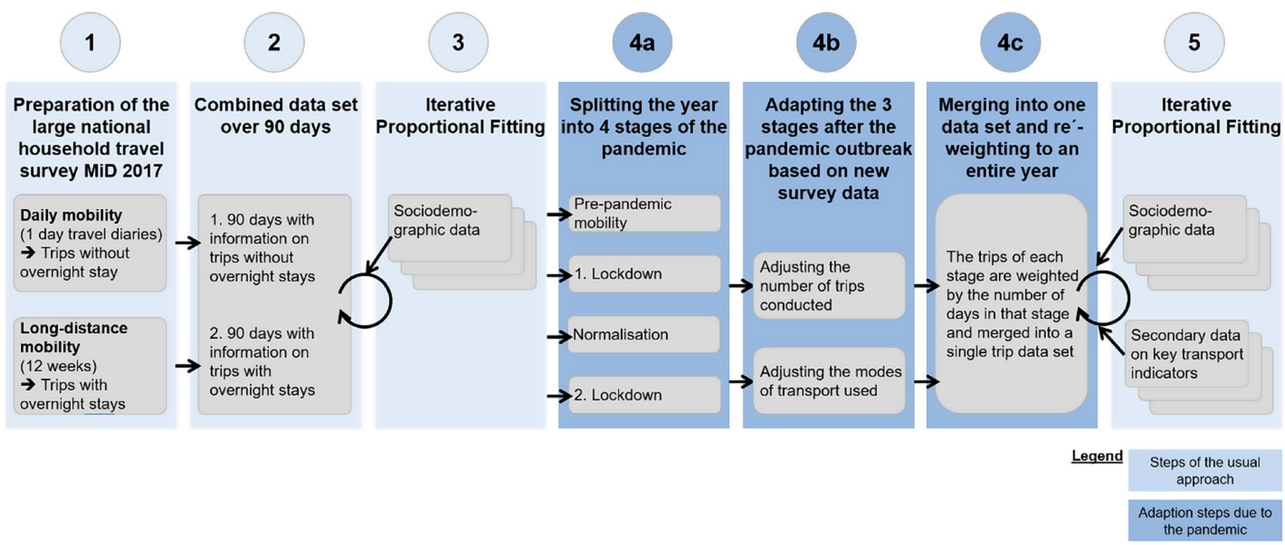

Fig. 4 The three steps of the usual approach for producing annual transportation statistics and the additional steps to capture the impact of the pandemic on travel behavior

by trip purpose and the mode of transportation used on these trips.

2.4 Adjusting the usual PKT approach

The insights on changes in travel behavior due to the pandemic gained from the three surveys were used to adjust the general data set of the PKT model so that it reflects the actual travel behavior in each of the three stages after the outbreak of the pandemic and the first lockdown in mid-March 2020 (Fig. 4). This resulted in three different data sets covering the actual travel behavior on an average day in the stage of the (1) Lockdown, the stage of Normalization, and the stage of the (2) Lockdown. In addition, the unadjusted data set of the PKT model was used to cover the travel behavior in the first 2 ½ months of 2020 which was not affected by the pandemic.

The adjustment of the data set of the PKT model to reflect the actual travel behavior in the three stages after the outbreak of the pandemic focused on trip purposes and modes of transport. The main objective was to generate separate data sets for each stage of the pandemic which reflect the actual travel behavior on an average day at that time in terms of two issues:

1) The number of trips conducted per trip purpose.
2) The mode of transportation used on these trips.

These two issues were assumed to cover the biggest changes in travel behavior during the pandemic. Consequently, a two-step procedure was developed to adjust the general data set of the PKT model on the basis of the three online surveys. First, changes in the number of trips per trip purpose and the mode of transportation used on these trips were determined for each stage after the outbreak of the pandemic on the basis of the three surveys. In some cases, the number of respondents that provided answers on the usage of a specific mode of transportation on a specific trip purpose in one of the stages of the pandemic was deemed too low to derive reliable results. Therefore, in these cases, further sources of data such as official statistics on the number of people travelling by public transportation were considered to determine actual changes in the modes of transportation used.

Second, the changes in travel behavior determined on the basis of the three surveys are transferred to the data set of the PKT model. This is done on the basis of homogenous person groups in terms of age and education, e.g. changes in travel behavior for people in the age of 20–29 with a university degree are calculated on the basis of the surveys and then transferred to the same group of people in the data set of the PKT model. In addition, further variables relevant for specific trip purposes such as home office for trips to work or online shopping for shopping trips were considered for this transfer. This means, among others, that people who already before the pandemic at least occasionally worked from home or shopped certain products online according to the data set of the PKT model, also gained a higher probability to work from home or to substitute shopping trips with online shopping during the pandemic.

The application of this two-step procedure resulted in four different data sets. Three adjusted data sets for the three different stages of the pandemic in 2020 and one unadjusted data set covering the pre-pandemic travel behavior in the first 2 ½ months of 2020. Each of these four data sets reflects the travel behavior of the population of Germany on an average day in the respective stage of 2020. In a next step, these four data sets were merged into one data set and the trips in each data set were reweighted by the number of days of the respective stage of 2020. In the fifth step, the regular iterative proportional fitting (IPF) approach was applied, which weights on the basis of sociodemographic data and on secondary data on transport indicators (see [34] for a detailed description of the IPF).

Eventually, the process described resulted in an adjusted data set of the PKT model that reflects the changes in travel behavior in Germany in 2020 in the different stages of the pandemic and before it. This final data set was used to calculate the annual transportation statistics for the year 2020 in Germany in the same manner as in the previous years.

2.5 Data sources for validation

Various data sources were used for the validation of the changes in travel behavior identified in this paper by the approach described. The Germany Mobility Panel and automated bicycle count stations constitute the two most important ones as they could be used for the most thorough comparisons.

The German Mobility Panel constitutes an annual longitudinal NHTS that has been carried out since 1994. Each year in autumn between 3,000 and 4,000 people representative for the population living in Germany are asked to report their daily travel over seven consecutive days [39]. To cover pandemic-related changes in travel behavior, the questionnaire of 2020 included various questions on how people adapted their behavior due to the COVID-19-pandemic. Furthermore, a special edition of the German Mobility Panel was carried out in January and February 2021 to provide data on travel behavior during the second lockdown in Germany.

Data of automated bicycle count stations spread-out all-over Germany were available via a public application programming interface when this study was conducted. The number of bicycles detected at each count station was downloaded in an hourly resolution for the time period of 01 January 2017–31 December 2020. Count stations with missing values for more than three consecutive hours were deleted from the data set as well as count stations with extremely low values over several weeks or months. The data of 229 automated bicycle count stations remained in the final data set after this data preparation.

3 Results

The official "Transport in Figures" statistics only report the overall annual quantifications for passenger transport demand. In order to better categorize the model results and assess their validity, we first discuss the key travel demand quantifications for the different stages of the pandemic. Second, the results for the entire year of 2020 are presented and compared to the results of the Transport in Figures compendium of 2019. Third, the results for the year 2020 are validated on the basis of other sources of data.

3.1 Results for the different stages of the pandemic

The Modal Split (Fig. 5) illustrates that the share of the actives modes of walking and cycling increased in all three stages of the pandemic in comparison to the pre-pandemic stage.

In contrast, the share of public transport (road and rail) decreased in all three stages of the pandemic in comparison to the pre-pandemic stage, while the share of car travel remained relatively stable. Airplanes only play a marginal role in daily mobility and have a share of less than 1% in the Modal Split before and during the pandemic. The most striking changes in the Modal Split in the different stages of the year 2020 are the large increases in the share of walking and the large decreases in the shares of public transport (road) during the two

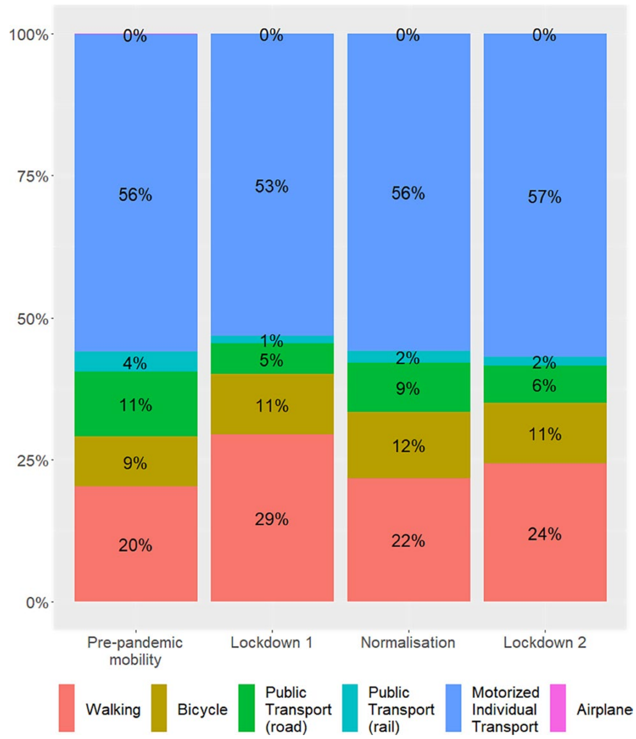

Fig. 5 Modal Split in the different stages of the pandemic

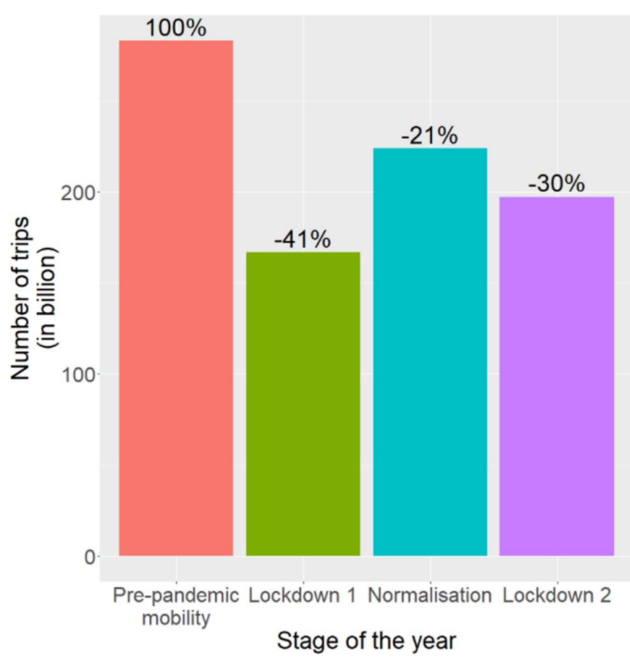

Fig. 6 Absolute number of trips per day in the different stages of 2020 and relative decrease in the number of trips per day in the three stages of the pandemic in comparison to the pre-pandemic stage

lockdown periods in comparison to the pre-pandemic stage.

Figure 6 shows the number of trips per day in the different stages of 2020. The number of trips per day decreases in all three stages of the pandemic in comparison to the pre-pandemic stage. The sharpest decrease occurs in the first lockdown and the lowest in the summer month of 2020 during the stage of normalisation. The overall kilometers travelled per day reveal a similar pattern over the different stages of 2020 (Fig. 7).

However, a more detailed of the daily kilometers travelled per mode of transport reveals a more nuanced picture. The daily kilometers travelled of walking trips, for instances, increased considerably during both lockdowns in comparison to the pre-pandemic stage. Also, the daily kilometers travelled of bicycle trips increased in the first lockdown in comparison to the pre-pandemic stage and remained roughly on the pre-pandemic level in the stage of normalisation and the second lockdown. In contrast, the daily kilometers travelled of all trips conducted by public transport (road, rail, and plane) decrease significantly in all stages of the pandemic compared to the pre-pandemic stage. In particular, the daily kilometers travelled of trips conducted by airplane almost decrease to zero during the first lockdown.

Fig 8 helps in explaining these different patterns by outlining the daily kilometers travelled per trips purpose.

The sharpest decreases in the daily kilometers travelled during the pandemic occur in business trips and holiday trips which are overproportionally conducted by airplane. In contrast, the smallest decreases take place in shopping trips and leisure trips which are overproportionally conducted by foot or by bicycle. In particular, leisure trips such as trips to restaurants, museums, cinemas etc. which were not possible during the two lockdowns as all of these institutions were shut down, were often replaced by walks in parks and recreational bicycle trips as these outdoor activities always remained possible.

3.2 Results for the entire year of 2020

Even though the travel demand results of the four stages shown in the previous chapter shows the highest level of detail concerning the model results in the various pandemic phases, the results are not presented in such detail in the statistics of "Transport in Figures". Instead, "Transport in Figures" shows key figures for the entire year 2020, which are then classified and analyzed in the time series. Therefore, key figures for 2020 are compared with them for 2019 in this chapter.

Figure 9 shows the relative changes in Modal Split from 2019 to 2020. Relatively speaking, there are only minor changes, the largest changes in the Modal Split have occurred in public transport and motorized individual transport. While the share of public transport (rail) shrinks by 1.5% from 2019 to 2020, the share of motorized individual transport increased by 1.5%. The shares of walking and cycling trips increase by 0.7% and

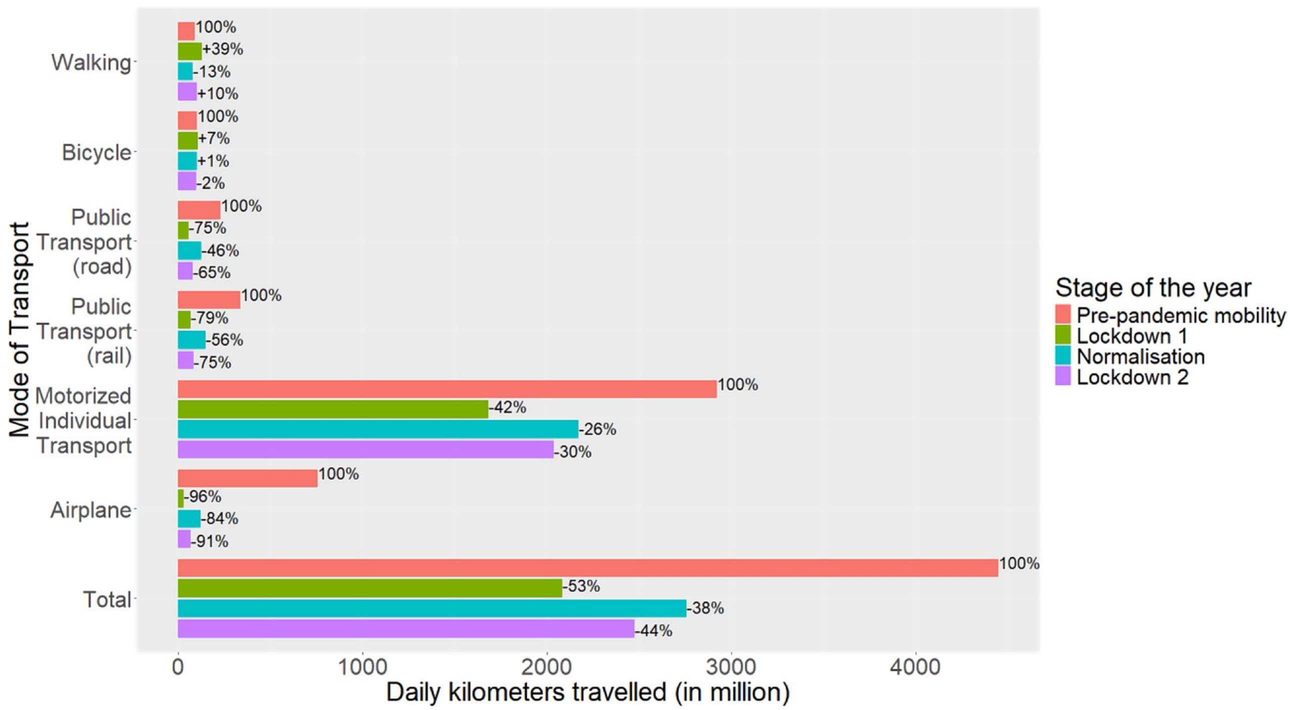

Fig. 7 Absolute daily kilometers travelled per mode of transport in the different stages of 2020 and relative change in the daily kilometers travelled in the three stages of the pandemic in comparison to the pre-pandemic stage

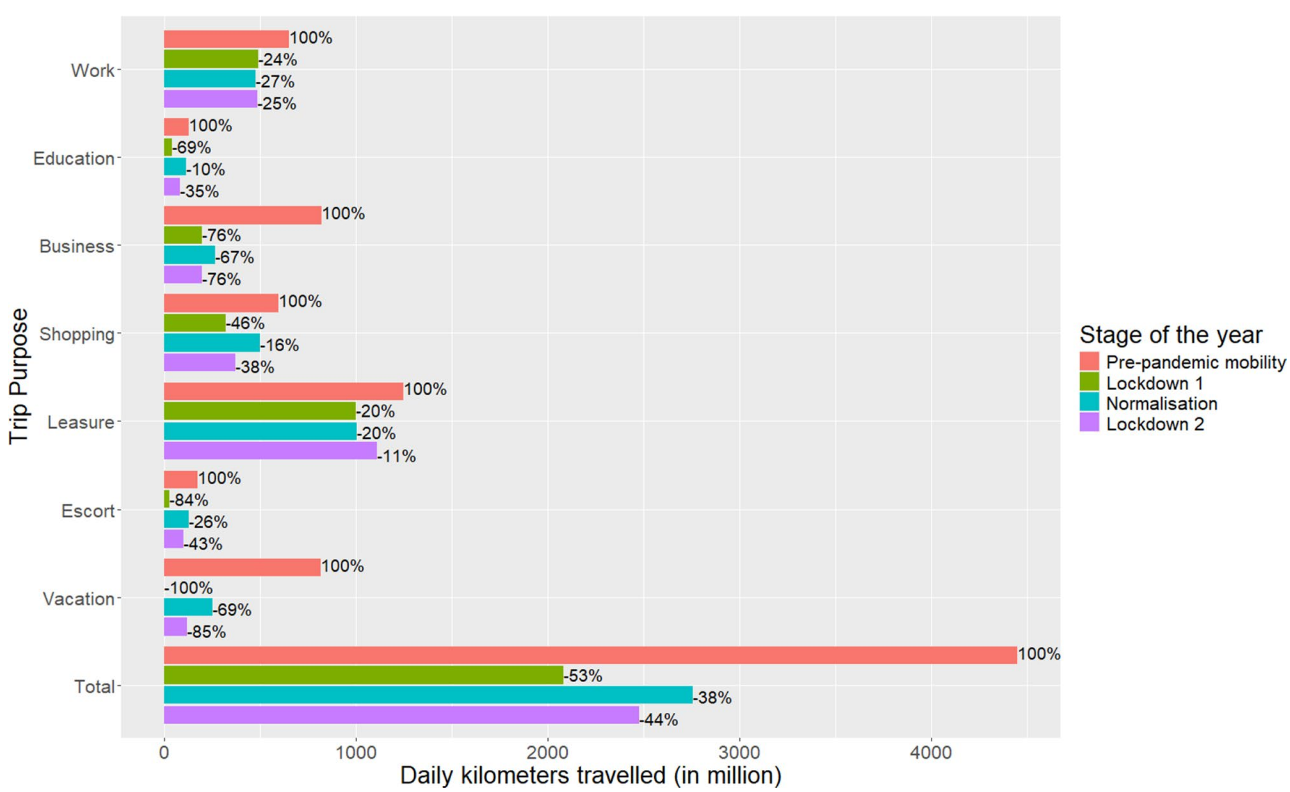

Fig. 8 Absolute daily kilometers travelled per trip purpose in the different stages of 2020 and relative changes in the daily kilometers travelled in the three stages of the pandemic in comparison to the pre-pandemic stage

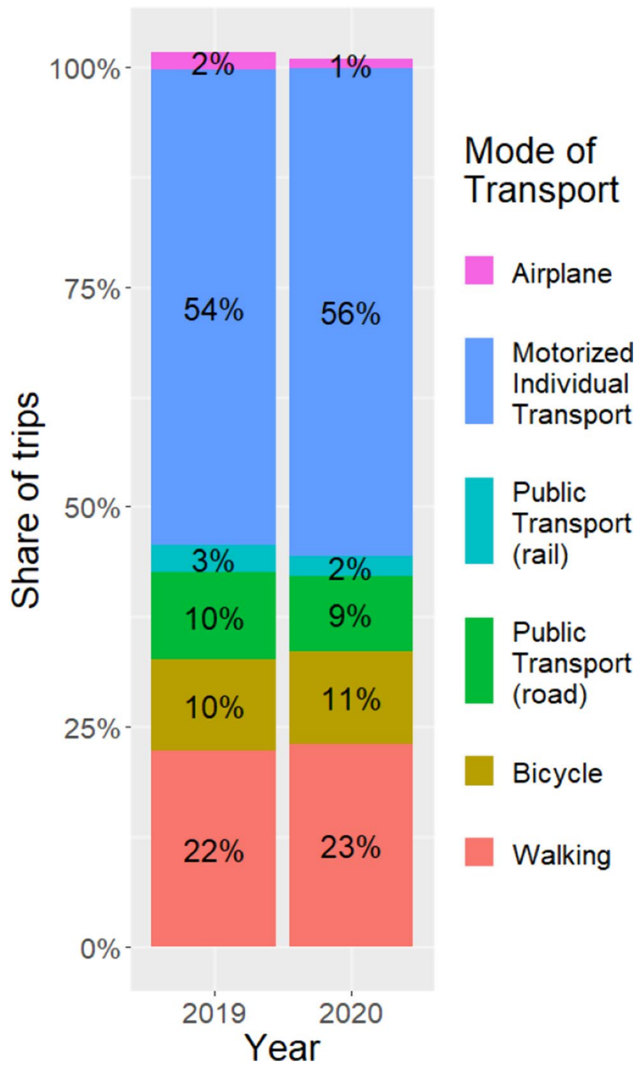

Fig. 9 Modal Split in 2019 and 2020

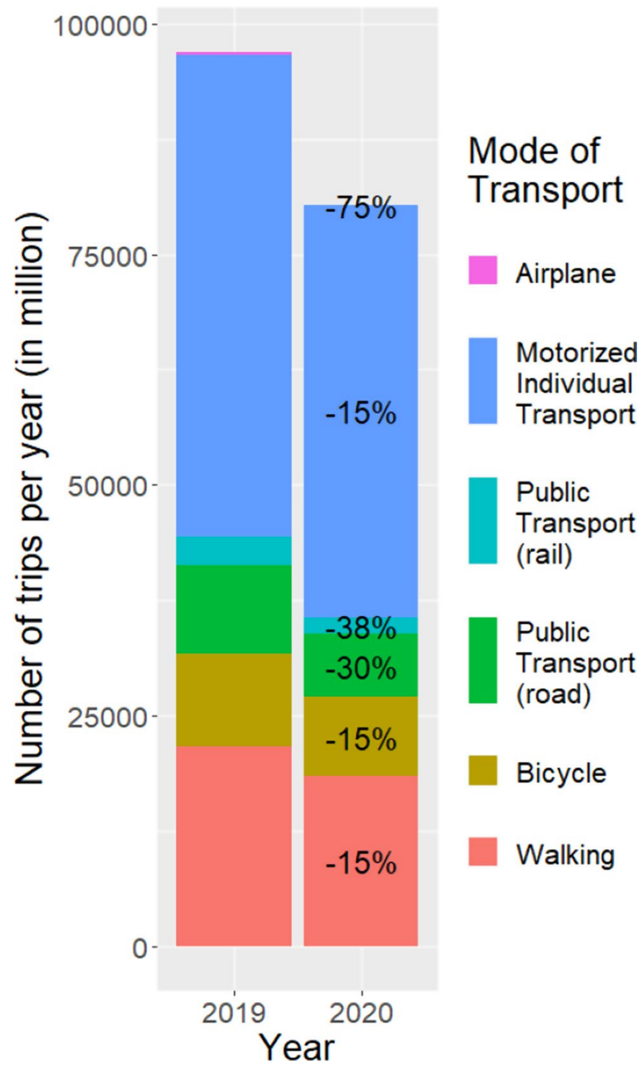

Fig. 10 Absolute number of trips per mode of transport in 2019 and 2020

0.3% respectively, while the share public transport (road) decreases by 0.8%.

These changes in the Modal Split are in part mirrored in Fig. 10 that displays the absolute number of trips per mode of transportation per year from 2019 to 2020. It can be seen that the total number of trips decreases considerably from 2019 to 2020. In fact, for all modes of transportation the number of trips is considerably lower in 2020 in comparison to the preceding five years.

In addition, Fig. 11 illustrates that the changes in the absolute number of kilometers travelled vary considerably among the different modes of transportation. While the decreases in the absolute number of kilometers travelled on walking and cycling trips from 2019 to 2020 are rather marginal, the kilometers travelled by airplane, public transport (rail) and public transport (road) decrease by 74%, 42%, and 42%. The decrease of 12% in the kilometers travelled by motorized individual transport from 2019 to 2020 is much smaller.

These decreases in the overall number of trips conducted and the kilometers travelled rely on less trips conducted across all different trip purposes as Fig. 12 illustrates.

In particular, the number of holiday trips and business trips shrinks in 2020 to around half the level of 2019. In contrast, the decline in the number of work, education, shopping, leisure and escort trips from 2019 to 2020 lies in the range of 4–30%. These different results for holiday trips and business trips on the one side and all other trips purposes on the other side can also be observed in Fig. 13 which outlines the absolute kilometers travelled per trip purpose in 2019 and 2020.

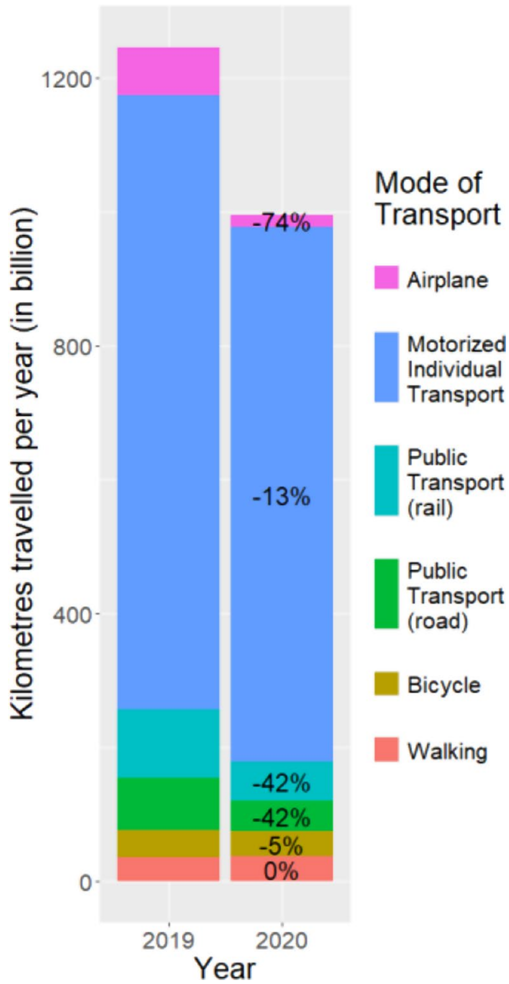

Fig. 11 Absolute number of kilometers travelled per mode of transport in 2019 and 2020

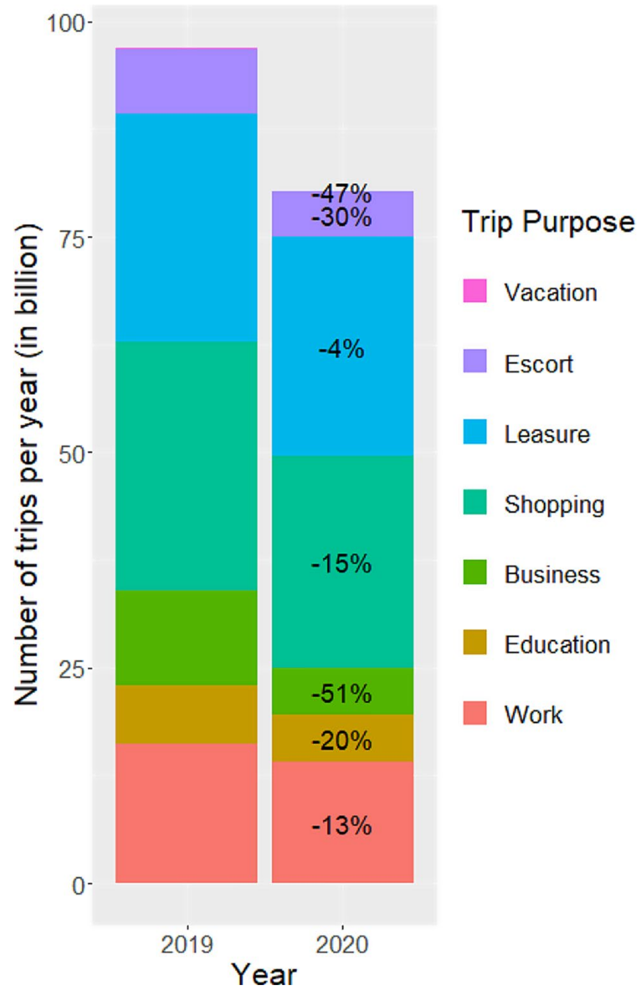

Fig. 12 Absolute number of trips per trip purpose in 2019 and 2020

3.3 Validation of the results on the basis of other sources of data

In order to check the validity of the results presented above, these were compared to the findings based on other data sources. However, it should be kept in mind that a one-to-one comparison to the results of other studies was not possible due to different measuring scopes, data collected in different periods of time, different methods of data collection and so on. In a nutshell, the main purpose of the comparison is not to search for the exact same numbers produced on the basis of other sources of data but rather to check whether the results of the paper at hand point in the same direction as the findings of other studies and reveal similar trends.

The German Mobility Panel is a longitudinal study of the travel behavior of the population in Germany [40]. For a comparison of the changes detected in daily travel behavior due to the pandemic, the results of the paper at hand for the number of trips conducted per person per day were contrasted with those of the German Mobility Panel where possible in terms of comparable modes of transportation and periods in time (Fig. 14):

The development of the overall number of trips per person per day as well the development of the number of trips conducted by bicycle, car or public transport per person per day follows very similar patterns in the study at hand and the German Mobility Panel in the different periods of time before and during the pandemic. Also, the number of trips conducted on foot per person per day decreases both in the paper at hand and in the German Mobility Panel in the stage of normalization in comparison to pre-pandemic times. However, while in the paper at hand the number of trips conducted on foot per person per day is lower in the second lockdown than in the pre-pandemic stage, in the German Mobility Panel the number of trips conducted on foot per person per day is higher in the second lockdown than in the pre-pandemic stage. Yet, in spite of this minor difference, the overall results of this study and the German Mobility Panel on the changes in travel behavior during the pandemic fit quite well to each other.

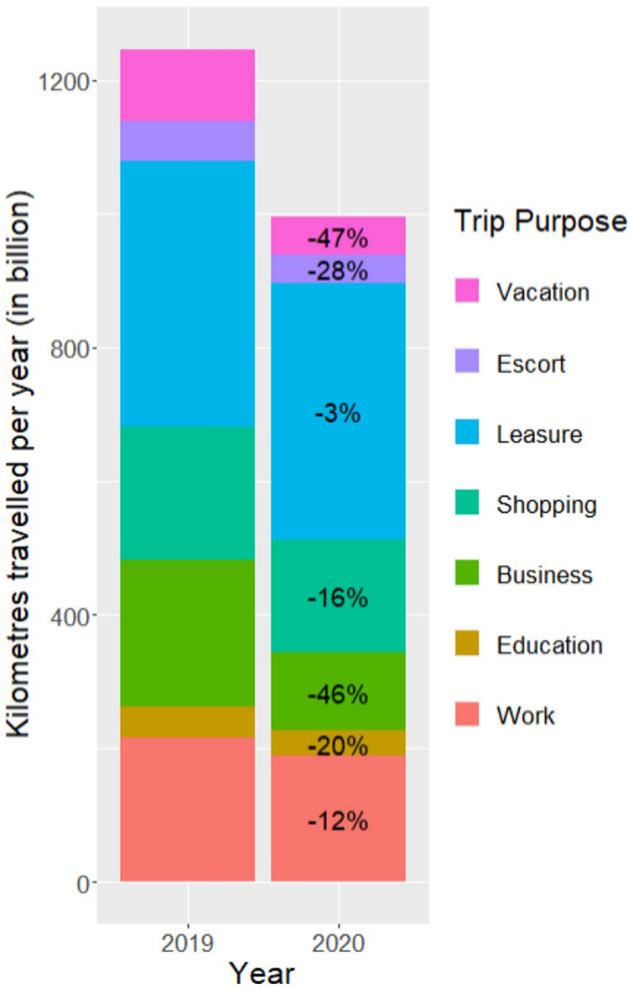

Fig. 13 Absolute kilometers travelled per trip purpose in 2019 and 2020

To check the validity of the specific results for bicycle traffic of this study, a comparison to data from automated bicycle count stations was carried out. Figure 15 illustrates the average number of bicycles detected per hour of the week at all available count stations in Germany in the month of April, July, and November in 2020 compared to the three-year-mean of 2017–2019 for the same months:

Noticeable differences in the comparison of the three-year-mean of 2017–2019 with 2020 are the higher morning peaks from Monday to Friday (hour 0-120) in April and the lower afternoon peaks from Monday to Friday in November. Most striking, however, is the considerably increased number of detected bicycles on weekends (hour 120–168) in all three months in 2020 in comparison to the three-year-mean of 2017–2019. This indicates an increased usage of bicycles for leisure trips. Therefore, Fig. 16 shows the daily kilometers travelled on trips conducted by bicycle per trip purpose for the different stages of the year 2020 as produced by the study at hand:

A large increase in leisure trips conducted by bicycle can be seen as well as a smaller decrease in bicycle trips in all three stages of the pandemic in comparison to pre-pandemic times. Furthermore, as the three months analyzed on the basis of the bicycle count data correspond to the three stages of the pandemic defined in this study, it can be seen that both the results of the study at hand and the bicycle count data show the largest increases in leisure trips conducted by bicycle in the first and the second lockdown in comparison to pre-pandemic times, with a much smaller increase during the stage of normalisation.

4 Discussion

In order to provide valid annual statistics for key indicators of mobility in Germany, the year 2020 was split up into four different stages. These stages were defined on the basis of the policy measure to contain the further spread of COVID-19 that prevailed at the time in question as well as the overall travel behavior at that time. The objective was to derive stages where people's travel behavior is as homogenous as possible within each stage, while it differs significantly between the stages.

However, it has to be acknowledged that this constitutes a pragmatic approach that considerably simplifies the actual reality and thus has its limitations. First, policy measures and travel behavior sometimes changed dramatically from one day to the other in the year 2020 in Germany. Second, policy measures and travel behavior differed considerably not just between the different Federal States of the country but at times even between different municipalities and counties. Yet, adjusting people's travel behavior separately for each day in each county is impossible due to missing data; moreover, it would increase model complexity unduly. Consequently, the division of the year 2020 into the four different stages can be seen as a pragmatic approach, which partly also relied on the available survey data and the periods of time that it covered.

That being said, the survey sizes of the three panel design surveys in 2020 (see Fig. 1) made further simplifications in certain analyses necessary. For instances, ideally changes in travel behavior would have been determined for different people based on various sociodemographic characteristics, e.g., sex, age, occupation, car ownership, travel behavior before the outbreak of the pandemic and trip characteristics, e.g., trip purpose, trip length, etc. as all of these issues could lead to different changes in travel behavior during the pandemic for different groups of people. Yet, splitting the sample up into too many subcategories resulted in very low absolute case numbers. Therefore, changes in travel behavior could not always be derived in the desirable granularity.

In spite of these limitations, however, our approach succeeds in reproducing.

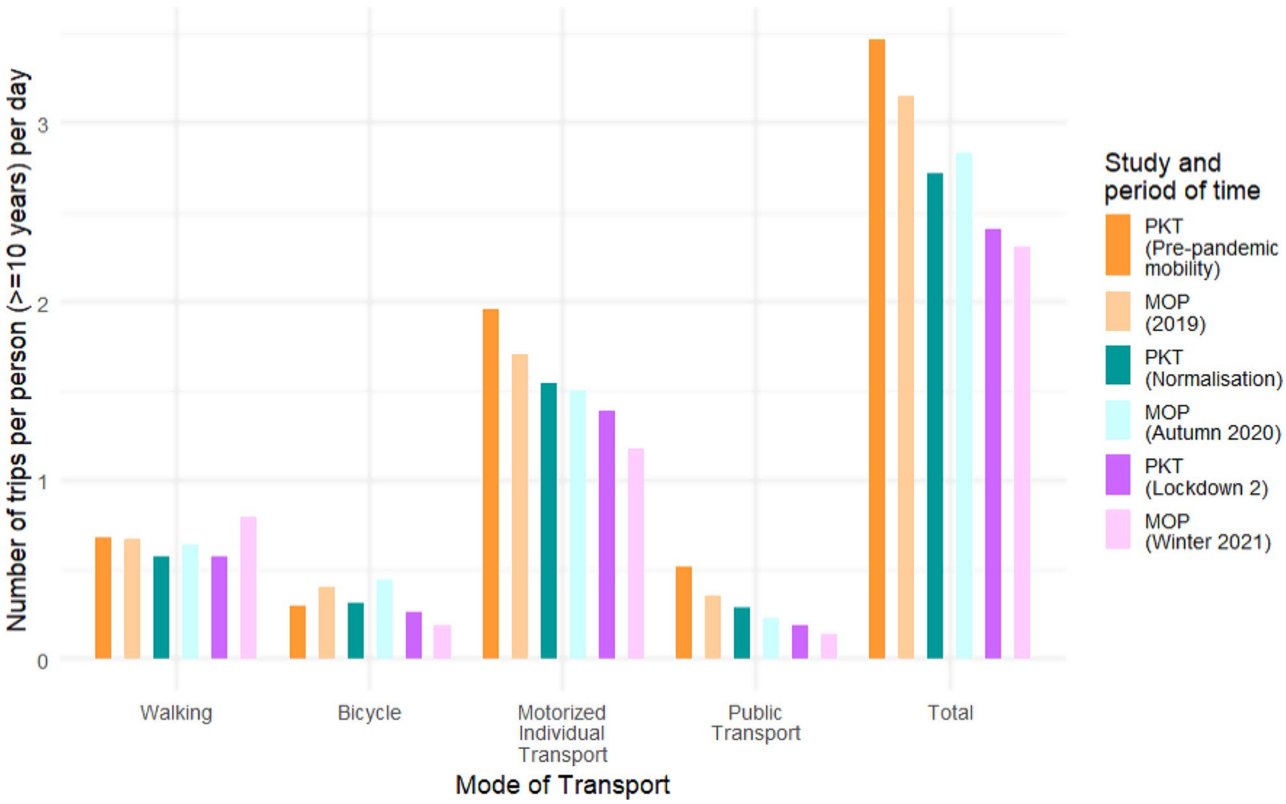

Fig. 14 Comparison of the PKT model results with the Germany Mobility Panel. PKT stands for Passenger Kilometers Travelled, while MOP stands for Mobility Panel. Autumn 2020 refers to September and October 2020, while Winter 2021 refers to January and February 2021

1) an altered travel behavior in terms of trip purposes-and choice of transport modes in the four stages of the year 2020;
2) key annual transportation indicators that are in line with official public transport passenger count statistics of the Federal Statistical Office of Germany, ensured by a comprehensive data weighting process;
3) travel demand data of the entire population living in Germany, ensured by a comprehensive data weighting process.

Furthermore, the approach illustrated provides results similar to those of other studies and data sources used for investigating the impact of the pandemic on travel behavior in Germany [7, 15, 41]. Although the results of the different studies are not directly comparable to our model results due to different periods of data collection, different methods of data collection, different samples of the overall population and many other issues, the general trends that they identify in the impact of the pandemic on travel behavior point in a similar direction. This speaks for the validity of our approach for data fusion and the results produced by it.

A comparison with the results of studies from other countries is even more difficult as not only differences in methods, samples, and pre-pandemic travel behavior have to be considered but also different political measures for containing the further spread of COVID-19. From a merely methodological point of view, for instances, the most comparable approach to the data fusion of this study has been developed by the Office of Transportation Statistics of Sweden [13]. However, in contrast to the radical lockdowns introduced in Germany, the political measures to contain the pandemic in Sweden were rather based on government recommendations and their citizens own responsibility; strict measures such as enforced shutdowns of retail shops or restaurants were not applied. This could partly explain why the Office of Transportation Statistics of Sweden calculated a decline of the overall trips of 22% from 2019 to 2020 for the months of March and April and of 12% for the months of July and August [13], while the results of the study at hand show a decline of 41% in the overall number of trips during the first lockdown in spring 2020 in Germany and a decline of 21% in the summer months in comparison to pre-pandemic mobility. Hence the decline in the overall number of trips is around twice as big in Germany as in Sweden. At first glance, these differences seem reasonable with regard to stricter political measures to contain the pandemic in Germany. However, due to the reasons explained above, the comparison of

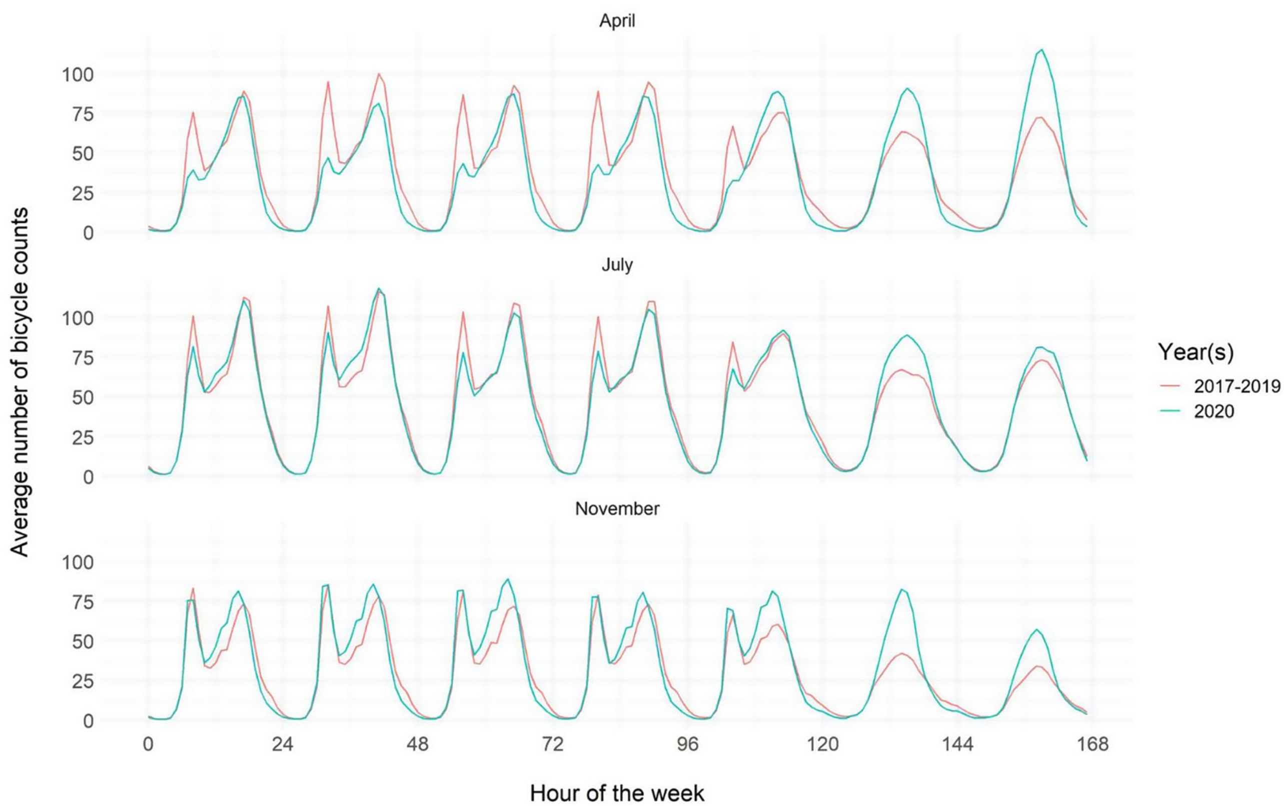

Fig. 15 Average number of detected bicycles at automated count stations per hour of the week (starting at 12AM on a Monday) in Germany

the PKT model results with other studies in Germany and abroad should be treated with care.

[32] used a multiwave survey to compare travel behavior during the first year of the pandemic in Canada with pre-pandemic times, while [24] conducted a survey in the UK to capture changes in mobility during the first lockdown. Both studies focused on changes in the modal split on commuting trips to work (and to school in the case of Canada) and also included that the trip was not conduced due to working from home or not working. The biggest changes in Canada were that 20% did not go to work or attend school during the pandemic, that working from home increased from 3% in pre-pandemic times to 16%, and that commuting by car shrank from 68 to 52% and commuting by public transport decreased from 16 to 4% [32]. In the UK 89% of the people who before the pandemic commuted to work by car continued to do so during the restrictions, while 10% started to work from home [24]. In contrast, only 72% of the people in the UK who before the pandemic commuted to work by public transport continued to do so during the restrictions, while 16% started to work from home and 12% chose other means which in most cases was the car [24].

It is not possible to directly compare the results of [32] and [24] with the findings of our study due to very different methodologies. However, it can be said that also our study detected a decrease in the overall number of trips to work conducted to an increased share of people working from home during all stages of the pandemic in 2020 in Germany. In addition, the share of public transport in the modal split over all trips decreased in Germany, too. However, our study distinguished changes in the modal split in different stages of the pandemic and also provides a more nuanced picture. While, for instance, the share of motorized individual transport in the modal split of all trips in Germany fell from 56% in pre-pandemic times to 53% in the first lockdown, which seems to confirms the findings of [32] and [24], the share of motorized individual transport increased again to 56% when restrictions were lifted and increased further to 57% during the second lockdown in Germany.

[30] analyzed changes in mobility induced by the pandemic throughout the year 2020 in Switzerland on the basis of GPS-based tracking data. While their sample of people who used the smartphone tracking app is not representative of the population of Switzerland in terms of level of education, age, car access, and some other sociodemographic features, it provides accurate tracking data for almost every day of 2020 [30]. Consequently [30], could conduct their analyses on much more fine-grained data than our study and did not need to split the year 2020 into different stages of the pandemic and to conduct

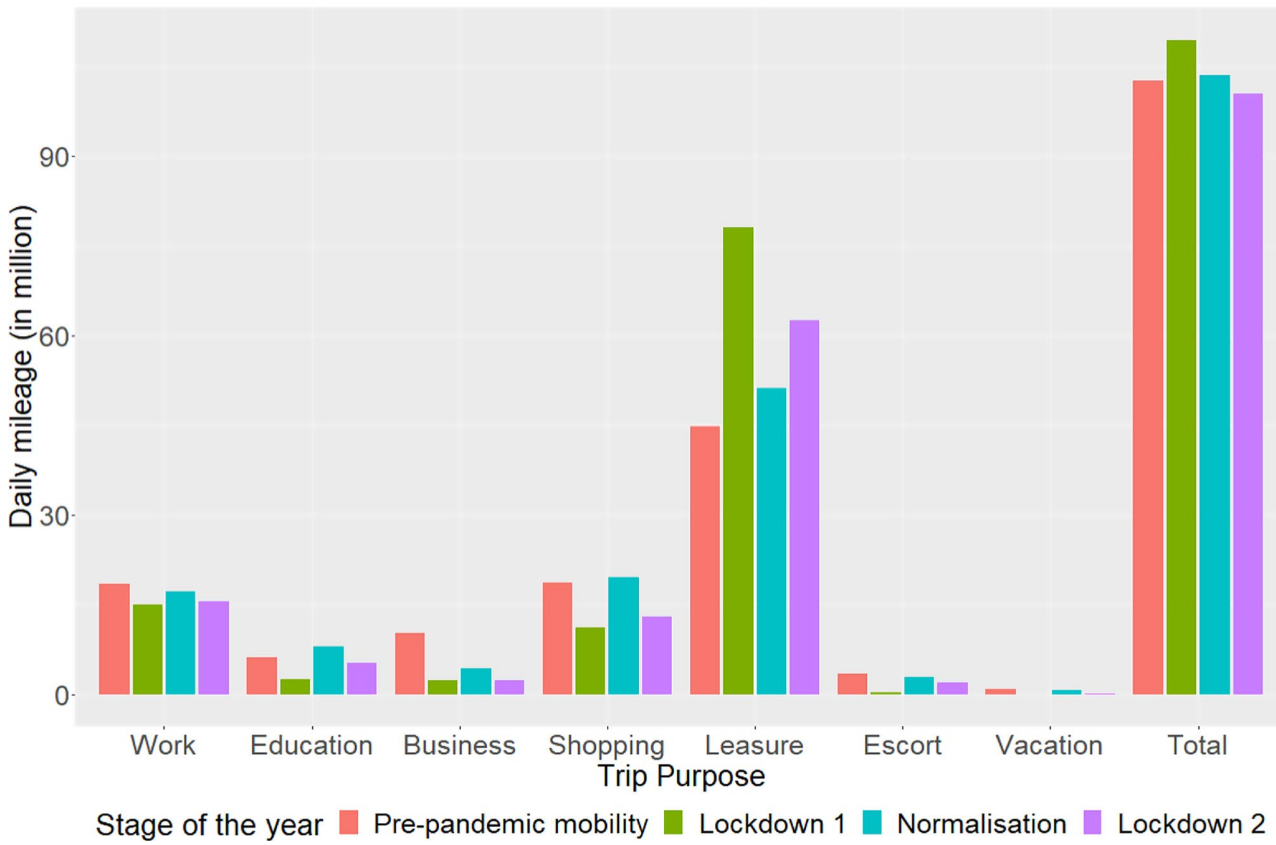

Fig. 16 Daily kilometers travelled on bicycle trips per trip purpose

a survey in each stage. Furthermore, it has to be kept in mind that there were considerably fewer restrictions in Switzerland during the pandemic than in Germany.

While [30] found an increase in the distances travelled by bicycle from mid-March to mid-October 2020 of up to 100% in comparison to pre-pandemic times and then a drop in the distances travelled by bicycle in the last weeks of 2020 to around 90% of pre-pandemic times, our study outlined an increase in the distances travelled by bicycle between 1 and 7% throughout all stages of the pandemic. Another difference is that [30] found decreases in the distances travelled by walking almost throughout the pandemic in comparison to pre-pandemic times except of a few days in July 2020, while our study illustrated increases in the distances travelled by walking of 39% in the first and of 10% in the second lockdown in Germany. In addition, in contract to [30], our study found a decrease of 13% in the distances travelled by walking in the summer of 2020 in Germany when many restrictions were lifted. The two studies also provide a different picture of the changes in the distances travelled by car. While [30] show a decrease in the distances travelled by car in spring and winter 2020 in comparison to pre-pandemic times and an increase in the distances travelled by car in the summer months of 2020 in Switzerland, our study outlines decreases in the distances travelled by motorized individual transport in Germany throughout the pandemic. Only in the case of public transport both studies provide similar findings and outline decreases in the distances travelled throughout the pandemic in comparison to pre-pandemic times.

[17] use congestion index and subway ridership data of eight Chinese cities to analyze changes during the lockdown in January and February and the subsequent lifting of restrictions from the end of February to the end of April in 2020. Their results show that the travel time on peak hours on workdays in the road network decreased to 54–79% and that the subway ridership sunk to 12% or less of the pre-pandemic level during the lockdown period [17]. In the reopening phase, the travel time on peak hours on workdays in the road network increased to 86–98% and the subway ridership increased to 30–51% of the pre-pandemic level.

A comparison of these results to the findings of our study are difficult due to different sources of data, different political measures used to contain the pandemic in China and in Germany, and different periods in time during which the lockdowns were imposed in the two countries. During the time of the first lockdown in China, no restrictions were in place in Germany, and when restrictions were being lifted again in China, the first lockdown was imposed in Germany. In spite of all these differences, the results of [17] and our study point in the same direction. Our study outlines a decrease of public transport (rail) to 21% and a decrease of motorized individual transport to 58% in the kilometers travelled during the first lockdown in Germany compared to the pre-pandemic level. When restrictions were lifted again in Germany the kilometers travelled increased to 44% for public transport (road) and to 74% for motorized individual transport of the pre-pandemic level.

[14] analyzed changes in travel beaviour during the first lockdown in the city of Thessaloniki in Greece on the basis of survey data. Their results show that the modal split changed considerably. While the modal share of the car shrank from 38% at pre-pandemic times to 30% in the lockdown and the modal share of public transport decreased from 22 to 0%, the share of the bicycle increased from 1 to 2% and the share of walking more than doubled from 30 to 65% [14]. A comparison of the findings of [14] to the results of our study is difficult as the modal split of a Greek city differed from the one of the country of Germany already before the pandemic and as the political measures taken to contain the pandemic were much stricter in Greece than in Germany in the first lockdown. Nonetheless, also our studys detected an increase in the modal share of walking from 20% in pre-pandemic times to 29% in the first lockdown and an increase in the modal share of cycling from 9 to 11%. In contrast, the modal shares of motorized individual transport and public transport (road) and public transport (rail) decreased from 56 to 53%, from 11 to 5%, and from 4 to 1%. Thus, the changes in the modal share of the different means of transport went in the same direction in Germany and in Thessaloniki with the difference that the changes in Thessaloniki were more profound for most modes of transport.

5 Conclusions

This study presented a data fusion approach to provide valid annual transportation statistics for Germany during the COVID-19 pandemic in 2020. Therefore, we adapted our existing model approach at generating annual figures on passenger kilometers travelled (PKT). Unlike in the existing model, we did not model the whole year as one, but we divided the year into four pandemic stages in order to model passenger transport demand as adequately as possible within each stage. The four stages are: a pre-pandemic stage in the first 2 ½ months of 2020 and three separate stages for the first lockdown in spring, the relaxation of measures in summer, and the second lockdown in winter. In each of the three stages after the outbreak of the pandemic online surveys were carried out to capture changes in travel behavior in Germany. Based on the survey results and further data sources, the large NHTS, used as main data source for the PKT model, was adjusted to reflect the changed travel behavior of the population in Germany in the different stages of the pandemic.

The results of the adapted PKT model for 2020 show a decline in the overall number of trips in 2020 in Germany of 17% in comparison to 2019 and decrease of 20% in the kilometers travelled. The two lockdowns (not surprisingly) brought about the largest declines in the number of trips and the kilometers travelled in 2020. These declines in travel demand were particularly large for trips conducted by public transport including road, rail, and air traffic. In contrast, the number trips and the kilometers travelled by motorized individual transport, bicycle, or foot decreased to a much lesser extent. In fact, the active modes of walking and cycling have even somewhat benefitted from the lockdowns due to a tremendous increase in recreational trips which at times constituted the only trip purpose allowed by law.

Our methodology represents a fundamental extension of the PKT model that is used for the development of annual transportation statistics in Germany. This extension was necessary in order to deal with the different impacts of the COVID-19 pandemic on travel behavior in 2020. However, also 2021 was characterized by the COVID-19 pandemic. The approach described here was also applied for the year 2021. Hence, we were able to ensure the availability of valid national statistics on passenger transport for Germany in the two pandemic years 2020 and 2021.

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Authors contributions
The authors confirm contribution to the paper as follows: study conception and design: A. Galich, C. Eisenmann; data collection: C. Eisenmann; analysis and interpretation of results: A. Galich, C. Eisenmann, K. Köhler; draft manuscript preparation: A. Galich, C. Eisenmann. All authors reviewed the results and approved the final version of the manuscript.

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Data availability
The data used in this article cannot be made public because the article mainly relies on survey data which is confidential in order to protect the privacy rights of the participants.

Declarations

Competing interests
The authors declare that they have no competing interests.

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