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Case Study

Mid-to-post-pandemic Mobility Patterns: A Case Study of Malaysia Highlighting Differential Trends in Work and Non-Work Trips

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic has had a significant impact on people's mobility patterns worldwide, with some effects still prevalent. This study examines mobility trends in Malaysia before, during, and after the COVID-19 pandemic period. Using trip information from community mobility reports, along with data on the number of COVID-19 cases and vaccination rates, this study investigates how work and non-work trips changed during 2020-2022 while also controlling for several socio-demographic factors. The results showed a strong correlation between mobility and the severity of lockdown, with a significant decline in all trip types during lockdowns. The number of new COVID-19 cases and deaths was also found to impact people's mobility. When controlled for other factors, vaccination rates, however, did not seem to affect trip patterns. The results also showed a rebound in all trip types during the post-pandemic period (April 2022 to October 2022); however, the recovery rates differed, with non-work trips recovering more rapidly than work trips. The study highlights the immediate impact of the post-pandemic on work habits and public behaviour and discusses implications for policymakers in general.

Keywords: COVID-19, mobility, non-work trips, post-pandemic, stay-at-home order, transit trips, work from home, work trips

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BACKGROUND

The COVID-19 pandemic brought a myriad of challenges to societies worldwide. One of the fundamental aspects profoundly affected was the mobility of individuals, as lockdowns and restrictions swept across the globe. It is estimated that over a third of the global population has faced significant mobility restrictions since the beginning of the COVID-19 pandemic (International Organization of Migration [IOM], n.d.). Limiting population movement stands out as a key strategy employed by various countries, including Malaysia (Dias et al., 2021; Shibayama et al., 2021). During these lockdowns, the public was urged to travel only for essential activities as an effective measure for disease control (Badr et al., 2020; Bergman & Fishman, 2023). A systematic review of more than 40 studies reporting on COVID-19 within the first half of 2020, investigating the correlation between human mobility and the transmission of COVID-19, revealed that while limiting human mobility decreased the spread of the virus, the efficacy and strictness of policy enforcement exhibited temporal and spatial variations during different phases of the pandemic (Zhang et al., 2022). Mobility patterns were significantly affected during the pandemic compared to pre-pandemic times due to COVID-19 and related sanitary concerns about overcrowding on certain modes of transportation. Planned transportation post-COVID indicated that challenges may persist for buying into public transport use compared to pre-COVID (Balbontin et al., 2024; Mukhtar et al., 2024).

Studies have been conducted on the effect of COVID-19 on mobility, as shifts in work-related commuting were observed, and working from home was provided as an alternative to commuting. A survey in Australia looked at the effect of the pandemic on respondents' travel behaviour by employment status, area of residence, and work-from-home (WFH) factor. The number of commuting and work-related trips reduced in metropolitan and regional areas, while non-work-related trips increased (Beck & Hensher, 2020a). In another study, post-pandemic work schedules of tech companies in the San Francisco Bay Area indicated a 180-degree shift to pre-pandemic behaviour. The post-pandemic period saw more than 95% of workers working either remotely or via a hybrid format, while almost three-quarters of the workers commuted to the office daily, pre-pandemic (Tan et al., 2023).

Public transport ridership was reported to be significantly reduced in many countries, between 50 to 80% during the early stages of the pandemic (Gramsch et al., 2022; Haseeb & Mitra, 2024; Kar et al., 2022). Changes in mobility behaviour during the pandemic, as well as in its aftermath, have also been attributed to the perception of users. A study conducted in Poland focused on public transport users found that the future of public transport in urban areas, as well as passengers' willingness to utilize it post-epidemic, hinges on the perceived comfort and safety experienced during the epidemic (Przybylowski et al., 2021). Initial predictions had indicated that public transport use would drop sharply during the pandemic, but was expected to recover post-pandemic, though not fully, remaining

below the pre-pandemic level (Currie et al., 2021). A study in Spain indicated that with necessary countermeasures in place, respondents were willing to keep using public transport post-pandemic (Awad-Núñez et al., 2021). While a study on three phases: pre-pandemic, during pandemic, and post-pandemic, found that modality profiles significantly changed during the pandemic but are expected to return to the pre-pandemic condition with time, especially private vehicle use and active mobility (Lodi et al., 2024; Ong et al., 2024). The improvement in public transport usage post-pandemic was reported in various countries, where transit use rebounded as restrictions were progressively eased (Bonera & Martinelli, 2023). However, in some areas, the shift from public transport to private vehicles observed during the pandemic's restrictive periods has persisted (Department for Transport [DfT], 2023; Iglesias & Raveau, 2024).

During the pandemic, travel related to non-essential services was reduced, and remote working was expected. Thus, work-related travel during the pandemic, especially during lockdowns, saw drastic reductions. The effect on work-travel, however, has been shown to differ between different socioeconomic statuses (SES) (Chang et al., 2021; Matson et al., 2021). High SES was found to be associated with a significant reduction in work travel and participation in recreational travel, while the medium and low SES groups travelled more for work, indicative of fewer opportunities to work from home as compared to the high SES group (Politis et al., 2021; Xi et al., 2023).

Similar to work-related trips, studies indicated that income was identified as a significant factor influencing the frequency of essential non-work-related trips as well (Beck & Hensher, 2020b; Sharma et al., 2020). High-income individuals were found to be less prone to completely avoiding travel during the transition to the lockdown period compared to those in the low-income group (Pawar et al., 2021). The frequency of travel for essential trips was notably higher than for non-essential ones. This suggests that people prioritized essential activities like grocery shopping during the transition to the lockdown period while minimizing recreational trips (Pawar et al., 2021). However, respondents in low-income families with children reported that the frequency of grocery shopping decreased during the pandemic (Sharma et al., 2020).

Although an extensive number of studies have evaluated the impact of the COVID-19 pandemic on people's movements, the effects during the post-pandemic period remain somewhat understudied, particularly in Malaysia, where empirical evaluations are still limited. Even though the lockdowns have been lifted throughout the country, their effects on mobility persist. The pandemic prompted significant shifts in work habits, transportation choices, and public activity patterns, some of which may have long-term implications. Understanding these changes is crucial for transportation planning, public transit management, and policymaking, particularly in preparing for future disruptions. The primary objective of this research is to investigate changes in mobility patterns during

and post-pandemic, exploring the impact of the restrictions imposed on various aspects of social and economic structure. To that end, mixed-effects linear regression models are estimated to discern the impacts of various lockdown policies and other important socio-economic and COVID-19-related information on various types of trips, including work trips, trips to transit stations, retail and recreational trips, and trips to grocery stores and pharmacies. Furthermore, as Malaysia declared COVID-19 an endemic issue in April 2022, signifying a transformative juncture in the country's approach, this study also investigates the subsequent recovery of mobility patterns. Beyond merely quantifying movements, this research seeks to unravel the socio-economic factors underlying these shifts, providing a comprehensive understanding of how a nation adapts and rebounds in the aftermath of a global health crisis.

DATA DESCRIPTION

This study gathered various data from different sources to understand how mobility changed during the pandemic and how it progressed after Malaysia declared COVID-19 an endemic issue in 2022. The following subsections briefly describe each data source utilized in this study.

COVID-19 Google Mobility Reports

The study leveraged open-access data from Google on mobility reports in Malaysia corresponding to the COVID-19 pandemic (Google, 2022). The data provides information on how movement trends to different places changed in each geographic region. It shows how visits and time spent at different locations changed with respect to a baseline value. The daily changes in movement are compared to a baseline value for the same day of the week (Equation 1), which, in this case, was the median value of five weeks from January 3 to February 6, 2020 (i.e., the pre-pandemic period). The dataset provided six different categories of places that are important to social distancing efforts, in addition to access to essential services. These categories included workplace, residential area, retail and recreation (e.g., restaurants and shopping centres), transit stations, grocery and pharmacy (i.e., these are combined as they can be considered as essential trips), and parks. For the purposes of this study, four categories were assessed: workplace transit station, retail and recreation, and grocery and pharmacy.

$$\%\ change\ in\ movement = \frac{Daily\ mobility\ - Median\ value\ of\ mobility\ of\ the\ same\ day\ from\ Jan\ 3\ to\ Feb\ 6,2020}{Median\ value\ of\ mobility\ of\ the\ same\ day\ from\ Jan\ 3\ to\ Feb\ 6,2020} \times 100\% \quad [1]$$

In this study, a three-year period of data, dating back from February 2020 to October 2022, was utilized. The end period was selected because it was the last month for which the data was updated. The data was arranged at the state-day level, with each observation (or row) representing the percentage change in movement for the state on a particular day. In the preliminary analysis, a total of 15,579 state-day observations were considered.

COVID-19 Data

The Ministry of Health provides an open-access database for COVID-19 information for each state and federal territory in Malaysia (Ministry of Health Malaysia [MOH], n.d.). This weekly updated data consists of information on the number of daily COVID-19 cases, COVID-19 deaths, and vaccination rates. These data were obtained for the time period that coincides with the COVID-19 community mobility reports.

Demographic Background

Data on demographic background and socioeconomic status were obtained from the official website of the Department of Statistics Malaysia (DOSM). These data consist of information on population demographics (by age, sex, development area, and race), income, and poverty rate (i.e., percentage of population living under the national poverty line income, US$471), among others. It should be noted that some of this information (e.g., poverty and unemployment rate) is at the state-month level, whereas other data, such as population and median income, are at the state-year level.

COVID-19 Timeline Data

The Malaysian National Security Council (NSC) provided information to the country on the standard operating procedure (SOP) with the help of other government sectors on managing the COVID-19 pandemic. One of the crucial pieces of information that the agency distributed to the public during the pandemic period was the lockdown information. In Malaysia, the lockdown due to COVID-19 can be divided into three different categories: Movement Control Order (MCO), Conditional MCO (CMCO), and Recovery MCO (RMCO). The main difference between these three categories is the level of restriction imposed on the public within their geographical region, where MCO had the strictest lockdown, and RMCO had the least restriction on people's movements.

Figure 1 shows the COVID-19 timeline in Malaysia. After the World Health Organization (WHO) declared the COVID-19 outbreak a global pandemic on March 11, 2020, the Malaysian government announced its first MCO on March 18, 2020 (Tang, 2020), which lasted until May 3, 2020. During this period, many restrictions were imposed, which included an interstate and inter-district travel ban, closure of all houses of worship

and most business premises, a maximum of 10 km travel radius, closure of all educational institutions, shutting down of all government and private sectors except those involved with daily essential services, border closure, and gathering bans, among others. To ensure compliance from the public with these restrictions, road closures were introduced by law enforcement throughout the country.

Beginning May 4, 2020, Malaysia transitioned into CMCO. Most economic sectors could operate by following the strict SOP introduced by the NSC. Houses of worship and some business premises were allowed to operate at limited capacity. However, educational institutions remain closed, and interstate travel is still banned. As COVID-19 cases continued to drop, the government started to further loosen the restrictions by introducing RMCO throughout the country starting June 10, 2020. During this period, interstate travel was allowed, tourism started to open, gathering activities with limited capacity were permitted, and educational institutions started to reopen in stages.

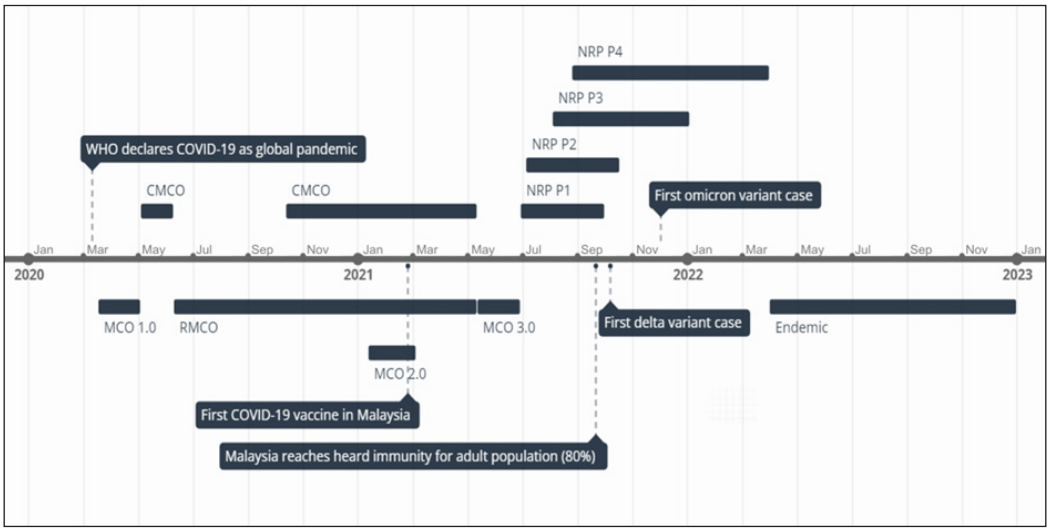

Figure 1. Timeline of lockdown in Malaysia
Note. WHO = World Health Organization; MCO = Movement Control Order; CMCO = Conditional Movement Control Order; RMCO = Recovery Movement Control Order; NRP = National Recovery Plan

As the restrictions continued to loosen up, the number of COVID-19 cases started to increase in several localities, resulting in the reinstatement of CMCO in these areas. As time progressed, more states started to transition back into CMCO, and by December 2020, 12 out of 16 localities were placed under CMCO. As the situation started to worsen, a second MCO was reintroduced between January 13 and March 4, 2021 (some states started early). After March 4, 2021, some states transitioned back to CMCO and some to RMCO, before the third MCO was reinstated for the whole nation on May 12, 2021. The

third MCO lasted until June 28, 2021, before the government introduced a new plan to combat COVID-19 called the National Recovery Plan (NRP).

The NRP consisted of four phases, and the transition between each phase depended on the average daily cases of COVID-19, the capacity of the public health system (i.e., rate of intensive care unit ward occupancy), and the percentage of the population that was fully vaccinated. Note that phase 1 of NRP was similar to the MCO restriction measures. The NRP-1 spanned from June to September 2021. For the NRP-2, it started from early July 2021 until October 2021, with some restrictions lifted for complete vaccination recipients. The NRP-3 period began in August 2021 and ended in January 2022, with inter-district travel allowed regardless of vaccination status. The last phase of NRP started in August 2021, with social activities allowed with limited capacity, and the interstate travel ban was lifted for fully vaccinated individuals. On April 1, 2022, Malaysia transitioned into the endemic phase, where all restrictions that were previously introduced were completely removed.

Data Summary

Table 1 shows the descriptive statistics of key variables of interest in this study. This includes the percentage change in mobility, socioeconomic and demographic factors, the COVID-19 time period, COVID-19 cases, and vaccination status. It should be noted that there are several variables obtained based on state-day level information, such as the percentage change in mobility, new COVID-19 cases and deaths, vaccination, and lockdown status. The remaining variables are based on the state-month level information, e.g., the unemployment rate information varies from state to state but remains the same within each month.

Table 1
Descriptive statistics of variables of interest

Variable	Min.	Max.	Mean	Std. Dev.
Sociodemographic factors				
Median income in RM1,000	3.01	10.23	5.73	2.01
Percentage of population below the national poverty line	0.10	25.30	7.58	6.02
Percentage of unemployment	1.00	8.00	4.04	1.58
Percentage of the Malay population	6.93	95.01	59.52	25.11
Percentage of the Chinese population	0.51	41.28	17.36	12.11
Percentage of the Indian population	0.17	13.49	4.88	4.36
Percentage of the rural population	0.00	55.90	26.04	18.02
Percentage of the female population	46.58	50.92	48.34	1.16
Timeline				

Table 1 *(continue)*

Variable	Min.	Max.	Mean	Std. Dev.
Sociodemographic factors				
Pre-pandemic period (Feb. 15 - Mar. 10, 2020)	0	1	0.03	0.16
No lockdown (Mar. 11 - Mar. 17, 2020)	0	1	0.01	0.08
MCO-1, (Mar. 18 - May 03, 2020)	0	1	0.05	0.21
MCO-2, (Jan. 13 – March 4, 2021)	0	1	0.04	0.19
MCO-3, (May 12 - Jun. 28, 2021)	0	1	0.05	0.22
CMCO	0	1	0.12	0.32
RMCO	0	1	0.23	0.42
NRP-1 (Jun. 29 - Sep. 30, 2021)	0	1	0.04	0.19
NRP-2 (Jul. 05 - Oct. 17, 2021)	0	1	0.05	0.22
NRP-3 (Aug. 04 - Dec. 31, 2021)	0	1	0.04	0.19
NRP-4 (Aug. 26, 2021 - Mar. 31, 2022)	0	1	0.16	0.36
No lockdown (Apr. 1 - Oct. 31, 2022)	0	1	0.20	0.40
COVID-19 cases and vaccination				
New COVID-19 cases per day per 100,000 people (7-day moving average)	**0.00**	**391.57**	**15.40**	**27.64**
New COVID-19 death per day per 100,000 people (7-day moving average)	0.00	4.32	0.10	0.28
Percentage of fully vaccinated people	0.00	159.47	37.63	43.86
Percentage change in mobility				
Workplace	-92	21	-18.24	19.16
Transit station	-100	247	-30.19	35.95
Retail and recreation	-90	165	-19.85	27.14
Grocery and pharmacy	-74	188	7.43	25.32

Note. Min. = Minimum; Max. = Maximum; Std. Dev. = Standard deviation; MCO = Movement Control Order; CMCO = Conditional Movement Control Order; RMCO = Recovery Movement Control Order; NRP = National Recovery Plan

Based on Table 1, the average median household income across states was RM5,730 per month. Figure 2 shows the average median income level (monthly) by state. The state of Kelantan shows the lowest income level when compared to other states. In terms of the poverty rate, the average across the states was 7.6%. The worst rate recorded was during the 2020 pandemic year, when the percentage of the population living under the national poverty line was 25.3% (DOSM, 2021). The unemployment rate ranged from 1 to 8%, with an average of 4%. Similar to the poverty rate, the highest average recorded for the unemployment rate was during the 2020 pandemic year, when Malaysia saw approximately 5.3% unemployment in the month of May (DOSM, 2025). For the population by race, an average of 59.5% of people are Malay. The data also showed that 26% of people resided in rural areas, on average.

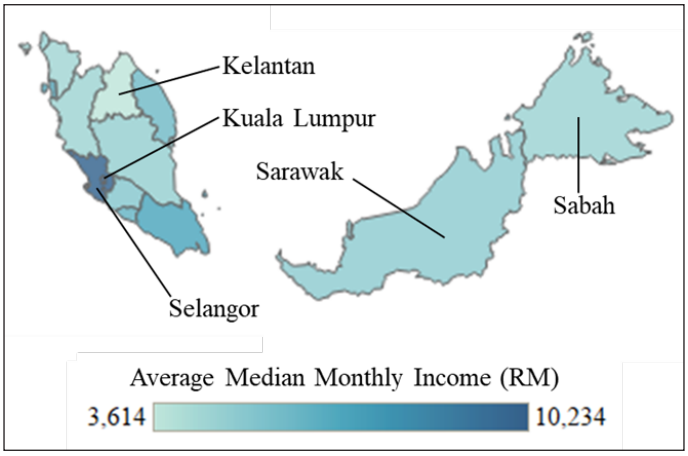

Figure 2. Average median monthly income by state

The timeline was divided into 12 categories based on the lockdowns. Note that the categories during the pandemic period correspond to the level of lockdown, and they reflect the restrictions imposed. Three percent of the data was from the pre-pandemic period; 20% from the post-pandemic period, and the remaining data was from the pandemic period.

The new COVID-19 cases and deaths were reported daily in Malaysia. Within the context of this study, a 7-day running average was calculated to account for any fluctuations in the reported data. Additionally, the data was normalized by the population of the state, resulting in the number of cases and deaths per 100,000 population. On average, new COVID-19 cases and deaths per 100,000 population across all states-days were 15.4 and 0.1, respectively. The vaccination rates represent the percentage of the population receiving at least two doses of the COVID-19 vaccine. On average, 38% of the people were fully vaccinated across states during the study period. Note that the maximum value recorded exceeds 100%. This may be due to some percentage of people receiving the vaccine from other states where they live. Particularly states that border federal territories, or vice versa.

In terms of mobility, trips to the workplace, transit stations, and retail and recreational trips reduced by 18, 30, and 20%, respectively, on average compared to January 2020 data; while grocery and pharmacy trips increased by 7%. Note that the data from Table 1 shows the aggregate information during the entire study period. Figure 3 shows the disaggregated information related to the percentage change in mobility by time and state. The red and blue colours indicate an increase and a decrease in the percentage change in mobility, respectively. The darker the colour, the greater the percentage change.

The pre-lockdown period showed only marginal changes in mobility for all trip types. During the lockdown periods, mobility for all trip types saw the highest reductions across the state due to the strictest lockdown imposed. As the period transitioned to the post-

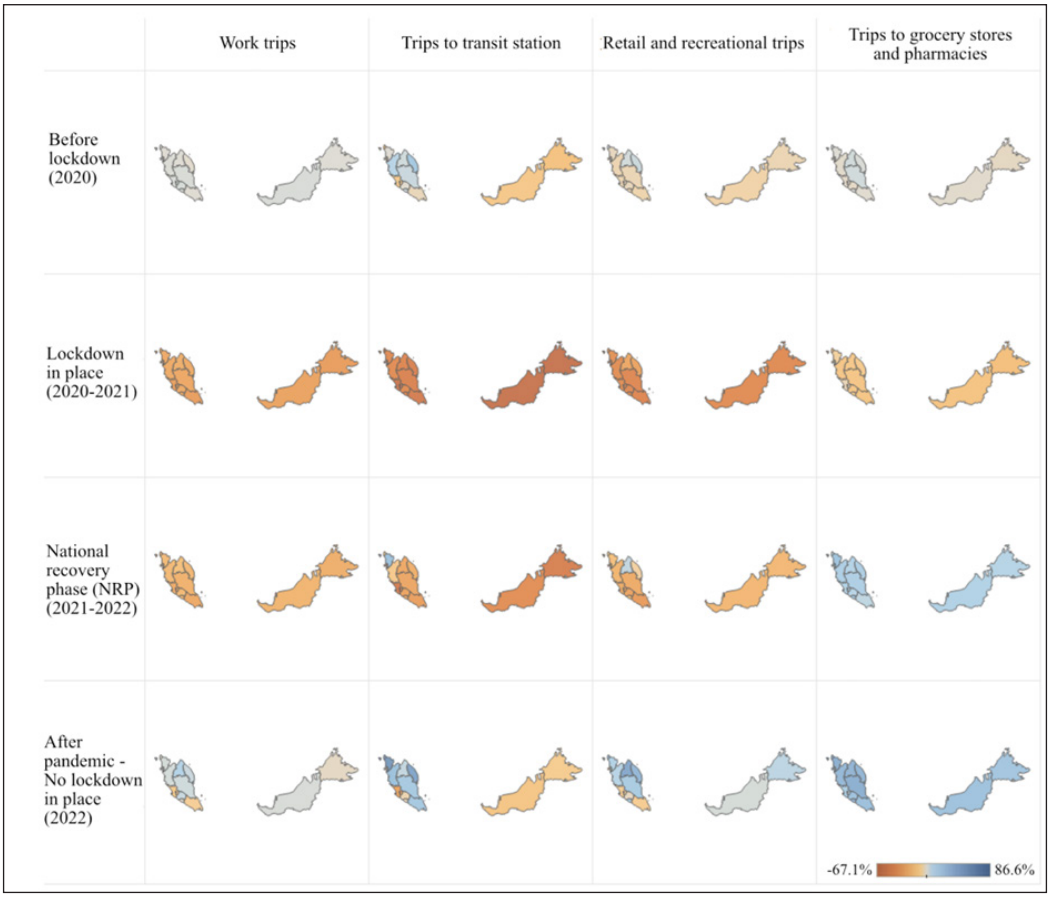

Figure 3. Average percentage change in mobility by time period and state

pandemic phase, all states showed an increase in mobility across all trip types. However, a few states and federal territories still experienced a negative change in mobility, particularly for work-related trips.

As time progressed, the percentage change in mobility started to increase. After the government announced the transition from global pandemic to endemic, all non-work trips saw an increase in mobility when compared to the pre-pandemic period. However, for workplace mobility, the average percentage change in mobility was still negative during the endemic period. Figure 4 shows the further disaggregation of the average daily trends of mobility for all trip types in Malaysia. It should be noted that the periods of holidays and weekends have not been removed from the data. These periods are indicated by sharp reductions in mobility, particularly for workplace trips, even in 2021-2022.

The global efforts to contain the pandemic resulted in the development of a vaccination against the virus. Figure 5 shows the trends in the number of COVID-19 cases and vaccines

administered in the country. It should be noted that even though COVID-19 was declared a pandemic in early March 2020 due to its rapid rise in some countries, such as the United States, the number of COVID cases in Malaysia remained substantially low during early 2020 due to the strict lockdowns in the early stages of the pandemic. As such, the rapid increase in the number of COVID-19 cases only began in October 2020, as seen in the figure. On February 24, 2021, the first COVID-19 vaccine was administered in Malaysia prior to its mass distribution (Anand, 2021). When comparing Figures 4 and 5, it is observed that as the percentage of the population receiving the full dosage increased, the percentage change in mobility also increased. By the end of the study period, more than 80% of Malaysia's population was fully vaccinated.

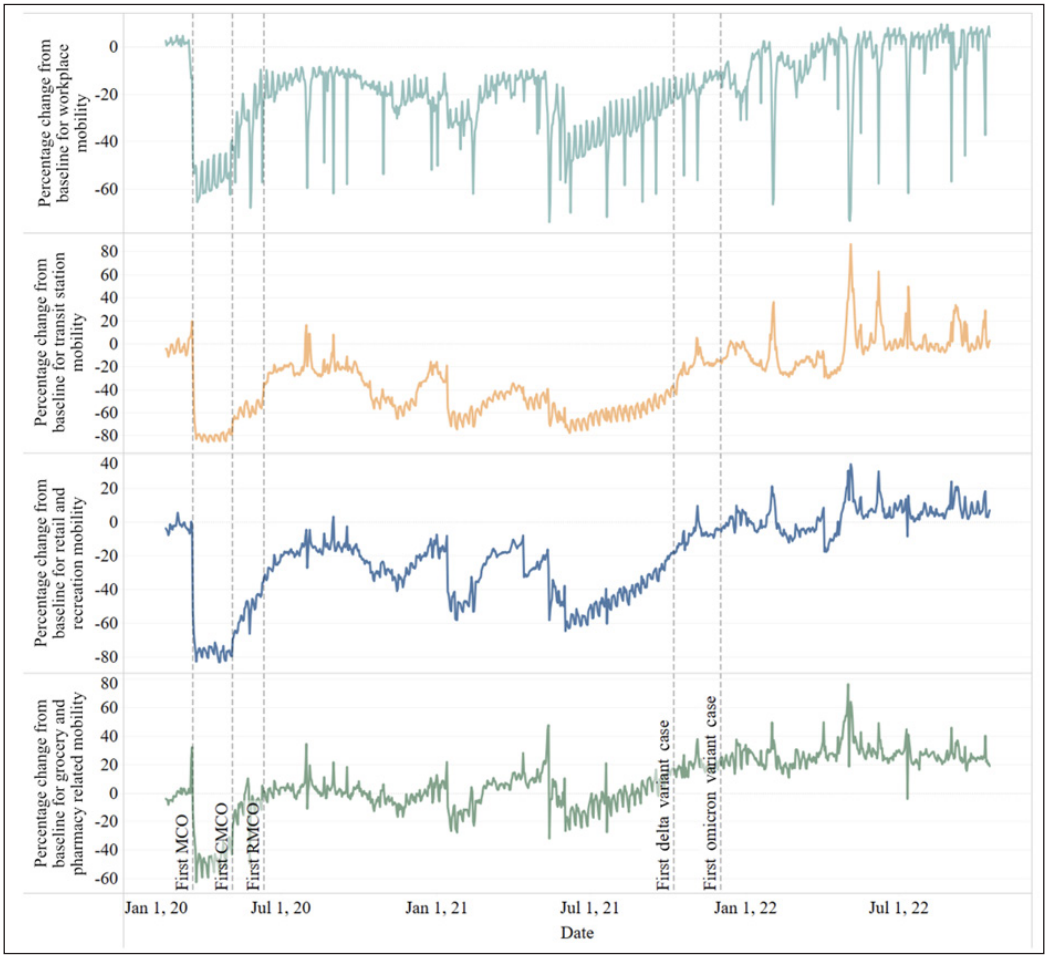

Figure 4. Average daily trends in mobility in Malaysia

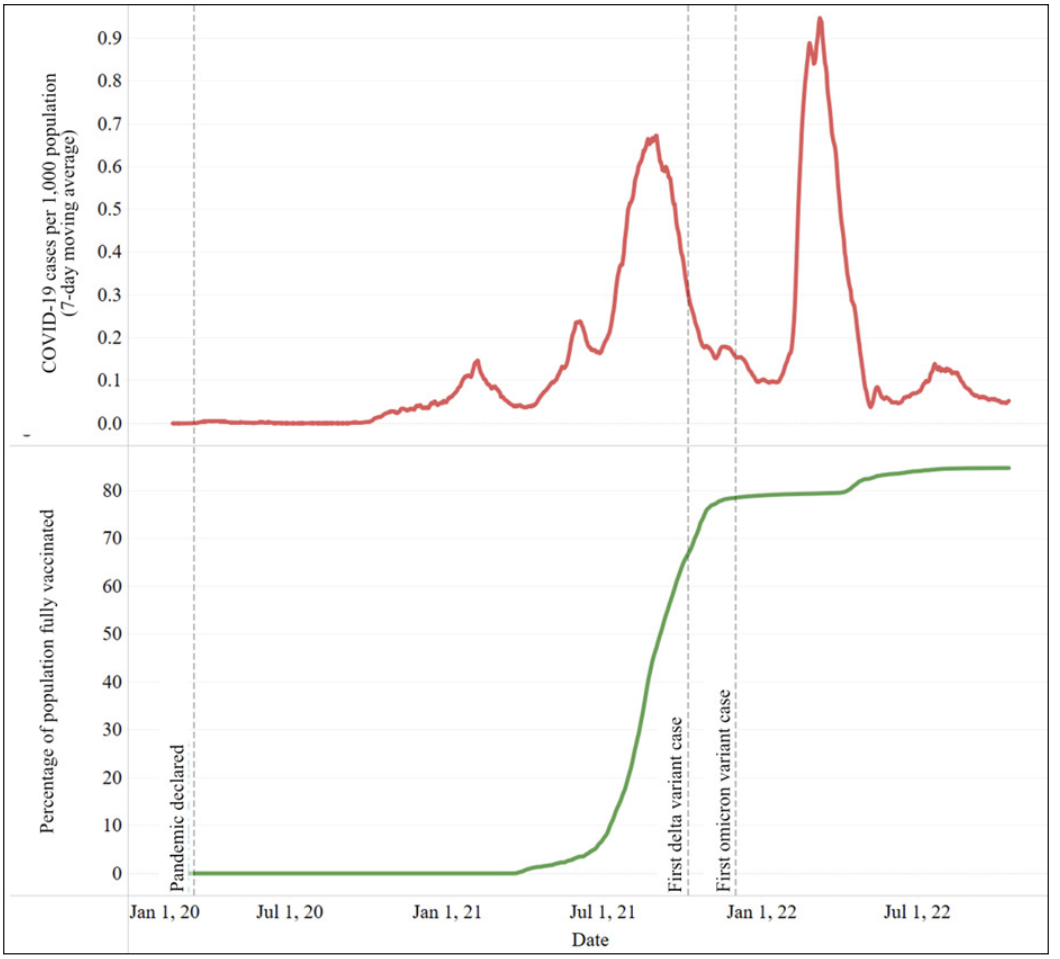

Figure 5. Average daily COVID-19 cases and vaccination trends in Malaysia

STATISTICAL METHODOLOGY

Separate regression models were estimated for each trip type to discern the impacts of different time periods on mobility patterns while controlling for other important variables. The analysis data were arranged based on the state-day level. In each of the models, the dependent variable was the percentage change in the number of trips as compared to the median value of January to early February 2020 data for the same day of the week. These variables were continuous in nature and exhibited normal distribution trends, with linear relationships with the predictor variables. Thus, linear regression models were estimated for each trip category.

Additionally, concerns arise due to repeated observation within each state over time, which may result in both spatial and temporal correlations in the dataset. This tends to

result in specific states showing a higher (or lower) number of trips made compared to other similar states. Failure to account for this correlation would result in a biased coefficient estimate, resulting in incorrect inferences. Thus, a mixed-effects framework was utilized, which allows for the estimation of a series of state-specific random effects, thus allowing the model to account for factors that are not being captured by the model directly due to state-specific variation. The general form of the model is shown in Equation 2:

$$y_{it} = \beta X_{it} + u_i + \varepsilon_{it} \quad [2]$$
$$u_i \sim N(0,\sigma_u^2)$$
$$\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$$

where y_{it} is the percentage change in the mobility for state i on day t; β is the estimated coefficient from the model; X_{it} is the predictor variables; u_i is the random effect that captures the unobserved state-level effect (varies from state to state but remains the same within a state); and ε_{it} is the error term.

Within the context of this study, time (i.e., date) was not treated as a random effect since time period-related variables were already included as predictors (i.e., fixed effects), which accounted for these effects in the models.

RESULTS AND DISCUSSION

Table 2 shows the results for mixed-effects linear regression models for the percentage change in various types of mobility between February 2020 and October 2022. When interpreting the results, a positive estimated coefficient indicates that the mobility in a given state increased as that variable increased. Conversely, a negative estimate coefficient demonstrates a reduction in mobility, while a close to zero coefficient indicates no change. The following sub-sections discuss the results obtained and their implications for each of these four categories of variables.

Demographic and Socioeconomic Factors

Several demographic and socioeconomic factors were assessed, including the percentage of the Malay population (the major race in Malaysia), the percentage of the rural population, sex, poverty rate, unemployment rate, and median income. The model results showed that an increase in the poverty rate or unemployment rate resulted in reduced mobility across various trip types, which is supported by prior studies (Bamney et al., 2022). Generally, these two factors were correlated and, thus, were not included in the model simultaneously. A one percent increase in the population living below the national poverty line resulted in a 1.6% and 1.8% reduction in workplace trips and trips to grocery stores and pharmacies, respectively. Similarly, a 1% increase in the unemployment rate resulted in a 2.4% reduction

in trips to transit stations. Retail and recreational trips did not seem to be impacted by these factors.

Table 2
Results of the mixed-effect linear regression model

Variable	Estimate coefficient			
	Workplace (n = 15,567)	**Transit station (n = 15,465)**	**Retail and recreation (n = 15,515)**	**Grocery and pharmacy (n = 15,508)**
Intercept	-1.622	961.454*	173.993*	9.532*
Sociodemographic factors				
Percentage of population below the national poverty line	-1.553*	N/A	N/A	-1.786*
Percentage of unemployment	N/A	-2.377*	N/A	N/A
Median income in RM1,000	1.771*	N/A	N/A	N/A
Percentage of the rural population	0.757*	N/A	N/A	N/A
Percentage of the Malay population	-0.164*	-1.186*	0.364*	N/A
Percentage of the female population	N/A	-18.405*	-4.114*	N/A
Timeline				
Pre-pandemic (Feb. 15 - Mar. 10, 2020)	Baseline			
No lockdown (Mar. 11 - Mar. 17, 2020)	-6.531*	8.941*	-1.746	10.112*
MCO-1, nationwide lockdown (Mar. 18 - May 03, 2020)	-57.166*	-74.061*	-74.184*	-43.364*
CMCO, varies by state and date	-28.086*	-46.223*	-32.663*	-2.772*
RMCO, varies by state and date	-19.064*	-25.772*	-16.916*	5.041*
MCO-2, varies by state (Jan. 13 – Mar. 4, 2021)	-36.487*	-54.283*	-43.887*	-12.986*
MCO-3, nationwide lockdown (May 12 – Jun. 28, 2021)	-44.260*	-57.843*	-48.764*	-10.276*
NRP-1 (Jun. 29 – Sep. 30, 2021)	-40.801*	-47.431*	-42.453*	-4.160*
NRP-2 (Jul. 05 – Oct. 17, 2021)	-33.615*	-46.344*	-32.818*	1.963*
NRP-3 (Aug. 04 – Dec. 31, 2021)	-26.785*	-18.603*	-9.706*	16.110*
NRP-4 (Aug. 26, 2021 – Mar. 31, 2022)	-17.595*	-3.724*	1.676*	20.816*
Post-pandemic (Apr. 2022)	-7.075*	-7.383*	1.072	31.747*
Post-pandemic (May 2022)	-19.216*	22.968*	13.524*	32.013*
Post-pandemic (Jun. – Oct. 2022)	-7.714*	N/A	N/A	N/A
Post-pandemic (Jun. 2022)	N/A	15.628*	11.305*	24.096*
Post-pandemic (Jul. 2022)	N/A	13.336*	8.987*	23.285*
Post-pandemic (Aug. 2022)	N/A	6.126*	9.448*	22.691*
Post-pandemic (Sep. 2022)	N/A	16.829*	12.025*	21.976*
Post-pandemic (Oct. 2022)	N/A	13.020*	10.730*	21.211*
COVID-19 information				

New COVID-19 cases per 100,000 population	N/A	-0.096*	-0.068*	-0.020*
New COVID-19 death per 100,000 population	-2.482*	N/A	N/A	N/A
Day of week				
Sunday		Baseline		
Monday	-5.325*	4.125*	2.473*	7.190*
Tuesday	-3.998*	3.207*	1.412*	6.256*
Wednesday	-2.903*	4.258*	2.046*	7.732*
Thursday	-3.069*	2.291*	1.726*	6.426*
Friday	0.003	1.429*	0.506	5.038*
Saturday	3.090*	1.759*	-0.054	1.875*
Variance of intercept, $\sigma^2(u_i)$	63.950	2749.900	99.760	234.700

Note. MCO = Movement Control Order; CMCO = Conditional Movement Control Order; RMCO = Recovery Movement Control Order; NRP = National Recovery Plan; Std. Err. = Standard error; *significant at 95% confidence; N/A = Not applicable due to multicollinearity or insignificant results

States with higher median income tended to have higher mobility related to the workplace, which is aligned with prior research (Beck & Hensher, 2020b). The workplace mobility increased significantly by 1.8% for every RM1,000 increase in median income. One potential factor contributing to this trend in Malaysia is the concentration of major corporations in states with higher income levels (e.g., Selangor, Johor, Pulau Pinang, and the three federal territories) (DOSM, 2023). Similar to prior studies (Bamney et al., 2021, 2022), states with a higher percentage of people living in rural areas tended to experience higher mobility to the workplace when compared to states with higher urban concentration. A 1% increase in the percentage of the rural population would increase mobility by 0.8%. Neither median income nor percentage of rural population showed a significant relationship with non-work trips.

The results also showed that the states with a higher percentage of Malay population tended to have lower mobility related to workplace and transit stations, and more trips for retail and recreational purposes throughout the study period. On average, the mobility for workplace and transit station decreased by 0.16 and 1.19%, respectively, and increased by 0.36% for retail and recreational trips for a 1% increase in the Malay population. For workplace trips, this could be attributed to the increase in unemployment rate among the Malay demographic, notably among those who graduated in 2020. According to the DOSM, the unemployed graduates increased by 22.5% between 2019 and 2020, with 70% of those comprising Malay graduates (Bernama, 2021).

Sex did not seem to have a significant effect on workplace mobility. However, states with a higher female population tended to have lower mobility to transit stations. This trend contrasts with the observation on-site, where 62% of regular public transport users were

female ("Making public transport", 2023). Although it should be noted that the analysed data included the entire female population in Malaysia, whereas the public transport users focused only on certain age groups.

COVID-19 Information and Day of Week

The daily announcements of new COVID-19 cases and deaths influenced mobility across various trip types. According to Table 2, mobility to workplaces decreased significantly by 2.5% with an increase in new COVID-19 deaths for every 100,000 population. For non-work trips, a reduction in mobility was observed as the number of COVID-19 cases increased. On average, for every unit increase in COVID-19 cases per 100,000 population, mobility to transit stations, retail and recreational mobility, and trips to grocery stores and pharmacies decreased by 0.1%, 0.1%, and 0.02%, respectively. These trends are consistent with prior studies (Bamney et al., 2021, 2022). When controlled for the number of COVID-19 cases and deaths, the vaccination rates did not show any significant relationship with any of the trip categories. The primary reason for this trend may be due to the strict lockdown that was still in place during the distribution of the COVID-19 vaccine, as shown in Figure 1.

The results were also controlled for day of the week variables. Results showed that weekdays generally had lower work trips compared to weekends (Saturday and Sunday). However, work trips on Saturday were significantly higher than on Sunday. This trend is somewhat unexpected but may be driven by some states (i.e., Terengganu, Kelantan, Kedah, and Johor) not observing Sunday as a holiday. The other trip categories, on the other hand, exhibited higher mobility on weekdays compared to weekends. This again supports the prior discussion that a reduction in work trips, possibly due to more people working from home or in a hybrid arrangement, increases the non-work trips due to more time available for such activities during weekdays.

Pandemic Period

The timeline was divided into three broad categories: before, during, and after the COVID-19 pandemic. To interpret the timeline variables, each variable is compared to the baseline period, which in this case is the mobility data before the WHO announced the COVID-19 outbreak as a global pandemic.

The model results showed that the pre-pandemic period exhibited approximately 1.6% (i.e., based on the intercept value) reduction in work trips when compared to the January/February data. However, this result was not statistically significant. Meanwhile, mobility during non-work trips was significantly higher in the same time periods.

After COVID-19 was declared a pandemic, mobility to the workplace saw a reduction of 6.5% before the first lockdown took place in Malaysia (March 11 to March 17, 2020). However, trips to transit stations, grocery stores, and pharmacies showed an increase. Retail

and recreational trips did not show any significant change during this period. The fear of the COVID-19 pandemic during the initial stages explains a reduction in work, retail and recreational trips, and an increase in trips to grocery stores and pharmacies to stock up on supplies for the upcoming lockdowns.

As the government announced the first MCO, Malaysia saw the most significant reduction in mobility across all trip types. Work trips reduced by 57% which was directly a result of various economic sectors being forced to shut down, forcing people to WFH. Trips to transit stations, retail and recreational trips reduced by 74% each, whereas trips to grocery stores and pharmacies showed slightly lower reductions at 43% compared to other trip categories. One reason for these trends, particularly for transit station trips, was the closure of all government and private sector premises ("14-day Movement Control Order", 2020), which are primarily concentrated within the vicinity of most public transit systems. Additionally, this may be due to the limited operating time of public transit during the lockdown period ("New schedule", 2020), resulting in a higher reduction in transit-related mobility. Whereas the closure of most services within this sector, except for restaurants, for a take-away option only, might explain the trends observed for retail and recreational trips.

As the number of COVID-19 cases decreased, the government began to ease some restrictions, and Malaysia transitioned into the CMCO phase, followed by the RMCO phase. During these two phases, the mobility across all trip types started to increase (i.e., the estimated coefficients are less negative). During the CMCO phase, the mobility to the workplace increased by 29.1%, and during the RMCO, it increased by another 9.0%. This increase in mobility to the workplace during these two phases may be driven by economic sectors, most of which were allowed to operate after the first MCO. Similarly, transit station trips, retail and recreational trips, and trips to grocery stores and pharmacies increased by 27.8, 41.5, and 40.6%, respectively, during the CMCO phase. During the RMCO phase, trips across these three categories increased further by 20.5, 15.7, and 7.8%, respectively. However, it should be noted that during both CMCO and RMCO phases, the mobility across all trip types was still lower than the mobility during the baseline period, except for trips to grocery stores and pharmacies. Grocery and pharmacy-related trips were consistently higher than the other trip categories. Moreover, the number of these trips was actually higher by 5% during the RMCO phase compared to the pre-pandemic period. These trends are expected, as these trips were considered essential trips and people were expected to make more such trips during relaxed lockdown periods.

It should be noted that both CMCO and RMCO phases varied by state and date, and the implementation of these phases depended on the number of COVID-19 cases recorded. As the number of COVID-19 cases started to increase again, a second MCO (MCO-2) was reintroduced in all localities, except for the state of Sarawak, on January 13, 2021. As expected, mobility decreased significantly across all trip purposes during this

period. Due to the surge in COVID-19 cases, the third MCO was reinstated, resulting in further reduction in mobility. However, during both MCO-2 and MCO-3, the reductions in trips were less pronounced compared to MCO-1. This was primarily due to the level of restrictions imposed and the nature of the implementation of these lockdowns. For example, all government and private sector premises were not allowed to operate during the first MCO, except for essential services ("14-day Movement Control Order", 2020). However, the second MCO saw some relaxation given to key economic sectors to operate with strict SOP ("Only 5 economic sectors", 2021). Moreover, unlike the first MCO, the second MCO had a different start date for each state.

As the COVID-19 pandemic started to get under control, the nation implemented the NRP in four phases. In terms of restrictions, NRP-1 had similar restrictions to MCO. However, more industrial, business, and commercial sectors were allowed to operate compared to the MCO phase. Thus, the NRP phases showed consistent recovery in mobility across all trip types. For example, between NRP-1 and NRP-2, the workplace-related mobility increased significantly by 7.2%; further increased by 6.8% between NRP-2 and NRP-3; and increased by 9.2% between NRP-3 and NRP-4. However, the workplace mobility during these transitions was still lower than the baseline. Similar trends were also observed for transit trips and retail and recreational trips. Trips to grocery and pharmacies, on the other hand, showed a much rapid increase and quickly exceeded the trips during the pre-pandemic period.

It is worth noting that various types of restriction variables (e.g., school closures, interstate travel bans, limited travel radius, and restaurant closures) were also analysed as a part of this study. However, since the time period variables accounted for these effects, correlations between independent variables were observed when types of restrictions were included in the models. Hence, these factors were not considered in the final model.

Post-Pandemic Period

The post-pandemic period was analysed by month to see if there were any changes in mobility as time progressed. For the workplace mobility model, three different categorical variables were created for this period: April 2022, May 2022, and June to October 2022. After the government announced the transition to the endemic phase on April 1, the mobility to the workplace increased significantly by 10.5% in the month of April 2022 compared to the NRP-4 phase. However, in May 2022, the mobility reduced again by 12.1%, and this could be mainly due to the national public holiday observed during this month. Between June and October 2022, mobility increased by 11.5% compared to May 2022. Interestingly, other trip categories, including transit station trips during the same time period, showed a marked increase. Beginning in April 2022, the transit station mobility began to increase, with the period between May and October 2022 showing even higher mobility than the

pre-pandemic periods. Similar trends were also observed for retail and recreational trips, as well as trips to grocery stores and pharmacies, the latter of which showed the greatest increase in mobility during the post-pandemic period.

It should be noted that all restrictions that were placed during the pandemic period were lifted on April 1, 2022. Despite this fact, work trips showed a much lower recovery even after the pandemic. On the other hand, non-work trips exceeded pre-pandemic levels between April and October 2022. Since the model captures the effects of unemployment on mobility explicitly or implicitly (through other variables such as poverty rate, median income), it is reasonable to assume that these changes in mobility are largely due to WFH activity. Lower levels of work trips, even after the pandemic, are thus likely due to increased WFH or hybrid work arrangements. As employees choose to WFH, they are more likely to engage in additional non-work trips, as the time saved from commuting can be reallocated to other activities (Moreno & Moeckel, 2016), which explains greater recovery among other trip categories. Prior studies also support this assertion. A local study utilizing a survey-based approach found that the WFH policy would not negatively impact the employees' efficacy (Prihadi et al., 2021). Another survey-based study conducted by the Malaysian Employers Federation found that about 62% of Malaysian companies that participated in the survey preferred a hybrid work arrangement (Malaysian Employers Federation [MEF], 2021). This might explain why more companies prefer their employees to WFH or have a hybrid work arrangement even after the pandemic.

From a transportation engineering and planning perspective, the persistent reduction in work-related trips has several implications. First, this could impact the future of the transportation system and land use in Malaysia. The shift toward remote and hybrid work arrangements may reduce peak-hour commuting demand, alter traffic patterns, and potentially decrease the need for large-scale office districts. Second, the four-step traditional demand forecasting model may need to be recalibrated to account for individuals working from home. This is particularly true for the trip generation model, where the probability of an individual working from home needs to be estimated (Moeckel, 2017). Additionally, this could also impact the mode choice model based on the increasing trend of mobility to transit stations, as also shown in prior studies (Hensher et al., 2022; Loa & Habib, 2023). Third, from a transportation infrastructure investment perspective, a continued decline in work trips could lead to financial risks if demand projections fail to account for these shifts. Historical evidence has shown that many road and rail projects tend to overestimate future travel demand (Flyvbjerg et al., 2006). With more employees working remotely, such overestimations could become even more pronounced, leading to underutilized infrastructure and misallocated resources. Furthermore, beyond transportation, these trends have broader implications for office-based employment. Given the pace at which technology is advancing, flexible work arrangements may be encouraged by both employers

and employees, which could reduce demand for traditional office space. Cities must adapt by ensuring that commercial real estate policies, zoning regulations, and transit planning align with these evolving work patterns.

CONCLUSION

The spread of the COVID-19 pandemic introduced unprecedented changes globally in the transportation sector. This study provides important insights into the impacts of the COVID-19 pandemic on mobility trends in Malaysia. The mobility trend data were obtained from Google's community mobility reports for the period from February 2020 to October 2022 at 24-hour aggregation for each state. Four different types of trips were investigated: work trips, trips to transit stations, retail and recreational trips, and trips to grocery stores and pharmacies. Additional data related to the number of COVID cases, vaccines administered, and COVID-related deaths were obtained for every state for each day. Census data for Malaysia were also obtained and integrated to get demographic details for each state. Lastly, details of lockdowns introduced by the government during the study period were also obtained.

The investigations showed interesting trends in mobility throughout the pandemic and the early stages of the post-pandemic. During March 2020, when COVID-19 started to spread and the WHO declared it a pandemic, the government introduced a series of MCOs, which resulted in a sharp decline in all types of trips. Work trips were reduced by 57%, while trips to transit stations and retail and recreational trips were reduced by 74%. Essential trips, including trips to grocery stores and pharmacies, were reduced by the least amount at 43%. With time, the restrictions were made less strict, resulting in an increase in mobility and the number of COVID-19 cases across the country. Similarly, in 2021, the changes in mobility across all categories were found to be correlated with the severity of lockdown and the number of COVID-19 cases, and population demographics. After the transition to the endemic phase, an increase in mobility was observed for non-work trips, but a reduction was observed for workplace trips.

One key finding in this study is the differential recovery rates of work and non-work trips following the post-pandemic period, highlighting the lasting impact of the COVID-19 pandemic on travel behaviour. While both types of trips are beginning to rebound, work trips are recovering at a slower rate than non-work trips. These results suggest that changes in work arrangements, such as hybrid and remote work models, may continue to shape urban mobility patterns in the long run. The implications of this trend are significant and provide insight for traffic engineers and city planners to consider when weighing the travel needs and expected traffic generation associated with the new travel patterns in Malaysia. For example, urban centres may experience prolonged periods of reduced congestion, which could influence future transportation planning and infrastructure investments. Public

transportation systems may also need to adapt to changes in demand and peak usage times. A related change could be in commercial and real estate demand, as demand for commercial spaces could decrease. Overall, the pandemic resulted in a major shift in transportation and mobility, and its effect may last well into the future. Understanding these shifts in mobility patterns can help policymakers design more resilient transportation systems to mitigate the impact of future crises, whether health-related or otherwise. Future research can build on these findings to explore the permanence of these behavioural shifts and their implications for urban planning, public transportation, and workplace policies.

While this study provides crucial insights into the changes in travel patterns due to the COVID-19 pandemic, there are several important limitations that are worth noting. First, the analysis uses data drawn from Google Mobility Reports, which might represent a subset of trips. Moreover, the data primarily comes from smartphone users with Google Location History enabled, which may lead to an underrepresentation of certain population demographics, such as low-income populations or people concerned with data privacy. Nevertheless, the study provides important insights into the overall mobility trends in Malaysia during and after the pandemic. Future studies could supplement this data with surveys or official transportation records to enhance representativeness. Another limitation was the selection of January and February 2020 as the baseline period, due to data constraints, despite the widespread news of COVID-19 spreading globally in late 2019. Although it is important to consider the varying impact of different time periods, this timeframe still represents a relevant reference point just before the country experienced significant impacts of COVID-19 on mobility. For future study, a longer baseline period should be considered, considering the availability of data. Additionally, a concern arises about the potential overlap between trips to workplaces and transit stations (i.e., a work trip might also be a trip to a transit station). However, a consistent trend was shown for other non-work trips, where significant increases in mobility were observed after the pandemic. Lastly, data on the percentage of the population working from home in Malaysia during various time periods were not available. This makes it challenging to determine the exact reasons for the reduction in work trips during various lockdown phases. However, since the analysis in this study controls for the impacts of unemployment on mobility, it is reasonable to assume that such reductions are largely due to increases in WFH activity.

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