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Disparity between expected spatial accessibility and actual travel time to vaccination sites: Implications for COVID-19 immunization delays

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ABSTRACT

The COVID-19 pandemic underscored the importance of equitable and timely vaccination access. This study examined the impact of discrepancies between actual and expected travel times to vaccination centers on the timeliness of full and booster COVID-19 vaccinations in Nueces County, Texas. Drawing on vaccination data from over 171,000 individuals aged 18 and older, we employed Cox proportional hazards models and survival analysis to explore how demographic characteristics, the Social Vulnerability Index (SVI), and geographic disparities influenced vaccination delays. Results revealed that longer-than-expected travel times significantly reduced the likelihood of timely vaccination (HR = 0.95 for full vaccination, HR = 0.89 for booster doses). Seniors demonstrated higher vaccination timeliness rates, but gaps persisted across gender, ethnicity, and race, with males and Hispanics experiencing greater delays. Interaction analysis highlighted compounded challenges for seniors and vulnerable populations when travel time discrepancies were larger. These findings emphasize the critical need for geographically targeted public health interventions to address socio-economic disparities and improve vaccine accessibility during health crises.

1. Introduction

The COVID-19 pandemic has profoundly affected global health, claiming millions of lives and highlighting the need for widespread vaccination efforts (WHO, 2024). Vaccines have proven effective in reducing severe illness and death (CDC, 2022a); however, achieving high vaccination rates has been a challenge, especially in addressing disparities related to geographic access and social vulnerability (Sang et al., 2022). Moreover, research suggests that increasing the interval between vaccine doses may impact their effectiveness (El Adam et al., 2022). Prior studies have shown that logistical barriers, such as travel distance to vaccination centers, influence vaccine uptake (Mazar et al., 2023). Demographic factors, including age, gender, and ethnicity, further shape vaccination behaviors, emphasizing the need for equitable distribution strategies (Cochran et al., 2021).

Despite these findings, significant gaps remain. Many studies have explored factors influencing vaccination rates but often focus on clinical determinants rather than the timing of vaccine doses. Better compliance with vaccination was observed among the elderly, individuals residing in urban areas, and those with a higher number of comorbidities, whereas rural residents and younger populations showed lower compliance with the second dose (Ioannou, Green, Locke, & Berry, 2021). These findings highlight the importance of logistical, demographic, and health-related factors as key predictors of vaccination adherence, emphasizing areas for future public health initiatives to improve vaccine equity and timely coverage. Additionally, another study offers an in-depth examination of COVID-19 timely vaccine uptake among U.S. veterans that reveals significant insights into the vaccination patterns among veterans, highlighting the importance of understanding the diverse influences on timely vaccine compliance to enhance public health strategies (Bajema et al., 2023). Moreover, few have examined how discrepancies between expected and actual travel times to vaccination centers impact vaccination timeliness, particularly for booster doses. Interactions between geographic barriers and demographic vulnerabilities, such as Social Vulnerability Index (SVI) scores, are also understudied. These limitations hinder the development of targeted public health interventions to improve vaccine access and equity.

To address these gaps, we posed the following research question: *What is the impact of travel time discrepancies and socio-demographic factors on the timing of full and booster COVID-19 vaccinations*? This study aimed to explore whether travel time discrepancies and socio-demographic factors, such as age, gender, ethnicity, race, residence area, and Social

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Vulnerability Index (SVI), influence the delays of receiving full and booster COVID-19 vaccinations. The analysis examined the extent to which these variables affected vaccination timing, considering the possibility of no significant association.

We employed survival analysis and Cox proportional hazards models to analyze data from over 171,000 individuals in Nueces County, Texas. This study investigated how travel time discrepancies interact with socio-demographic factors to influence vaccination timeliness, focusing on the interplay between geographic and social barriers.

This research introduces a novel approach by integrating spatial accessibility metrics with demographic and social vulnerability data. Unlike previous studies, the work addresses both the timing and the socio-geographic disparities in vaccine uptake. By identifying critical barriers, this study seeks to inform public health interventions, improve vaccine accessibility, and enhance preparedness for future health emergencies.

2. Methods

2.1. Study area and data source

Nueces County, located along the Texas Gulf Coast, is a predominantly Latinx/Hispanic South Texas community. According to the 2020 census, the county's total population was 353,178, with more than 62 % identifying as Hispanic. The county's largest and most densely populated area is Corpus Christi, which accounts for approximately 80 % of the county's total population. According to recent U.S. Census Bureau estimates, the majority of the population resides in urban and suburban areas, while the remainder lives in smaller towns and rural communities such as Robstown, Bishop, and Port Aransas (C. Bureau, 2023). By February 28, 2022, 66.4 % of the population had received at least one vaccine dose, 56.8 % had completed the primary series, and 43.4 % had received a booster dose as of May 2023 (CDC, 2023). This urban-suburban-rural mix, coupled with socioeconomic and racial diversity, makes Nueces County a compelling case study for evaluating disparities in COVID-19 vaccination access.

While Nueces County is located in South Texas, immigration status is not a predominant factor influencing healthcare access in this region. According to 2020 Census data, 94.6 % of the county's residents are U.S. citizens—above the national average—and only 8.73 % were born outside the United States, a rate lower than the national average of 13.5 % (Census, 2020).

This research utilized a dataset provided by the county's health department, containing vaccination records from December 2020 to February 2022. The dataset included home addresses, ages, genders, races, ethnicities, and vaccination details of the residents. The study was reviewed and deemed exempt by the Institutional Review Board associated with the authors' affiliations.

During this period, the county's public health district administered vaccinations through 129 sites, representing 16 provider types, including local health departments, pharmacies, hospitals, and private practices. Approximately 95 % of all vaccinations were provided by local health departments, pharmacies, hospitals, or private practices. The majority of vaccination sites are clustered in the central and eastern portions of the county, especially within Corpus Christi—the county's primary urban area. Rural regions, particularly in the western and southern parts of the county, show relatively sparse vaccination site availability (Fig. 1). Urban versus rural residences were identified using block group data from the United States Census Bureau (C. Bureau, 2023).

2.2. Baseline characteristics and sample selection

This study focused on adult residents of Nueces County. The SVI developed by the Centers for Disease Control and Prevention (CDC), was used to assign vulnerability scores to residents based on their census tract (CDC, 2020). This index, calculated using 16 U.S. census variables, measures a community's potential negative effects from external stresses on human health.

The study included Pfizer, Moderna, AstraZeneca, and other vaccine types, excluding Janssen vaccines due to significant differences in recommended dosing intervals. Full vaccination was defined as receiving two doses of the specified vaccines, while booster vaccination required an additional dose after full vaccination. Participants with vaccine records administered outside the county or without valid home addresses were excluded. Records with missing gender, ethnicity, or SVI data were also omitted. To prevent outlier effects, vaccination records with intervals of less than 21 days for full vaccination or 150 days for booster doses were excluded (CDC, 2022b).

Fig. 2 outlines the analytic sample selection. Starting with 235,970 records, exclusions were applied to remove individuals without valid geocoded addresses, those under 18 years old, records missing

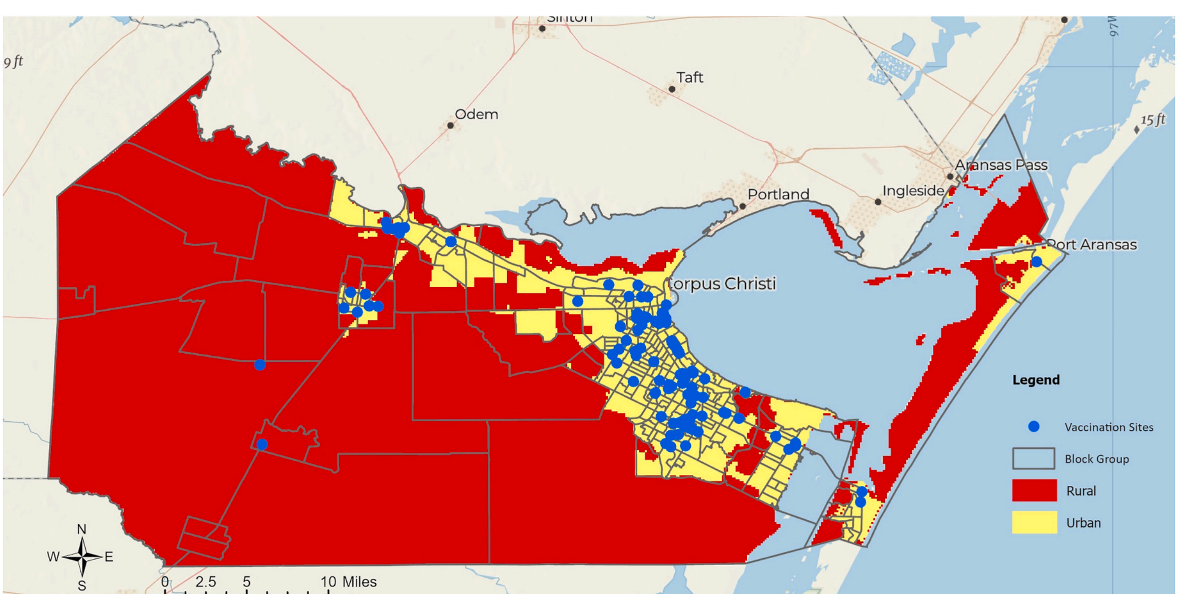

Fig. 1. Distribution of COVID-19 vaccination sites in Nueces County, Texas.

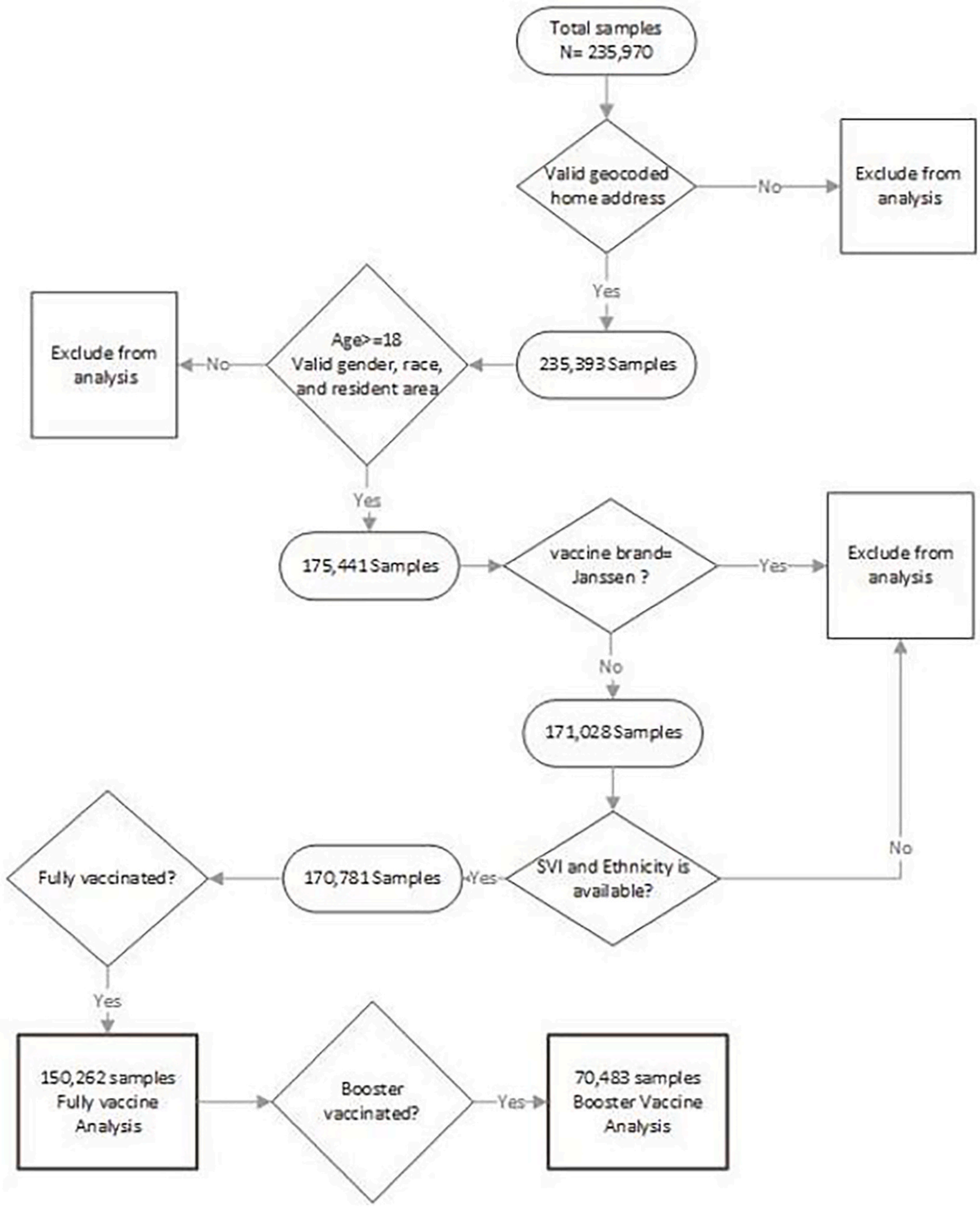

Fig. 2. Flowchart of sample selection for the fully vaccinated and booster vaccine analysis.

demographic details, and those vaccinated with the Janssen vaccine. This process resulted in 150,262 samples for full vaccination analysis and 70,483 samples for booster vaccination analysis.

2.3. Discrepancies in travel time

To assess the impact of travel time for previous doses on the likelihood of receiving full and booster vaccine doses, the researchers first calculated the travel time required to obtain the vaccines. Driving travel time was initially determined based on the distance from individuals' home addresses to the vaccination centers using the OSMnx package in Python (Boeing, 2017). Initial calculations with OSMnx revealed that individuals living very close to vaccination sites had extremely short driving travel times. To ensure a comprehensive analysis of travel times to vaccination sites, walking travel times were assigned to these individuals, providing a more accurate representation of the time required for those whose homes were within a 2-min driving distance of the sites.

We used a travel index to evaluate how much individuals traveled beyond what was expected to receive previous vaccine doses. This index accounted for the spatial accessibility of different areas within the city (urban and rural) to enable a fair comparison of travel times to vaccination centers. The two-step floating catchment area (2SFCA) method (Su et al., 2022), a widely used approach for measuring spatial accessibility to healthcare facilities, was utilized to evaluate access to vaccination centers from the population center of each block group in a previous study (Naderi et al., 2023). This method employs a service-to-population ratio to assess resource and facility accessibility. Specifically, it calculates the number of service providers within a designated catchment area and divides this by the total population residing in that area (McGrail, 2012).

To evaluate vaccine accessibility, the first step of the 2SFCA involved determining the availability of vaccine services at each facility by calculating the supply-to-demand ratio for the population within the designated catchment area of each site. This calculation reflects how well the available services meet the demand in a specific location (Zhou et al., 2021).

For the analysis concerning full vaccination, the difference between the normalized actual travel time to vaccination sites for the first dose and the normalized accessibility value was calculated for each sample. Similarly, for the booster dose analysis, the mean actual travel time to vaccination sites for the first and second doses was normalized, and the differences between these normalized values and the normalized spatial accessibility were calculated to derive the distance index for the booster vaccine. A negative result indicated that individuals traveled less than expected, while a positive result signified that they traveled further. Travel time discrepancy metric is distinct from SVI; while SVI captures socioeconomic vulnerability at the community level, travel time discrepancy quantifies geographic accessibility gaps.

2.4. Statistical analysis

The association between demographic and spatial factors and the timeliness of full and booster vaccinations was analyzed using survival models, specifically the Cox Proportional Hazards (CoxPH) model (Cox, 1972) and the Kaplan-Meier estimator (Kaplan & Meier, 1958). These methods are widely used to evaluate the likelihood of events over time. Traditionally, survival analysis relies heavily on the Cox model, which stands out for its straightforwardness, ease of application, and clarity of its results. Known as a proportional hazards model, the Cox model operates under the assumption that the hazard ratios associated with each explanatory variable remain constant throughout the study period (Su et al., 2022). The CoxPH model assumes constant hazard ratios for explanatory variables over the study period and was used to examine associations between demographic factors (age, gender, race, ethnicity, residence area, SVI, and travel time discrepancies) and vaccination timing. The Cox proportional hazards model assumes that the hazard ratios between groups remain constant over time, meaning the relationship between the independent variables and the hazard is proportional (Kleinbaum & Klein, 2012), and it was evaluated graphically using log(-log) plots and Schoenfeld residuals (**Appendix**).

The Kaplan-Meier method provided cumulative incidence curves for vaccination events, allowing for a comparison of vaccination timing across groups. Analyses were conducted using Python version 3.12 and RStudio version 2023.06.01.

3. Results and findings

3.1. Descriptive statistics

As shown in Fig. 2, we identified 170,781 individuals aged 18 years or older who had received at least one COVID-19 vaccine dose as of March 15, 2020. Of these, 150,262 (87.98 %) were fully vaccinated, and 70,527 (46.93 %) had received a booster dose. Travel time discrepancies for the first dose ranged from −0.818 to 0.818, with a median of −0.729 and a mean of −0.633. For the average travel time discrepancy between the first and second doses, the range was −0.9 to 0.9, with a median of −0.644 and a mean of −0.55.

Table 1 summarizes the demographic and geographic characteristics of vaccinated residents across the first, second, and booster doses. Among the 150,262 individuals who received full vaccines, 55.4 % were female, with females slightly more represented among booster dose recipients (56.9 %) compared to males (43.1 %). Age distribution showed that 32.2 % were young adults (18–40 years), 33.3 % were adults (41–60 years), and 34.5 % were seniors (≥61 years). Seniors were most likely to complete booster vaccination, with 48.7 % of seniors achieving full vaccination and 34.5 % receiving a booster dose. For females, the median difference in travel time for the first dose is −0.729, indicating that actual travel time is, on average, slightly shorter than expected; the trends are similar across doses. Travel time discrepancies by age revealed that seniors had shorter-than-expected travel times, with a median of −0.744 for the first dose and −0.742 for the average of the first and second doses combined, suggesting better access or prioritization during vaccine rollout.

Ethnic disparities were evident, as 53 % of second-dose recipients were Hispanic/Latino, but this dropped to 49.1 % among booster-dose recipients. Non-Hispanic individuals had higher booster dose uptake, comprising 50.9 % of booster recipients. Travel time discrepancies for Hispanic residents had a median of −0.768 for the first dose, compared to −0.69 for non-Hispanic residents. Racial disparities were also observed, with White residents making up 60.06 % of second-dose recipients but only 56.2 % of booster-dose recipients, indicating relatively higher booster uptake among non-White populations. For the median, the disparity for White individuals was −0.727, while for non-White residents it was −0.737, further suggesting that travel times were shorter than expected across racial groups. Urban residents accounted for 95.4 % of the fully vaccinated population, with a median travel time discrepancy of −0.752 compared to −0.063 for rural residents to receive

Table 1
Characteristics of Nueces vaccinated residents.

	Second dose		Booster Dose		Discrepancy of the first dose travel time			Discrepancy of average travel time 1st and 2nd doses		
					Max	Median	Mean	Max	Median	Mean
Total	150,262		70,483		0.818	−0.729	−0.633	0.9	−0.644	−0.55
Sex										
Female	83200	55.4	40113	56.9	0.818	−0.729	−0.634	0.818	−0.727	−0.634
Male	67062	44.6	30370	43.1	0.793	−0.73	−0.632	0.793	−0.728	−0.63
Age										
Young (18≤age≤40)	48325	32.2	13452	19.1	0.798	−0.733	−0.65	0.797	−0.728	−0.65
Adult (41≤age≤60)	49976	33.3	24792	32.2	0.818	−0.724	−0.624	0.818	−0.72	−0.623
Senior (61≤age)	51961	34.5	32239	48.7	0.818	−0.744	−0.626	0.766	−0.742	−0.625
Ethnicity										
Hispanic/Latino	79628	53	34631	49.1	0.82	−0.768	−0.671	0.793	−0.767	−0.671
Not Hispanic or Latino	70634	47	35852	50.9	0.81	−0.69	−0.589	0.818	−0.657	−0.588
Race										
White	90241	60.06	39625	56.2	0.81	−0.727	−0.623	0.793	−0.726	−0.622
Not White	60021	39.94	30858	43.8	0.82	−0.737	−0.65	0.818	−0.733	−0.647
Urban vs. Rural										
Rural	6924	4.6	3031	4.3	0.81	−0.063	−0.006	0.81	−0.063	−0.009
Urban	143338	95.4	67452	95.7	0.561	−0.752	−0.663	0.561	−0.751	−0.66
SVI										
Low (2.87≤SVI≤6.99)	52572	34.99	25675	36.4	0.562	−0.566	−0.469	0.562	−0.564	−0.466
Medium (7≤SVI≤8.99)	53554	35.64	25129	35.7	0.797	−0.799	−0.712	0.797	−0.8	−0.712
High (9≤SVI≤12.05)	44136	29.37	19679	27.9	0.818	−0.819	−0.728	0.819	−0.82	−0.730

the first dose.

The SVI scores range from 2.872 to 12.045, revealed disparities in vaccination access. Low-SVI areas exhibited the largest median travel time discrepancy (−0.566), while high-SVI areas showed the smallest (−0.819), reflecting greater-than-expected travel times for residents in more vulnerable regions. These findings highlight the critical impact of social vulnerability and geographic location on vaccination accessibility.

3.2. Travel time discrepancies and geographic disparities

Fig. 3 illustrates the spatial distribution of average travel time discrepancies for receiving full and booster COVID-19 vaccinations across block groups in Nueces County. Areas with higher discrepancies, represented in red, were concentrated in rural and outlying regions, highlighting significant geographic disparities in vaccination accessibility. Urban residents consistently exhibited shorter-than-expected travel times, while rural residents faced longer-than-expected travel times, suggesting greater challenges in accessing vaccination sites. This disparity underscores the need for targeted interventions to address rural access barriers.

3.3. Cumulative incidence of vaccination

The cumulative event curve is displayed in Fig. 4 the proportion of individuals receiving their booster COVID-19 vaccine dose over time, stratified by age groups, ethnicity, urban/rural living, and race. The cumulative event curves generally are nearly identical, indicating minimal differences in vaccination timing between different factors. Other factors' cumulative curves for full and booster vaccination that are demonstrated in the **Appendix,** emphasize the impact of demographic, geographic, and social factors on vaccine accessibility and uptake over time.

3.4. Factors associated with full and booster vaccination

Cox proportional hazards regression analysis was conducted to evaluate two significant vaccination events: full vaccination (time between the first and second doses) and booster vaccination (time between the second and third doses). Hazard ratios (HRs) quantified the likelihood of timely vaccination, with HR > 1 indicating a higher likelihood and HR < 1 indicating a lower likelihood relative to the reference group.

Table 2 presents results from four CoxPH models examining associations between demographic and geospatial factors and vaccination timing. The discrepancies between actual and expected travel time independently represent the significant association between vaccination site proximities and full vaccination on time (HR = −0.02, $p = 0.002$). Similarly, this relation is observed on booster vaccination even stronger (HR = −0.14, $p <$ 2e-16).

- Model 1: The results indicate that males were less likely to receive timely full vaccination compared to females (HR = 0.94, $p <$ 2e-16). Older age groups, particularly seniors, were significantly more likely to receive full vaccination on time (HR = 1.08, $p <$ 2e-16 for seniors). Non-Hispanic individuals (HR = 1.11, $p <$ 2e-16) and White in comparison to non-White individuals (HR = 0.94, $p <$ 2e-16) demonstrated a higher likelihood of delays in vaccination. Residents in high SVI areas had significant delays in receiving timely vaccination compared to those in low SVI areas (HR = 0.93, $p <$ 2e-16), while urban residents were more likely to receive vaccinations on time than their rural counterparts (HR = 1.06, $p <$ 1.4e-4). Additionally, the analysis of travel time discrepancies for the first dose revealed that individuals who traveled farther than the ideal time were more likely to delay receiving full vaccination (HR = 0.95, $p =$ 7.2e-8).

Model 2: Model 2 builds upon Model 1 by incorporating interaction terms between sex, age, and SVI categories with travel time discrepancies for first-dose vaccination. These interactions highlight the possibility that the likelihood of receiving full vaccination depends on a combination of demographic factors and travel time discrepancies. The findings supported those of Model 1 but revealed that seniors with higher travel time discrepancies experienced delays in vaccination (HR = 0.96, p = 0.03). Conversely, residents in high-SVI areas demonstrated a more pronounced negative interaction with travel time discrepancies (HR = 0.92, p = 0.0014), indicating significant access challenges for these vulnerable populations. Overall, travel distance emerged as a small but significant negative predictor of timely vaccination (HR = 0.98, p = 0.04). This model reveals that the association between factors and delay in receiving the vaccine remained stable compared to Model 1.

Model 3: This model examined predictors of timely booster receipt.

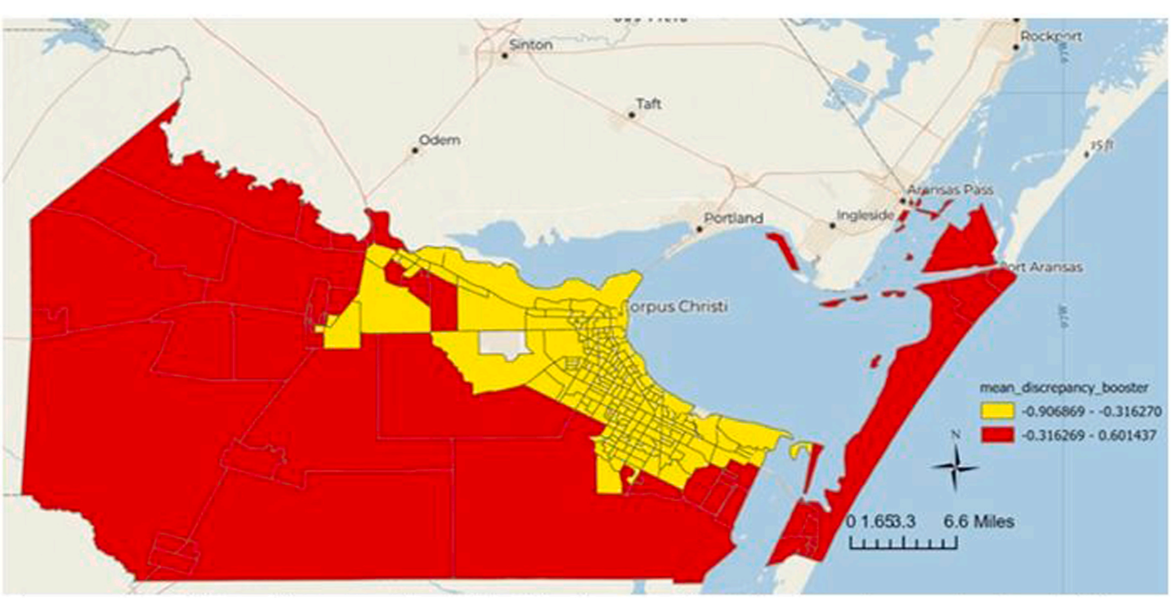

Fig. 3. Average travel time discrepancies in the block group level for booster vaccination in Nueces County.

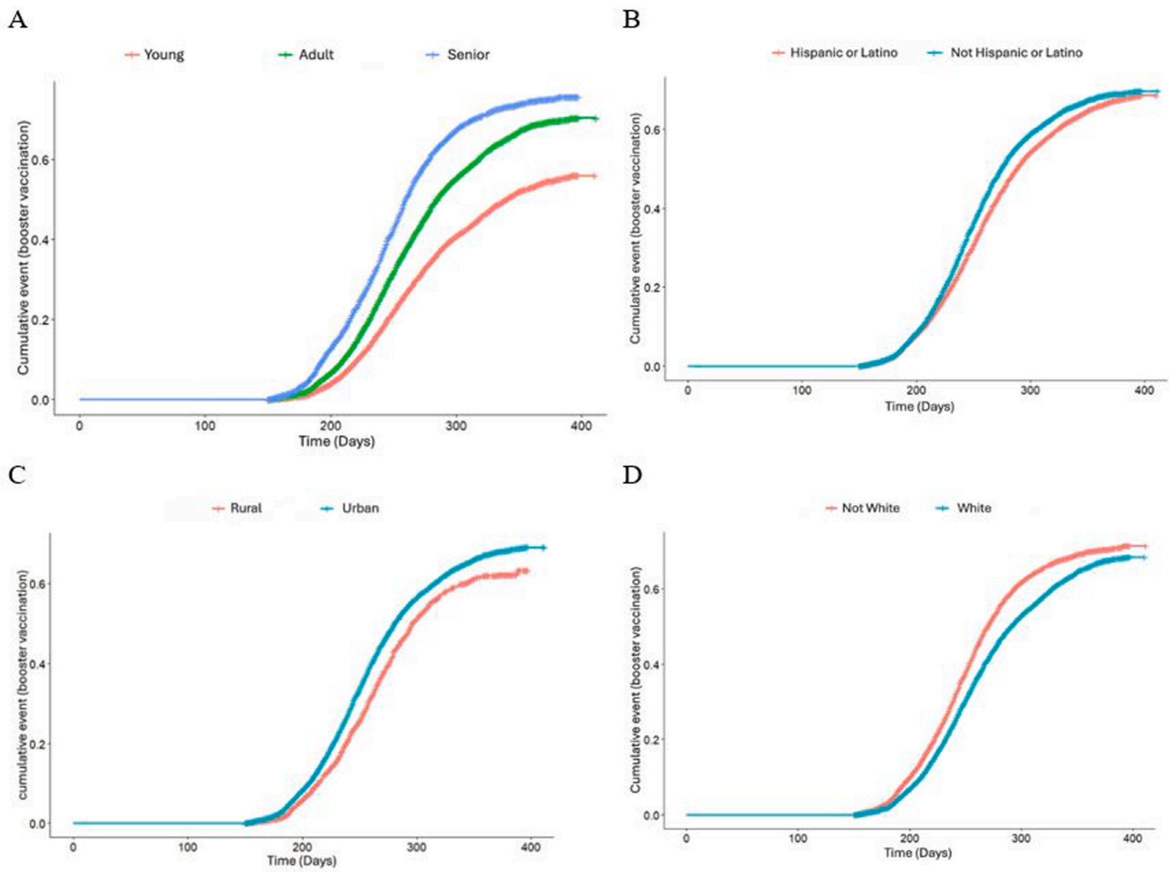

Fig. 4. Cumulative survival curves for the event (receiving the booster COVID-19 vaccine dose.

Males were weakly but significantly associated with timely booster uptake compared to females (HR = 1.02, p = 0.04). Seniors were substantially more likely to receive boosters in a timely manner than younger adults (HR = 2.08, p < 2e-16). High-SVI-area residents exhibited a mild increase in booster usage (HR = 1.03, p = 0.018), while medium-SVI areas showed no significant difference. Travel time discrepancies continued to present significant barriers, with a highly negative association observed: HR = 0.89, p < 8.9e-16, underscoring the importance of geographic access.

Model 4: This model extended Model 3 by incorporating interaction terms between demographic categories (sex, age, and SVI) and discrepancies in the average travel time between the first and second doses and expectations. Most factors in Model 4 represent the same association with Model 3 to booster vaccination timely. Considering the interaction demographic factors with discrepancies of travel time for receiving previous doses, seniors living farther from vaccination sites were more likely delays to receive boosters (HR = 0.9, p = 0.004). Residents in high-SVI areas also showed reduced likelihood of receiving booster vaccines on time when accounting for travel time discrepancies (HR = 0.91, p = 0.8). Across all models, seniors, urban residents, and those in low-SVI areas consistently demonstrated a higher probability of timely vaccination, while greater travel time discrepancies strongly correlated with delays, particularly in high-SVI areas. Interactions involving age and geographic barriers emerged as dominant predictors of vaccination timing.

While Table 2 provides an overarching analysis of demographic and geospatial factors influencing timely COVID-19 vaccination, Table 3 delves deeper by stratifying the analysis into urban and rural populations, highlighting the differences in factors affecting vaccine uptake across these distinct residence types. Table 3 presents the statistical results from the CoxPH model, analyzing the association between demographic and geospatial factors and the timing of receiving COVID-19 vaccination, stratified by urban and rural residents. Four models were constructed to evaluate these relationships. Models 1 and 2 analyze the likelihood of timely full vaccination, while Models 3 and 4 focus on timely booster vaccination in these populations.

In Model 1, which examines full vaccination among urban residents, males were less likely to receive vaccinations on time compared to females (HR = 0.94, p < 2e-16). Age showed a positive association, with adults (HR = 1.1, p < 2e-16) and seniors (HR = 1.08, p < 2e-16) more likely to receive full vaccination on time compared to younger individuals. Non-Hispanic individuals (HR = 1.11, p < 2.7e-12) and non-White individuals in comparison to Whites (HR = 0.94, p < 2e-16) demonstrated significant associations. Residents in high SVI areas had reduced odds of timely vaccination (HR = 0.93, p < 2e-16), while closer proximity to vaccination sites increased the likelihood of timely vaccination, as indicated by the negative association with the discrepancy of travel time (HR = 0.95, p < 1.8e-6).

Model 2, analyzing timely full vaccination among rural residents, adults (HR = 1.14, p = 3.2e-5) and seniors (HR = 1.11, p = 0.002) were less likely to delay on vaccination. High SVI areas were associated with lower odds of timely vaccination (HR = 0.92, p = 0.026), while the discrepancy in travel time exhibited a strong negative effect, with greater distances leading to delays (HR = 0.9, p = 0.006).

On the other hand, Model 3, focusing on the timing of booster vaccination among urban residents, revealed that males were slightly more likely than females to receive boosters on time (HR = 1.02, p = 0.0067). The positive association between age and vaccination timeliness persisted, with seniors (HR = 2.07, p < 2e-16) significantly more likely to receive booster doses on time. Non-Hispanic individuals (HR = 1.06, p < 5.5e-13) maintained a strong association, while residents in high SVI areas showed a modest positive association with timely booster

Table 2
Statistical results from the CoxPH model analyzing the association between demographic and geospatial factors and time to receive COVID-19 vaccination.

Variables	Category	Discrepancy model (fully vaccine)		Model 1(fully vaccine)			Model 2(fully vaccine)			Discrepancy model (booster)		Model 3 (booster)			Model 4(booster)		
		Coeff.	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)			Coeff.	P-Value	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)
Discrepancy travel time		−0.02 **	0.98(0.96–0.99)	−0.055	7.2e-8***	0.95(0.93–0.97)	−0.019	0.04*	0.98(0.94–1.02)	−0.14 ***	0.86(0.84–0.89)	−0.12	8.9e-16***	0.89(0.86–0.91)	−0.021	0.56	0.98(0.91–1.05)
Sex	Female																
	Male			−0.063	<2e-16***	0.94(0.93–0.95)	−0.05	2.6e-5***	0.95(0.93–0.97)			0.017	0.04*	1.02(1–1.03)	−0.01	0.5	0.99(0.96–1.02)
Age	Young																
	Adult			0.09	<2e-16***	1.1 (1.09–1.12)	0.083	2.45e-8***	1.09(1.06–1.12)			0.43	<2e-16***	1.45(1.5–1.57)	0.39	<2e-16***	1.47(1.41–1.54)
	Senior			0.08	<2e-16***	1.08(1.07–1.1)	0.05	6.2e-4***	1.05(1.02–1.08)			0.73	<2e-16***	2.08(2.03–2.12)	0.67	<2e-16***	1.96(1.88–2.05)
Ethnicity	Hispanic																
	Not Hispanic			0.106	<2e-16***	1.11(1.1–1.13)	0.105	<2e-16***	1.1(1.1–1.12)			0.059	2.4e-12***	1.06(1.04–1.08)	0.06	1.79e-12***	1.06(104–1.08)
Race	Not White																
	White			−0.059	<2e-16***	0.94(0.93–0.95)	−0.059	<2e-16***	0.94(0.93–0.95)			−0.18	<2e-16***	0.83(0.82–0.85)	−0.18	<2e-16***	0.83(0.82–0.85)
SVI	Low																
	Medium			−0.023	9.9e-4***	0.98(0.96–0.99)	−0.03	0.02*	0.97(0.94–1.0)			0.03	5.3e-4***	1.04(1.02–1.06)	0.3	0.055*	1.04(1–1.08)
	High			−0.07	<2e-16***	0.93(0.92–0.95)	−0.12	6.9e-12***	0.88(0.085–0.92)			0.03	0.018*	1.03(1.-1.05)	0.02	0.38	1.02(0.97–1.07)
Urban vs. Rural	Rural																
	Urban			0.057	1.4e-4***	1.06(1.03–1.09)	0.041	0.011*	1.04(1.01–1.08)			0.103	1.08e-5***	1.11(1.06–1.16)	0.102	4.5e-5***	1.11(1.05–1.16)
Sex * Discrepancy travel time							0.021	0.19	1.02(0.9–1.06)						−0.051	0.04*	0.95(0.9–1)
Adult * Discrepancy travel time							−0.019	0.36	0.98(0.94–1.02)						−0.77	0.04*	0.93(0.86–1)
Senior * Discrepancy travel time							−0.045	0.03*	0.96(0.92–1)						−0.1	0.004**	0.9(0.84–0.97)
SVI medium* Discrepancy travel time							−0.02	0.3	0.98(0.94–1.02)						0.003	0.92	1(0.94–1.07)
SVI high * Discrepancy travel time							−0.08	0.0014**	0.92(0.88–0.97)						−0.009	0.8	0.91(0.94–1.06)

Table 3
Statistical results from the CoxPH model analyzing the association between demographic and geospatial factors and time to receive booster COVID-19 vaccination in urban and rural areas.

Variables	Category	Fully vaccine						Booster					
		Model 1(Urban)			Model 2(Rural)			Model3(Urban)			Model 4(Rural)		
		Coeff.	P-Value	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)	Coeff.	P-Value	HR(95 %CI)
Discrepancy travel time		−0.051	1.8e-6***	0.95(0.93–0.97)	−0.10	0.006**	0.9(0.84–0.97)	−0.126	2.9e-15***	0.88(0.85–0.91)	−0.195	9.5e-4***	0.82(0.73–0.92)
SEX	Female												
	Male	−0.06	<2e-16***	0.94(0.93–0.95)	−0.032	0.216	0.97(0.92–1.02)	0.023	0.0067**	1.02(1.01–1.04)	−0.13	0.001**	0.88(0.81–0.95)
Age	Young												
	Adult	0.09	<2e-16***	1.1(1.08–1.11)	0.1	3.2e-5***	1.14(1.07–1.21)	0.43	<2e-16***	1.53(1.5–1.57)	0.51	<2e-16***	1.67(1.49–1.88)
	Senior	0.08	<2e-16***	1.08(1.07–1.11)	0.1	0.002**	1.11(1.04–1.18)	0.72	<2e-16***	2.07(2.02–2.11)	0.86	<2e-16***	2.38(2.12–2.67)
Ethnicity	Hispanic												
	Not Hispanic	0.106	2.7e-12***	1.11(1.1–1.13)	0.091	0.001**	1.1(1.04–1.16)	0.062	5.5e-13***	1.06(1.05–1.08)	−0.02	0.64	1(0.9–1.07)
Race	Not White												
	White	−0.06	<2e-16***	0.94(0.93–0.95)	−0.07	0.012*	0.93(0.88–0.99)	−0.18	<2e-16***	0.84(0.82–0.85)	−0.22	1.4e-7***	0.8(0.74–0.87)
SVI	Low												
	Medium	−0.02	0.001*	0.98(0.96–0.99)	0.015	0.71	1.02(0.94–1.1)	0.03	0.0033**	1.03(1.01–1.05)	0.2	8.6e-4***	1.23(1.09–1.38)
	High	−0.06	<2e-16***	0.93(0.92–0.95)	−0.085	0.026*	0.92(0.85–0.99)	0.03	0.047*	1.02(1–1.05)	0.2	0.005**	1.18(1.05–1.33)

uptake (HR = 1.02, p = 0.047). The discrepancies in travel time continued to play a critical role, with greater distances linked to delays in booster vaccination (HR = 0.88, p < 2.9e-15).

Moreover, Model 4, examining timely booster vaccination among rural residents, showed stronger associations. Males were slightly less likely than females to receive boosters on time (HR = 0.88, p = 0.001), and seniors demonstrated the highest likelihood of timely booster uptake (HR = 2.38, p < 2e-16). Like urban populations, residents in high SVI areas among rural populations exhibited a small positive association with timely vaccination (HR = 1.18, p = 0.005). However, the discrepancy in travel time remained a significant barrier, with greater discrepancies linked to delays in booster uptake (HR = 0.88, p < 9.5e-4). Overall, Table 3 reveals that through urban and rural populations, older adults, particularly seniors, consistently demonstrated higher likelihoods of timely vaccination. Non-Hispanic individuals were more likely to be vaccinated on time than Hispanic individuals in urban settings. Remarkably, discrepancies in travel time were significant barriers across both populations, with stronger effects observed in rural areas. It is obvious that travel time larger than expected in previous doses caused delays in Covid-19 full and booster vaccination.

Although stratified models revealed that travel time discrepancies were more impactful in rural areas, future research could benefit from testing interaction terms between rural/urban status and travel time to further explore compounded geographic effects.

4. Discussions

This study provides a comprehensive analysis of demographic and geospatial factors influencing the delays of full and booster COVID-19 vaccinations in Nueces County, with a unique focus on travel time discrepancies as a determinant of vaccine access. Results stratified by urban and rural populations, along with interaction terms embedded in our models, bring more nuanced insight into access challenges and disparities shaping vaccination uptake. The findings highlight significant disparities in vaccination timeliness driven by demographic, socioeconomic, and geographic barriers.

4.1. Sociodemographic factors

Gender differences were observed, with males generally having more delays than females in receiving their initial doses. Interestingly, males showed slightly better timeliness for booster doses, suggesting evolving behavioral or systemic influences during the later stages of vaccination campaigns. It is important to note that while a similar study in Nueces County found that males had lower booster vaccination rates (Huang et al., 2024), that study used a larger dataset and focused specifically on booster vaccination rates rather than the timing of vaccinations. This difference in study focus and dataset may explain the variation in results. In this study, most of the models showed the trend where males exhibited a lower probability of timely receiving the second dose, as earlier work has already suggested (Bajema et al., 2023). On the other hand, being male was associated differently with the timely receipt of booster shots. This trend aligns with findings from several studies indicating that men generally exhibit greater intentions and uptake of COVID-19 vaccines compared to women (Sileo et al., 2023; Zhu, Zhang, & Wagner, 2023.; Zintel et al., 2023). While these findings align with prior research, further investigation is warranted to explore the underlying causes.

Consistent with previous studies, older adults showed higher rates of timely vaccination for both full and booster doses, likely reflecting targeted public health campaigns. This trend reflects the continued prioritization of older adults in urban and rural campaigns, which is critical given their increased risk of severe outcomes from COVID-19 (Huang et al., 2024; Ioannou, Green, Locke, & Berry, 2021). These results confirm previous studies that identified vaccination priorities set by the FDA and health concerns for high-risk individuals as contributing to these differences among different age groups, specifically for booster doses (Dooling et al., 2021). However, younger populations exhibited lower uptake rates, underscoring the need for tailored strategies to improve their vaccination coverage.

Ethnic and racial disparities were evident, as non-Hispanic individuals and non-White populations demonstrated a higher likelihood of timely vaccination compared to their Hispanic and White counterparts. Earlier studies align with our findings, showing that Hispanic residents experienced higher delays in taking additional COVID-19 doses, which may reflect systemic challenges in outreach, education, or distribution targeting this demographic (Huang et al., 2024). While early work examined racial and ethnic considerations in terms of primary vaccination uptake, our results extend this framing to booster dose timeliness, where disparities persist (Marus et al., 2022). The exact etiology of these disparities is difficult to discern because the data are based on self-reporting, and a significant number of individuals reported mixed race, complicating the interpretation of ethnic and racial differences. These differences likely reflect systemic inequities in healthcare access and vaccine outreach. Targeted interventions, including culturally sensitive education and community-based outreach, are critical to closing these gaps (Kriss et al., 2022).

The SVI was a strong predictor of delayed vaccination, particularly in urban areas. While both SVI and travel time discrepancies are associated with vaccination timeliness, they reflect distinct types of barriers: social versus geographic. High SVI scores, reflecting socioeconomic disadvantages, were associated with lower rates of timely vaccination. This finding is consistent with previous studies that have shown how social vulnerabilities, such as lower socioeconomic status and limited access to healthcare, can delay vaccination uptake (Huang et al., 2024) and decrease overall vaccination rates (Chien, Marquez, Smith, Tu, & Haboush-Deloye, 2024). Although individuals in higher SVI areas appeared to have a higher likelihood of receiving booster shots on time, this association was not statistically significant. This result might be influenced by several factors, such as the potential avoidance of additional medical costs due to fear of infection, which has been shown to significantly increase the intention to get vaccinated in various populations (Mertens et al., 2022; Wong et al., 2020; Yahaghi et al., 2021.). Some studies claimed that the willingness to pay for COVID-19 vaccines in low-income regions highlights the perceived value of vaccination in preventing costly healthcare expenses. Individuals from these areas recognize that avoiding severe illness through vaccination is economically beneficial (Cerda & García, 2021). These findings reinforce the importance of addressing socioeconomic barriers to achieve equitable vaccine distribution.

4.2. Geographic barriers and travel time discrepancies

Among all variables analyzed, travel time discrepancy emerged as one of the strongest and most consistent predictors of delays in both full and booster COVID-19 vaccinations. Unlike static geographic distances, this dynamic metric captures the accessibility gap experienced by individuals in different spatial contexts. Unlike prior studies that mainly examined spatial access, which measured “expected” or “theoretical” accessibility without considering actual travel behavior, our study uniquely introduces a travel time discrepancy metric—capturing the gap between actual travel time and expected spatial accessibility to vaccination sites. This variable offers a more equitable and realistic measure of access, reflecting real-world barriers to timely vaccination. By focusing on timeliness, we not only underscore the operational challenges in vaccine delivery but also emphasize its critical role in ensuring effective immunization during COVID-19 campaigns.

The analysis reveals that travel time discrepancies significantly impacted vaccination timeliness, particularly among rural populations. Similar findings have been reported in other studies, highlighting the need for mobile vaccination units or other outreach strategies to improve access in rural areas (Ioannou, Green, Locke, & Berry, 2021; Murthy et al., 2021; Sun & Monnat, 2022). Our analysis demonstrates a strong negative association between greater travel time from vaccination centers and the likelihood of receiving both full and booster doses on time. The current results confirm that longer travel times significantly reduce vaccine uptake. These findings align with previous studies, which have consistently identified geographical barriers as key constraints to healthcare service utilization, including vaccination facilities (Cochran et al., 2023; Mazar et al., 2023).

Longer-than-expected travel times were associated with delays in both full and booster doses, with rural residents facing the greatest challenges. The current findings suggest that those who needed shorter travel times for their two-initial doses were more likely to complete their booster doses on time, implying proximity as a key determinant in sustaining vaccination uptake. This finding is critical because it highlights an underrecognized but actionable barrier to vaccine access. Time discrepancy reflects the compounded impact of infrastructure, service distribution, and spatial inequality—factors that traditional measures like distance or SVI alone may not fully capture.

Considering earlier studies, the discrepancies between actual and expected travel times can be considered one of the factors notably affecting the timely administration of vaccines, especially booster doses (Mazar et al., 2023; Zhang et al., 2022). To address this issue and improve booster dose uptake, it is essential to focus on better distribution and easier access to vaccination locations (McPhedran et al., 2022). Strategically placing vaccination centers closer to residential or workplace areas could minimize travel-related barriers and promote higher vaccine compliance rates. This approach is especially vital for booster doses, where maintaining accessibility is key to achieving widespread immunity and completing full vaccination regimens. Interventions such as mobile vaccination units or community-based clinics can further address these disparities, ensuring equitable vaccine distribution and improved public health outcomes (Dropkin, 2022).

4.3. Limitations and future research

This study has some limitations. First, it focuses on Nueces County, which may limit the generalizability of findings to regions with different demographic and healthcare characteristics. Second, the analysis did not account for alternative modes such as public transportation. Given that bus services are limited and underdeveloped in most parts of Nueces County, this may have affected accessibility for individuals without access to personal vehicles. However, Nueces County has a high rate of vehicle ownership among residents, with approximately two cars per household. Additionally, reliance on self-reported data introduces potential biases and may not fully account for confounding variables, such as health beliefs or localized outreach efforts. Although we did not apply a predefined threshold for long travel times, descriptive statistics indicated that fewer than 6 % of all individuals traveled more than 30 min to vaccination sites. While this proportion was higher among rural residents (up to 18 % for the first dose), the overall sample size for long-travel-time individuals was not sufficient to significantly affect model results. Additionally, COVID-19 infection rates may influence the timeliness of vaccination uptake. However, due to limited data availability, this study was unable to incorporate infection rate information into the analysis.

Future research should validate these findings across diverse settings and investigate the mechanisms driving the differential effects of travel time across demographic and geographic perspectives. A multiscale analysis could help identify spatial interventions that influence individuals’ decisions to receive the COVID-19 vaccine.

5. Conclusion

This study emphasizes that discrepancies between expected and actual travel times significantly delay COVID-19 vaccination uptake. These discrepancies are not only statistically significant—they are practically meaningful indicators of structural inequities in vaccine accessibility. Our findings suggest that accessibility gaps—such as longer travel distances, high SVI scores, and rural residency—contribute to delays in vaccination uptake and may exacerbate vaccine hesitancy. These barriers disproportionately affect vulnerable populations, highlighting the compounded effect of geographic and socioeconomic inequities on public health outcomes.

The consistently higher vaccination rates among older adults reflect the success of targeted campaigns prioritizing high-risk populations. However, persistent disparities based on ethnicity, race, and geographic location emphasize the need for equitable public health strategies. Hispanic individuals, White populations, and residents in rural or high-SVI areas were particularly impacted, underscoring systemic challenges in healthcare access and outreach. Focusing public health interventions solely on demographic or social factors may overlook critical geographic barriers. By integrating travel time discrepancy into vaccination planning, policymakers can more precisely identify underserved areas and respond with geographically tailored solutions such as mobile clinics or redistributed vaccine sites.

This study underscores the importance of geographically targeted and culturally tailored public health interventions. Expanding vaccination site networks, deploying mobile clinics, and addressing socioeconomic barriers are critical steps to reduce disparities and improve vaccination timeliness across all population segments. By addressing these accessibility gaps, public health efforts can ensure fair and equitable vaccine distribution, ultimately enhancing population immunity and mitigating the impact of future health crises.

CRediT authorship contribution statement

Hossein Naderi: Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Methodology, Investigation, Formal Analysis, Data curation. **Ziba Abbasian:** Writing - original draft, Visualization, Software, Investigation, Formal analysis. **Yuxia Huang:** Writing - review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data Curation, Conceptualization.

Ethical statement

The study protocol was approved by the Institutional Review Board (IRB) of Texas A&M University–Corpus Christi (IRB Number: TAMU–CC–IRB-2022-0448). Informed consent was waived due to the retrospective nature of the study, which utilized anonymized secondary data without identifiable personal information. All data were handled in accordance with applicable regulations and were restricted to adult participants.

Data availability statement

The data used in this study is confidential and not publicly available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2025.101804.

Data availability

The data that has been used is confidential.

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