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Current Patterns of Trauma Center Proliferation Have Not Led to Proportionate Improvements in Access to Care or Mortality After Injury: An Ecologic Study

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AM is chief investigator. **AM**, **JB**, and **SA** drafted the manuscript. **JB** and **SA** conceived the study concept and design, in concert with all authors. All authors had access to the study data, contributed to analysis and interpretation, and reviewed and approved the final manuscript. **AM** had final responsibility for the decision to submit for publication.

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Abstract

Background: Timely access to high level (I/II) trauma centers (HLTC) is essential to minimize mortality after injury. Over the last 15-years there has been a proliferation of HLTC nationally. The current study evaluates the impact of additional HLTC on population access and injury mortality.

Methods: A geocoded list of HLTC, with year designated, was obtained from the American Trauma Society, and 60-minute travel time polygons were created using OpenStreetMap data. Census block group population centroids, county population centroids, and American Communities Survey data from 2005 and 2020 were integrated. Age-adjusted non-overdose injury mortality was obtained from CDC, Wide-ranging Online Data for Epidemiologic Research (WONDER), and the Robert Wood Johnson Foundation (RWJF). Geographically weighted regression models were used to identify independent predictors of HLTC access and injury mortality.

Results: Over the 15-year (2005–2020) study period, the number of HLTC increased by 31.0% (445 to 583), while population access to HLTC increased by 6.9% (77.5% to 84.4%). Despite this increase, access was unchanged in 83.1% of counties, with a median change in access of 0.0% (IQR 0.0 – 1.1%). Population-level age-adjusted injury mortality rates increased by 5.39/100,000 population during this time (60.72 to 66.11/100,000).Geographically weighted regression controlling for population demography and health indicators found higher median income and higher population density to be positively associated with majority (≥50%) HLTC population coverage, and negatively associated with county-level non-overdose mortality.

Conclusions: Over the past 15 years, the number of HLTC increased 31% while population access to HLTC increased only 6.9%. HLTC designation is likely driven by factors other than population need. To optimize efficiency and decrease potential oversupply, the designation process should include population level metrics. GIS methodology can be an effective tool to assess optimal placement.

Level of Evidence: Level IV

Introduction

Appropriate and timely access to care after injury improves survival and functional outcomes. Among the severely injured, best outcomes are achieved when definitive care is provided at high level (Level I/II) trauma centers (HLTC) that are designated by state and/or verified by the American College of Surgeons Committee on Trauma (ACS-COT).[1–3] For the benefits of definitive care at HLTC to accrue at the population level, there needs to be population level access to HLTC care as demonstrated in studies evaluating outcomes within organized state and regional trauma systems.[4–6]

Over the past 15 years, there has been a rapid increase in the number of designated/verified HLTC in the U.S..[7,8] However, there is paucity of research on how this increase impacts population level access to care and injury related mortality. The current study utilizes geographic information systems (GIS) to address this gap in knowledge and aims at: 1) evaluating changes in population level access to HLTC care over time; and 2) determining the impact of timely access to HLTC care on injury mortality. Additionally, the study evaluates demographic and socioeconomic factors associated with HLTC access and injury mortality.

Methods

Study design

Cross-sectional study that utilizes GIS to determine county-level timely (≤60 minutes) access to HLTC and how the access has changed over the study period (2005-2020). Geographically weighted regression (GWR) was employed to associate county level access, injury related mortality and identify demographic and socio-economic factors associated with access to HLTC. Institutional Review Board approval was obtained for this study (Study ID: CHRMS 17-0467).

Reporting of this work adheres to Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (Supplemental Digital Content,) http://links.lww.com/TA/C905.

Data sources

Census block groups were used as the unit of analysis for calculating access. Block group access was then summarized up to the county-level for analyses. The GIS and GWR models were created with data on current (2020) U.S. hospitals, including geocoordinates, trauma center designation, and bed capacity obtained from the Trauma Information Exchange Program (TIEP), which were cross-referenced with State Health Department websites for accuracy.[9] In case of discrepancy, the highest level of designation/verification was assigned to the facility. Historic (2005 and 2012) trauma center designation and geolocation data were obtained from the Penn Injury Science Center.[10] Trauma center data were obtained for the years 2005, 2012, and 2020, covering roughly even intervals during the study period. Helicopter and aeromedical EMS (HEMS) station locations were obtained from the Department of Homeland Security.[11] Additionally, a geocoded set of air rescue stations run by the U.S. Coast Guard was obtained from Jarman et. al.[12]

Census county and block group demographics were obtained from the 2005-2009, 2011-2015, and 2016-2020 American Communities Surveys, and temporally matched to county and block group population centroids obtained from the US Census Bureau (based on 2000, 2010, and 2020 decennial census data).[13,14] Census block groups were utilized to calculate access as they are the smallest geographic unit for which detailed demographic information is available, typically containing 600-3,000 persons. Counties and statistical equivalents (henceforth all referred to as counties) were used to associate variation among their contained block groups to population health outcomes, as they are static across intercensal years and have detailed data available from a variety of sources. Injury mortality rates by bridged race category and year for all U.S. counties were obtained from the CDC Wide-ranging ONline Data for Epidemiologic Research (WONDER).[15] Additional detailed county-level demographic data were obtained from the Robert Wood Johnson Foundation (RWJF) County Health Rankings dataset.[16]

Coverage and Access Time Estimates

OpenStreetMap and the OpenRouteService were used to calculate 60-minute EMS ground transport isochrones around each trauma center.[17] Trauma centers were considered to cover a population centroid that fell within its defined 60-minute drive time isochrone. A 60-minute cutoff was chosen due to the widely studied mortality impact of definitive trauma center care received within this "Golden Hour," though the construct has been contested in large-scale retrospective studies.[7,8,18] HEMS travel time was calculated according to methods described by Jarman et. al, where the straight-line distance from base to centroid, and centroid to hospital was converted to time at a constant flight velocity of 120mph, with added constant delays for dispatch (4.4 minutes), chute (11.9 minutes), and scene time (33.6 minutes).[19]

This methodology of population-level access presumes homogenous injury distribution. To ensure that the results were not skewed due to this assumption, sensitivity analysis was performed using temporally matched, geocoded motor vehicle fatality data from the U.S. Department of Transportation Fatality Analysis Reporting System (FARS) dataset as a measure of real-world traumatic injury distribution.[20]

Population characteristics and mortality

Overlays of population-level demographics from census block groups and counties were utilized to identify demographic and socioeconomic factors predictive of timely trauma center access. Demographic covariates were selected for inclusion based upon previous literature on trauma care access, investigator discretion, collinearity, and significance in univariate models.

Injury mortality rates were calculated to include only non-overdose deaths, as identified by International Classification of Disease, Tenth Revision (ICD-10) underlying cause-of-death code. Codes X40–44 (unintentional overdose), X60–64 (suicide by overdose), X85 (homicide by overdose), or Y10–Y14 (overdose, undetermined intent) were excluded.[21]

Statistical analysis

Generalized binomial and Poisson GWRs were utilized to estimate county-level factors associated with access (measured by EMS ground transport coverage to a trauma center within 60-minutes), and the impact of trauma center access on injury mortality rates (per 100,000). For the global access model, data was available for 3,133 (97.27%) counties and for the mortality model, 2020data was available for 1,632 (50.67%) counties. Longitudinal mortality data covering 2005 through 2020 was only available for 1,359 (42.19%) counties. This discrepancy is due to limitation of the WONDER dataset that suppresses mortality data from counties with ≤10 fatalities. Counties with suppressed fatality numbers are sparsely populated representing ≤10% of the U.S. population and hence unlikely to affect the analysis. Spatial dependence was assessed using Moran's i, and was accounted for in GWR models, as described by Fotheringham et. al.[22] An adaptive bisquare kernel was used to determine bandwidth and coefficients for each model, allowing for individual county regression parameters. Variance inflation factor (VIF) was used to assess local and global multicollinearity - variables with a VIF ≥ 10 were stepwise removed from the model until no variable had a VIF ≥ 10.

All covariates except population density and median income were entered into the model as rates per 100 (percentages). Median income was scaled to $1,000s (e.g., 52,000 became 52), while population density was unscaled (persons per square kilometer). Following model estimation, coefficients were exponentiated into incidence rate ratios (IRRs). All analyses were conducted in R 4.2.1, using OpenStreetMap for routing, GWmodel for GWR analysis, dplyr for data manipulation, ggplot and tmap for map creation, and Stargazer and kableExtra for table generation.[23–30] Group comparisons were performed using chi-square and ANOVA for categorical variables, and t-tests for normally distributed continuous variables and non-parametric tests for not normally distributed variables as appropriate.

Results

Changes in Access

The 3,133 counties included in the analysis contained 211,005 and 242,335 block groups in 2005 and 2020, respectively. During the 15-year (2005-2020) study period, the U.S. population grew by 12.41%, from 295,516,599 to 331,449,281 and the included counties contained 99.51% of the 2020 U.S. population. In the same period, the numbers of HLTC increased by 31.01% (445 to 583). HLTC growth by year is visualized in Supplemental Digital Content, Appendix A1, http://links.lww.com/TA/C906. HLTC proliferation was not temporally constant, adding only 13 centers from 2005 to 2012: 90.59% of the growth in HLTCs occurred in the latter half of the study period (2012 to 2020). Despite this significant increase in the numbers of HLTC, population access to HLTC care within 60 minutes by ground ambulance grew by only 6.9% (from 77.5% in 2005 to 79.07% in 2012, and to 84.4% in 2020).

When HEMS coverage was added to these estimates, population access improved only marginally (adding 1.8% coverage in 2005, 1.4% in 2012, and 0.8% in 2020). Socio-demographic details of counties categorized in access quartiles are presented in Table I. In general, when compared to counties in the highest quartile of coverage, counties in the lowest quartile were more rural (70.8% vs 38.1%), had a greater proportion of population identifying as white (81.4% vs 79.8%), had lower median household income (US $47,707 vs US $60,701), worse (fair or poor) overall health status (18.7% vs 16.8%), and higher rates of uninsured (12.6% vs 9.9%) - $p<0.05$ for all.

To compare counties with changing or static coverage over time, counties that changed overall access by at least one quartile were considered expanding if coverage increased by at least one quartile, contracting if coverage decreased by at least one quartile, and static if the coverage did not change. Even though overall U.S. population access to HLTC improved by 6.9%, at the county level, the change in access was not uniform. Access expanded in 409 (12.7%), contracted in 142 (4.2%) and was static in the remaining 2649 (83.1%) counties (Figure 1).

Among the expanding counties, population-level access increased by a median 63.6%, while in contracting counties, population-level access decreased by a median31.5% (Table 2). When expanding and contracting counties were compared in terms of socio-demographics, expanding counties resembled counties in the highest access quartile, and the contracting counties were similar to the lowest access quartile (Tables 1 and 2).

Injury Related Mortality

The overall age-adjusted, non-overdose injury related mortality across the U.S. increased from 60.72/100,000 population in 2005 to 66.11/100,000 population in 2020. At the county level, there was a serial decrease in mortality across the access spectrum (Table 1) with the highest mortality observed in counties falling in the lowest access quartile, and the lowest mortality observed in those in the highest access quartile ($p<0.001$). In line with the national increase in injury related mortality, increased mortality was observed in counties with expanding, contracting or static coverage. However, the greatest increase in mortality was observed in counties with contracting coverage (from 64.3 to 72.4/100,000 population) and the lowest increase in counties where coverage was expanding (from 65.5 to 69.6/100,000 population) - $p<0.05$ (Table 2).

Geographically Weighted Regression

Both HLTC access and injury mortality were found to be spatially dependent via Moran's i (0.595 and 0.390 respectively), strongly suggesting the inclusion of geography in these models. In the global binomial model of county level HLTC access, higher median income (IRR 1.53, 95% CI 1.404, 1.690) and higher population density (IRR 7.234, 95% CI 5.120, 10.428) were found to be associated with majority (≥50%) HLTC population coverage. Rurality (IRR 0.938, 95% CI 0.902, 0.975), higher proportion aged ≥65 (IRR 0.520, 95% CI 0.409, 0.657), and higher proportion uninsured (IRR 0.669, 95% CI 0.551, 0.811) were predictive of minority (<50%) population HLTC coverage (Table 1). Counties with majority (≥50%) HLTC access had lower non-overdose injury-related mortality (IRR 0.933, 95% CI 0.921-0.946).

Additionally, counties with higher median income (IRR 0.912, 95% CI 0.907-0.917) and higher population density (IRR 0.992, 95% CI 0.991-0.993) had lower mortality. Conversely, counties that were more rural (IRR 1.041, 95% CI 1.038-1.044), with higher proportion of population ≥65 years (IRR 1.027, 95% CI 1.011-1.043), with higher proportion uninsured (IRR 1.067, 95% CI 1.052-1.081) and with higher proportion of non-whites (IRR 1.069, 95% CI 1.065-1.073) had higher injury mortality (Table 1). The higher mortality observed among non-whites was despite overall greater access. Maps displaying the spatial variation in GWR local model coefficients are available in Supplemental Digital Content, Appendix A2-A7, http://links.lww.com/TA/C906.

Sensitivity Analyses

Estimated HLTC coverage of ultimately fatal motor vehicle collisions (MVCs) reported to the U.S. Department of Transportation was universally lower than estimates derived from population centroids. In 2005, 66.44% of fatal MVCs occurred within 60 minutes of HLTC access by ground EMS. In 2012, this had increased by 0.57% to 67.01%; by 2020 it increased another 9.23% to 76.15% of MVCs. These measures are a relative 14.32%, 15.25%, and 9.80% lower than their corollary 2005, 2012, and 2020 population-level estimates of HLTC coverage. This suggests that while population-based models are not perfect due to the assumption of uniform injury distribution, they function well as a "best guess" of the true injury location coverage, bolstering the validity of these methods. A detailed summary of coverage estimates by facility, transport type, and data-year are available in Table 2.

Comparative population-level mortality data in rural counties was often censored for privacy, leading to a high degree of missingness for cross-year comparisons, and in turn a risk of biased model results. However, with these counties being highly rural, cross-year mortality data was available for more than 90% of the U.S. population, minimizing the effect of this bias. To test this assumption using a naïve approach to imputation, we ran the global models including these missing-data counties. These counties were assigned an injury mortality rate equivalent to the population mean for low access counties (79.2 / 100,000, Table 1). The new imputed model coefficients carry similar sign, significance, and scale to previous models, apart from age > 65, which returns as non-significant (likely being collinear with rurality). Our main independent variable (majority HLTC coverage) remains consistent in effect size, significance, and sign. We take this to suggest that our exclusion of these counties, though their mortality data is not missing completely at random due to rurality, is not likely to impact the validity of our models as presented.

Discussion

Summary of results

The current study describes national changes in trauma center access within 60 minutes in the United States, over a 15-year period spanning 2005-2020. Analysis was carried out using a population-level spatial accessibility and injury-covering model, which could inform assessment and direction of U.S. trauma systems.[31] Despite a 31.0% increase in the number of HLTC during the study period, population coverage increased by only 6.9%. Addition of HEMS into this model resulted in minimal coverage gains. We posit that this difference between the large increase in trauma centers and a much smaller gain in population level access is a factor of location: the vast majority of newly designated/verified HLTC were co-located inside of existing coverage areas.

Geographically-weighted regression uncovered strong sociodemographic predictors of county-level HLTC access and non-overdose injury mortality. In global models, densely-populated, high-income, younger, insured, and urban communities had greater access to prompt HLTC care. Strong independent predictors of lower county-level injury mortality included high median income, younger age distribution, low rurality, and a lower non-white population percentage. Controlling for these factors, counties with higher HLTC coverage had lower injury mortality.

Contextualization with the literature

Evaluating predictors and barriers to trauma center care access and identifying geographic disparities can facilitate objective and data-driven trauma system planning.[8,32,33] National trauma center access and geographic trends over time have not been well studied, and there is discordance among the few reports covering this topic. Geographic access to trauma centers was first comprehensively described in 2005 by the Trauma Resource Allocation Model for Ambulances and Hospitals (TRAMAH) project, which found that an estimated 69.2% and 84.1% of all US residents had access to a HLTC within 45 and 60 minutes, respectively.[7]

In a recent cross-sectional study of U.S. trauma center access an estimated 22.8% of the population was found to lack access to any trauma center within 60 minutes, and the proportion of the population with timely access was reported to not improve significantly between 2010 and 2019.[19] Another geographic analysis evaluating 60 minute access to ACS-COT verified trauma centers found an increase in population coverage between 2013 and 2019 from 78 to 91% respectively.[34] While the current study's findings of population level access improvement is more congruent with the latter of these two reports, we found that the increased designation/verification of HLTC between 2005 and 2020 resulted in a disproportionately lower improvement in population coverage.

There are few studies that have evaluated the association between population level timely HLTC access and injury mortality, and no study that we are aware of has done so with county-level granularity. In a state-level analysis of adult trauma deaths reported to the CDC (1999 to 2016), states with more HLTC access had a lower age-adjusted mortality rate, and states with a high pre-hospital death burden had a lower proportion of population with access to HLTC within 60 minutes.[8] The current study validates this association by demonstrating a univariate and multivariate reduction in county-level age-adjusted injury mortality as HLTC access increases. This relationship has been challenged by conflicting studies, which have found minimal effects of trauma center and EMS care falling within the 60-minute "Golden Hour," emphasizing the need for higher level evidence to form a clear picture of this relationship.[35–37]

When controlling for geographic and demographic factors, the current study found that higher median income is significantly associated with HLTC access and lower age adjusted injury mortality. Additionally, at the county level as the proportion of uninsured population increased there was significantly less access and higher mortality. These findings taken together suggest that economic drivers as opposed to population benefit likely play a major role in hospitals seeking HLTC designation/verification. A cross-sectional geographic study in the state of Maryland found that odds of death decreased by 27% when neighborhood per-capita income was greater than $25,000, supporting the finding that socioeconomically disadvantaged counties have worse outcomes.[38] In addition to median income, the current study also supports the findings of multiple other studies that there are significant geographic and socioeconomic disparities in access to trauma center care within the U.S..[19,33,38–43]

Despite greater access to HLTC, after controlling for other factors, counties with higher proportion of non-whites had higher non-overdose injury mortality incidence. Racial disparities in access to HLTCs have been demonstrated in three major U.S. cities in small-area analyses of trauma deserts, defined as travel distance >5 miles to the nearest HLTC. These analyses found that black majority census areas are more likely than white majority areas to be located within a trauma desert in Chicago, Los Angeles and New York.[44] Independent of other socioeconomic factors, it has been demonstrated that black patients experience higher odds of trauma mortality in comparison to white patients.[42] Strong advocacy is needed for targeted solutions to resolve racial and socioeconomic inequities among injured patients.[45]

In the context of U.S. public policy, the passage of the 2010 Affordable Care Act saw massive changes to funding and evaluation structures available to hospital systems. One such change relevant to this study was the allocation of increased funding for trauma care centers in the form of federal grants and uncompensated care awards.[46] A 2022 meta-analysis found that the implementation of the ACA was associated with increased post-acute care access, but had limited effect on trauma mortality.[47] In their 2017 paper, Scott et. al. estimated that the expanded insurance coverage offered by the ACA has the potential to increase national reimbursement for inpatient trauma care by over $1 billion.[48] This finding suggests that ACA provisions may have afforded economic viability for the expansion of trauma care centers nationwide. Our present study bolsters these findings, with the majority (90.59%) of growth in HLTC occurring from 2012-2020, after the ACA was enacted. Although direct causality cannot be made between the ACA and the rapid growth in HLTC, future work with state-level claims data could be conducted to elucidate this relationship.

Way Forward

For optimized trauma system design, data-driven approaches with geographic and population need based analyses should be considered when allocating resources and center designation.[33,49] Establishing new trauma centers without identification of populations in greatest need could compromise the quality of regional trauma care by generating oversupply and competition while neglecting underserved areas.[45] ACS-COT advocates that trauma center designation be based upon the needs of the population, rather than the needs of individual health care organizations or hospital groups, and HLTC designation be balanced, fair, and equitable.[49]

While the addition of new trauma centers is an appropriate means of improving access to timely trauma care, other strategies should also be considered. Hospital systems must approach increasing access to trauma from a multifocal lens, including discussions about the roles Emergency Medical Services (EMS), barriers to transportation and trauma training protocols. A systematic review found that shorter transfer-time and swift transport to the care facility by EMS is associated with a decreased odds of mortality.[50] Current literature demonstrates that transportation barriers pose a credible threat to timely access to care, particularly among uninsured and lower income communities.[51]

The findings of the current study clearly demonstrate that factors other than the needs of the population are the primary drivers of new HLTC designation/verification. The Needs Based Assessment of Trauma Systems (NBATS) has been proposed as an objective method of assessing where additional trauma centers and EMS resources should be located.[52] The current study demonstrates that geospatial analysis can inform objective, data-driven trauma system organization and supplement NBATS methodology.

Based on the findings of the current study, actionable areas for trauma system planning should focus on: 1) regions with high injury mortality that have low population access to HLTC (Red in Figure 2) that will benefit from additional HLTC designation; and 2) regions with both high access and high injury mortality (Purple in Figure 2) likely represent either a disproportionate number of non-survivable injuries (e.g. firearm injury) or poor system performance. These areas will benefit from performance improvement programs and strong injury prevention initiatives.

Additional studies focusing on specific regions and discrepancies in access and outcomes could facilitate the identification of gaps and approaches for targeted interventions and outcome improvement. State and regional studies could help to objectively and appropriately identify specific facilities for targeted HLTC upgrades and improved population access. Future investigations could also explore barriers to upgrading existing hospitals to HLTC in regions with low access and high mortality rates.

Limitations

Like all studies, the current study has limitations. First, the model estimates for ground access are based on estimated road network EMS travel time, and due to data availability cannot be compared with similar, real-world EMS data. To mitigate this limitation, models were calculated using OpenStreetMap's transport layer, which is well validated and commonly used in this setting.[53–56] Additionally, though the HEMS time estimates include scene, chute, and response time, ground EMS estimates do not. Thus, our coverage estimates represent a "best-case" scenario with instant ground EMS availability, and true population coverage is likely lower than our estimates.

Second, WONDER and RWJF age-adjusted county-level injury mortality rates have been utilized, as opposed to individual-level, risk-adjusted data points. This limitation is common to cross-sectional studies of this nature and introduces the possibility of ecologic fallacy influencing the measured associations. Due to this potential bias, results from cross-sectional studies should be interpreted with some caution and their associations tested for replicability and causal directionality

Third, population centroid density moderately correlates with optimal EMS base locations, and does not mirror actual geographic injury density as evidenced by our sensitivity analysis.[56] Future studies of this nature should attempt to obtain incident location information to better calibrate coverage estimates. These calibrated models could employ multiple weighting methods to obtain a confidence interval of coverage for multiple mechanisms of injury, better reflecting the landscape of care.

Conclusions

Over the past 15 years, despite a 30% increase in the number of HLTC, population access increased by only 7%. Counties with expanding HLTC access experienced lower age-adjusted injury mortality rates. Prioritization of HLTC expansion should occur in regions with high mortality and low population coverage, while targeted quality improvement and/or injury prevention programs could benefit regions with both high population HLTC coverage and injury mortality. GIS methodology can be a vital tool in objectively identifying existing centers that, if upgraded to HLTC, would benefit the population maximally.

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Figure Legends

Figure 1: Visualization of the percentage change in county-level access to ground HLTC care within 60 minutes between 2005 and 2020. Counties with increased coverage are lighter (yellow), decreased coverage darker (purple), and counties with constant coverage are in between (green).

Figure 2: Bivariate map comparing tertiles of county-level HLTC coverage and non-overdose injury mortality. Counties with increased coverage are lighter blue, and those with higher injury mortality darker red. Counties with high injury mortality, and low HLTC coverage will be only dark red, while those with high coverage and low mortality only light blue. Counties falling in the middle are categorized by the respective hue in the legend.

Supplemental Digital Content

SDC 1. STROBE Checklist

SDC 2. Appendix

A1: High Level Trauma Center Growth by Year and Level

A2-A7: Geographically Weighted Local Model IRR, P-Value, and Covariate Maps

A2: Age >= 65

A3: Median Income

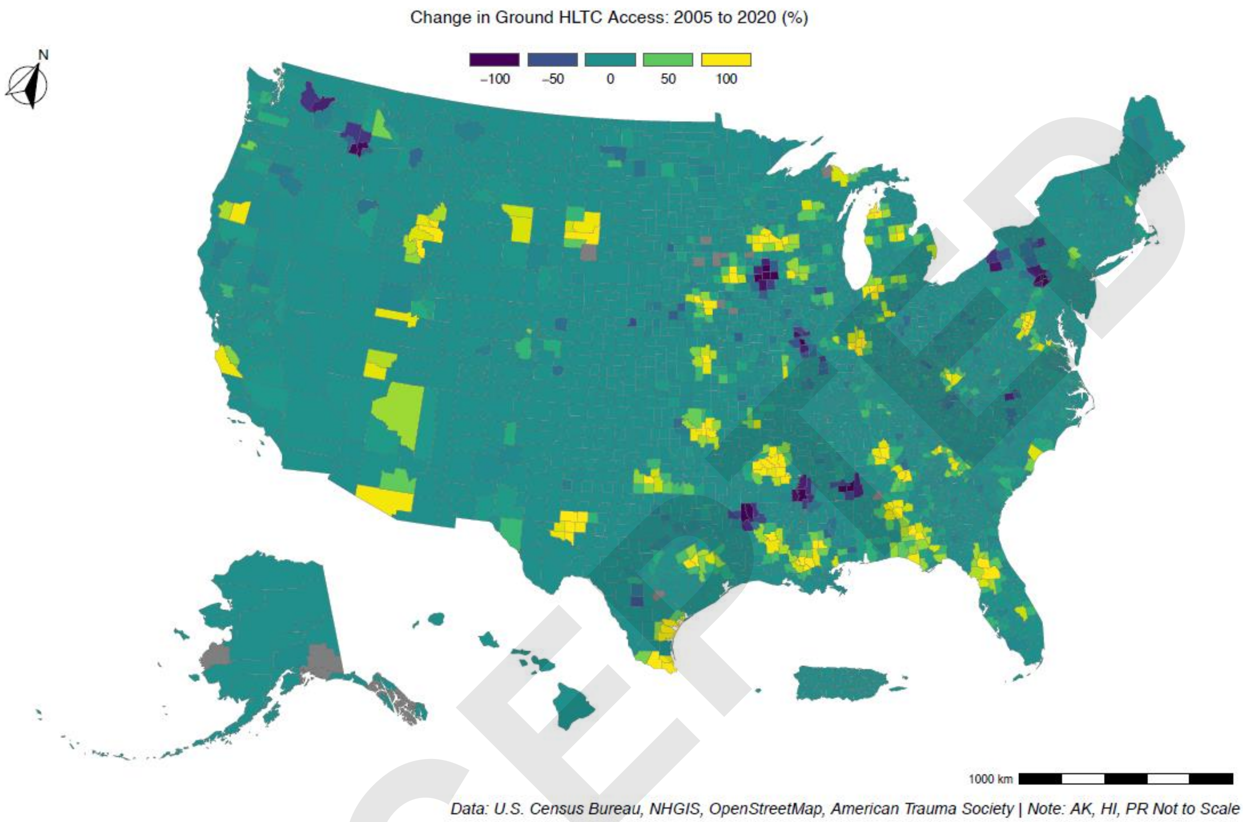
A4: Non-White Population

A5: Population Density

A6: Rural Population

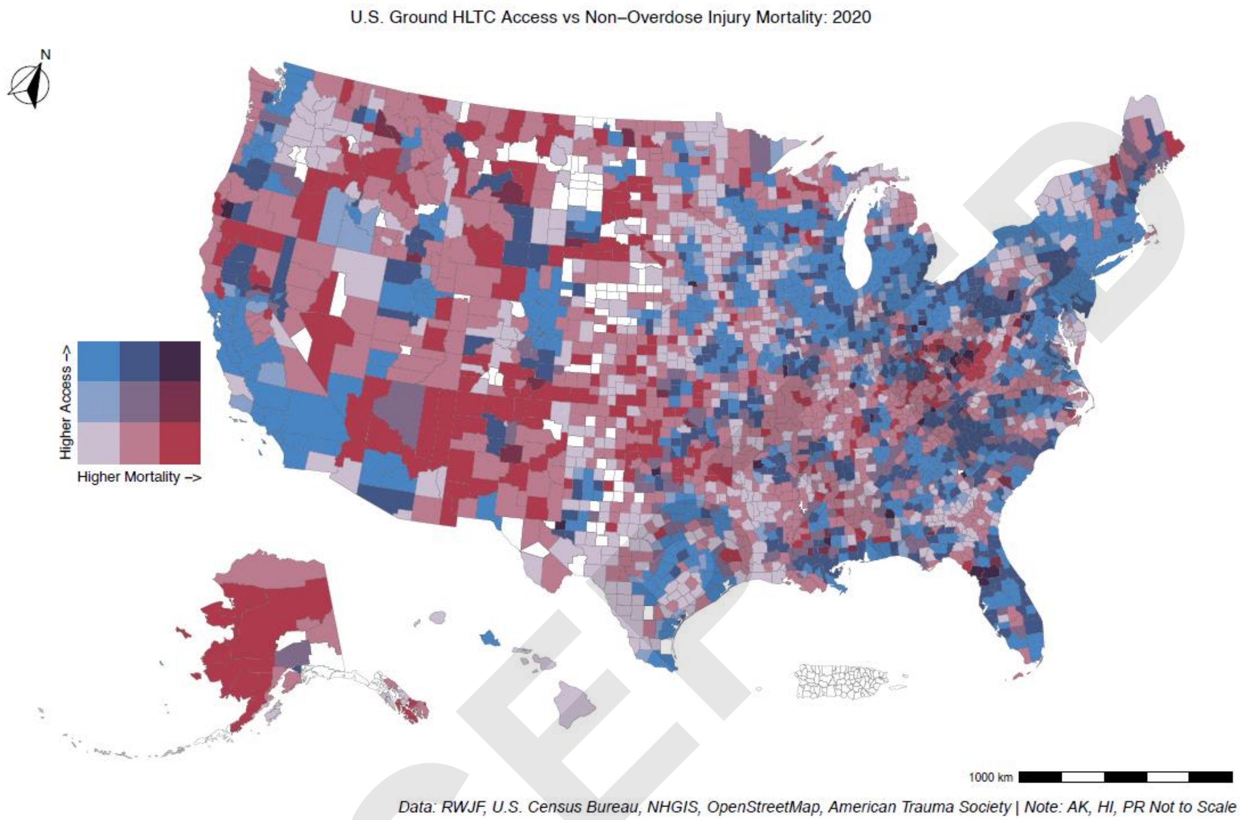
A7: Uninsured Population

Figure 1



Change in Ground HLTC Access: 2005 to 2020 (%)
N
−100
−50
0
50
100
1000 km
Data: U.S. Census Bureau, NHGIS, OpenStreetMap, American Trauma Society | Note: AK, HI, PR Not to Scale

Figure 2


U.S. Ground HLTC Access vs Non–Overdose Injury Mortality: 2020
N
Higher Access ->
Higher Mortality ->
1000 km
Data: RWJF, U.S. Census Bureau, NHGIS, OpenStreetMap, American Trauma Society | Note: AK, HI, PR Not to Scale

		HLTC Access Quartile				
County Characteristic (2020)	Overall	0-24%	25-49%	50-74%	75-100%	Missing (%)
n	3221	1668	181	223	1149	
Injury Deaths per 100,000*[a]	64.8 [51.9, 81.2]	78.2 [62.9, 94.9]	72.6 [62.1, 84.5]	69.7 [57.8, 86.6]	57.5 [47.3, 70.6]	49.3
Race: White, %	81.2 (17.3)	81.4 (18.7)	84.1 (15.6)	84.6 (15.1)	79.8 (15.7)	0.0
Age Over 65, %	19.3 (4.7)	20.6 (4.9)	20.0 (3.6)	19.4 (3.8)	17.2 (4.0)	2.5
Population Rurality, %	58.6 (31.5)	70.8 (27.5)	73.0 (23.0)	65.5 (22.6)	38.1 (28.5)	2.7
Median Income, $USD[a]	50,566.5 [43,680.5, 58,840.5]	46,930.0 [40,795.0, 53,187.5]	50,376.0 [43,755.0, 55,334.0]	49,344.0 [43,946.0, 56,779.0]	57,675.0 [50,122.0, 67,434.0]	2.5
Fair or Poor Health Status, %	17.9 (4.7)	18.7 (5.2)	18.5 (4.6)	18.4 (4.7)	16.8 (3.8)	2.5
Uninsured, %	11.5 (5.1)	12.6 (5.3)	11.3 (4.9)	11.4 (4.9)	9.9 (4.5)	2.5

Note:

Differences between groups are all significant at $p < 0.05$

All variables are summarized as Mean (Standard Deviation) unless otherwise specified
[a] Described using Median [Interquartile Range]

Data Sources: CDC WONDER, U.S. Census Bureau, Robert Wood Johnson Foundation, OpenStreetMap, NHGIS

*WONDER Data at the county level are only available for counties with at least 10 fatalities

Table 1: *County Characteristics by Ground HLTC Access: 2020.* Descriptive statistics of U.S. counties as of 2020, stratified by ground HLTC access in 2020. Means, medians, ranges, standard deviations, and missingness is reported for each variable, as well as the total across all counties, regardless of coverage status.

		HLTC Access Change			
County Characteristic	Overall	Contracting	Static	Expanding	Missing (%)
n	3221	142	2649	409	
Injury Mortality Change ('20 - '05), Rate*[a]	4.9 [-4.1, 15.1]	8.8 [0.1, 16.7]	4.9 [-3.7, 15.1]	3.3 [-5.7, 15.1]	57.8
HLTC Access Change ('20 - '05), %[a]	0.0 [0.0, 1.1]	-31.5 [-68.5, -17.6]	0.0 [0.0, 0.0]	63.6 [32.8, 90.5]	0.7
Race: White, %	81.2 (17.3)	82.8 (18.8)	81.1 (17.5)	82.0 (15.1)	0.0
Age Over 65, %	19.3 (4.7)	19.3 (3.5)	19.3 (4.8)	19.2 (4.8)	2.5
Population Rurality, %	58.6 (31.5)	62.2 (27.3)	58.2 (32.2)	59.7 (27.9)	2.7
Median Income, $USD[a]	50,566.5 [43,680.5, 58,840.5]	50,187.5 [44,375.2, 56,047.2]	50,391.5 [43,495.8, 59,265.8]	51,487.0 [44,903.0, 57,676.0]	2.5
Fair or Poor Health Status, %	0.2 (0.0)	0.2 (0.1)	0.2 (0.0)	0.2 (0.0)	2.5
Uninsured, %	11.5 (5.1)	10.1 (4.2)	11.5 (5.2)	11.9 (5.1)	2.5
Note:					
Differences between groups are all significant at p = 0.05					
All variables are summarized as Mean (Standard Deviation) unless otherwise specified. [a] Described using Median [Interquartile Range]					
Data Sources: CDC WONDER, U.S. Census Bureau, Robert Wood Johnson Foundation, OpenStreetMap, NHGIS					
*WONDER Data at the county level are only available for counties with at least 10 fatalities					

Table 2: County Characteristics by Ground HLTC Coverage Change: 2005-2020. Counties which changed from a lower quartile in 2005 to a higher one in 2020 were considered "Expanding," while those which changed from a higher quartile to a lower one were considered "Contracting." Those which did not change access quartile were considered "Static." Means, medians, ranges, standard deviations, and missingness is reported for each variable, as well as the total across all counties, regardless of coverage status.

	Model	
	≥50% HLTC Access (y/n)	*Injury Mortality Rate (per 100K)*
≥50% HLTC Coverage (y/n)		0.933^{***} (0.921, 0.946)
Race: Non-White (%)	0.998 (0.933, 1.066)	1.069^{***} (1.065, 1.073)
Population / sq.km	7.234^{***} (5.120, 10.428)	0.992^{***} (0.991, 0.993)
Rurality (%)	0.938^{***} (0.902, 0.975)	1.041^{***} (1.038, 1.044)
Median Income ($1,000 USD)	1.539^{***} (1.404, 1.690)	0.912^{***} (0.907, 0.917)
Population Over 65 (%)	0.520^{***} (0.409, 0.657)	1.027^{***} (1.011, 1.043)
Uninsured (%)	0.669^{***} (0.551, 0.811)	1.067^{***} (1.052, 1.081)
Intercept	0.338^{**} (0.145, 0.787)	77.515^{***} (73.454, 81.804)
Observations	3,133	1,632
Log Likelihood	−1,540.590	−8,378.057
Akaike Inf. Crit.	3,095.180	16,772.110
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 3: Independent Predictors of County-Level HLTC Access and Injury Mortality. Global model results from binomial and Poisson GWRs predicting ≥% HLTC coverage and injury mortality rate, respectively. All output is shown as IRR (95% CI). IRRs for race, rurality, population age, and uninsured rate represent a 10% increase in the predictor. The IRR for population density reflects a 100 persons/(km^2) increase, and IRR for median income represents a $10,000 increase.

Level	Coverage Estimate Type							
	Population Centers (%)				MVC Fatality (%)			
	2005	2012	2020	Diff.	2005	2012	2020	Diff.
Ground & HEMS								
Level I	66.85	67.72	70.72	3.87	53.59	54.13	59.64	6.05
Level II	63.20	64.63	72.47	9.27	51.09	51.81	62.80	11.71
Level I/II	79.30	80.51	85.21	5.91	68.28	68.45	77.05	8.77
Ground								
Level I	65.96	67.29	70.71	4.75	52.85	53.88	59.64	6.79
Level II	57.95	59.99	70.03	12.08	46.63	47.91	60.05	13.42
Level I/II	77.54	79.07	84.42	6.88	66.44	67.01	76.15	9.71
HEMS								
Level I	22.38	21.60	21.75	-0.63	13.19	13.27	15.40	2.21
Level II	12.18	12.45	12.95	0.77	8.03	8.23	9.23	1.2
Level I/II	27.02	26.58	27.03	0.01	16.90	17.19	19.53	2.63
Note:								
Differences between groups are all significant at $p < 0.05$								
Data: Fatality Analysis Reporting System, U.S. Census Bureau								

Table 4: Change in U.S. County-Level Trauma Center Access, 2005-2020. This table shows the change in TC access between 2005, 2012, and 2020, for each level of TC, as well as grouped I/II (HLTC), broken out by Ground access, Air access (HEMS), and combined (Ground + HEMS access).

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation
Title and abstract	1 ✓	(*a*) Indicate the study's design with a commonly used term in the title or the abstract
	✓	(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found
Introduction		
Background/rationale	2 ✓	Explain the scientific background and rationale for the investigation being reported
Objectives	3 ✓	State specific objectives, including any prespecified hypotheses
Methods		
Study design	4 ✓	Present key elements of study design early in the paper
Setting	5 ✓	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6 ✓	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants
Variables	7 ✓	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources/ measurement	8* ✓	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9 ✓	Describe any efforts to address potential sources of bias
Study size	10 ✓	Explain how the study size was arrived at
Quantitative variables	11 ✓	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why
Statistical methods	12 ✓	(*a*) Describe all statistical methods, including those used to control for confounding
	✓	(*b*) Describe any methods used to examine subgroups and interactions
	✓	(*c*) Explain how missing data were addressed
	✓	(*d*) If applicable, describe analytical methods taking account of sampling strategy
	✓	(*e*) Describe any sensitivity analyses
Results		
Participants	13* ✓	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed
	✓	(b) Give reasons for non-participation at each stage
	✓	(c) Consider use of a flow diagram
Descriptive data	14* ✓	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders
	✓	(b) Indicate number of participants with missing data for each variable of interest
Outcome data	15* ✓	Report numbers of outcome events or summary measures
Main results	16 ✓	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included
	✓	(*b*) Report category boundaries when continuous variables were categorized
	✓	(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17 ✓	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses

Discussion		
Key results	18 ✓	Summarise key results with reference to study objectives
Limitations	19 ✓	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20 ✓	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalisability	21 ✓	Discuss the generalisability (external validity) of the study results
Other information		
Funding	22 ✓	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

Supplemental Digital Content

A1: HLTC Growth by Year & Level

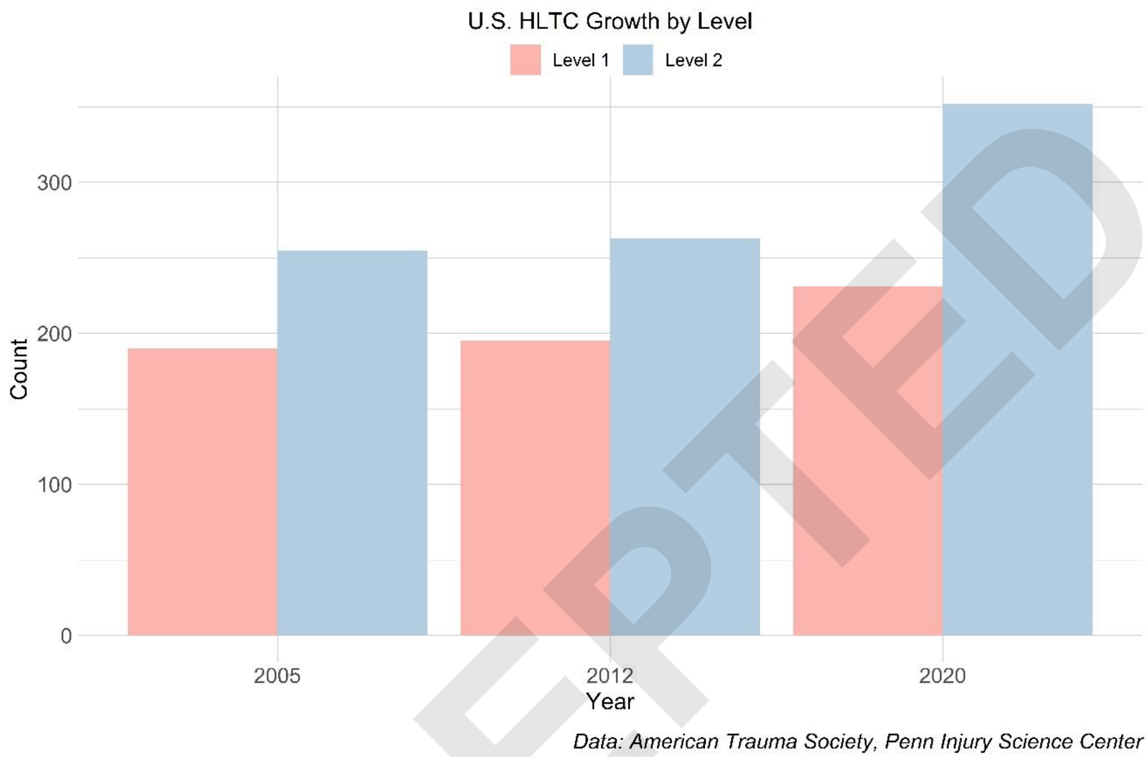


Figure A1: Number of high level trauma center (HLTC) designated hospitals in the United States by year. Level 1 designated hospitals are in red, Level 2 in blue. Data were obtained from the American Trauma Society and the Penn Injury Science Center.

A2-A7: GWR Local Model IRR, P-value, and Covariate Distributions

Shown in Appendices 2-7 are maps of local GWR IRR and P-value for each variable in the presented models (HLTC access and per-capita injury mortality). Subplot A shows the geographic distribution of the IRR in the access model, C shows the injury model. Lighter green colors show a positive association (faster HLTC access, or higher injury), while darker red shows a negative association (slower HLTC access, or lower injury). Subplots B and D show the local p-values for the associations in plots A and B, respectively, with deeper purple indicating lower p-value for significance. Subplot E shows the distribution of the covariate at the county level.

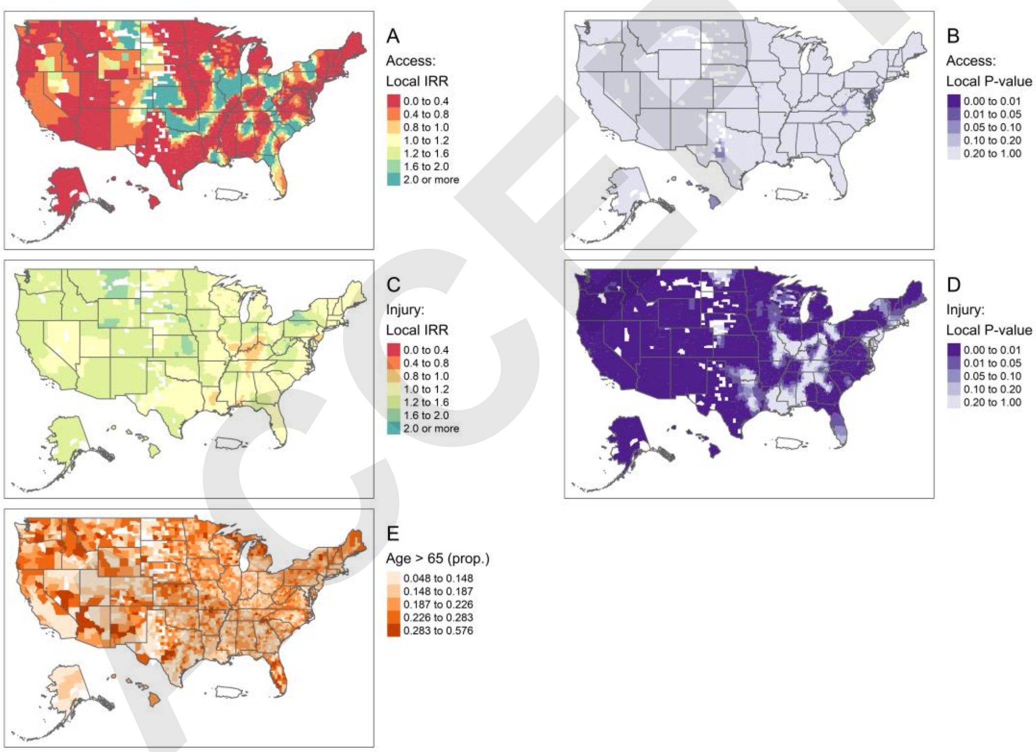


Figure A2: Age ≥ 65 (%)

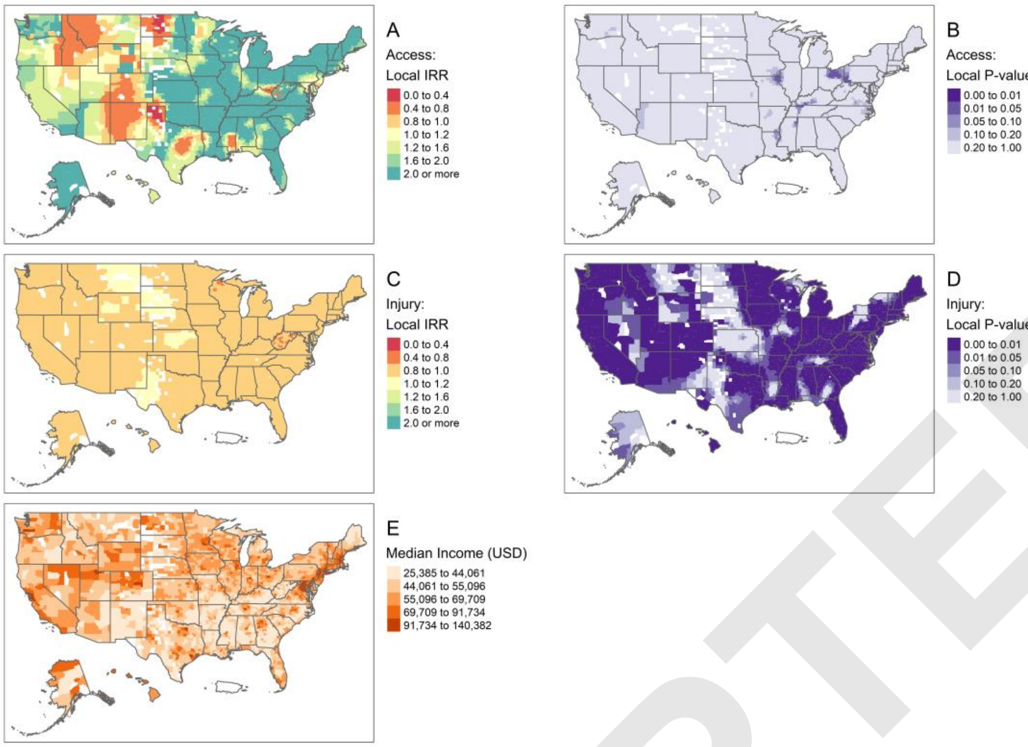


Figure A3: Median Income (USD)

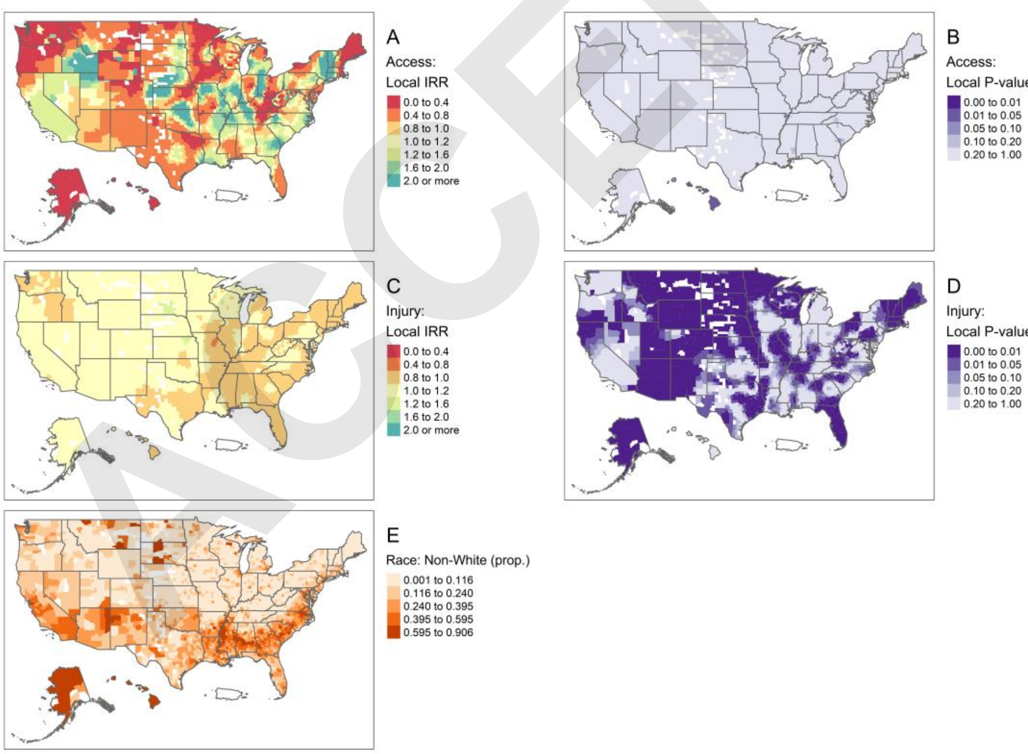


Figure A4: Non-White Population (%)

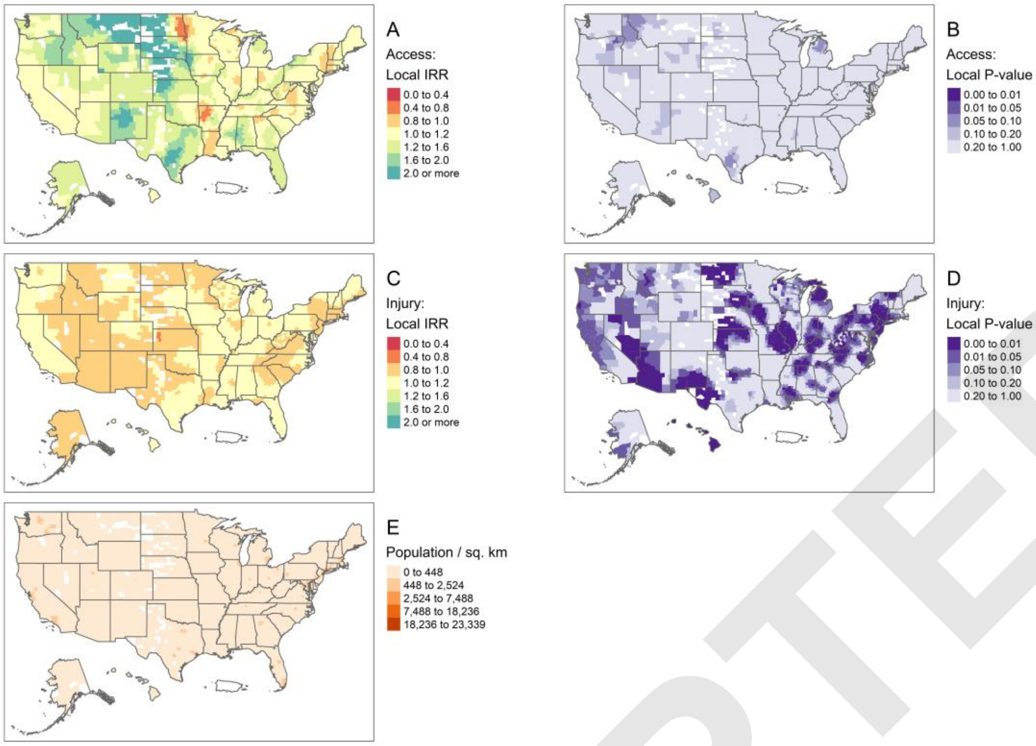


Figure A5: Population Density ($\frac{persons}{km^2}$)

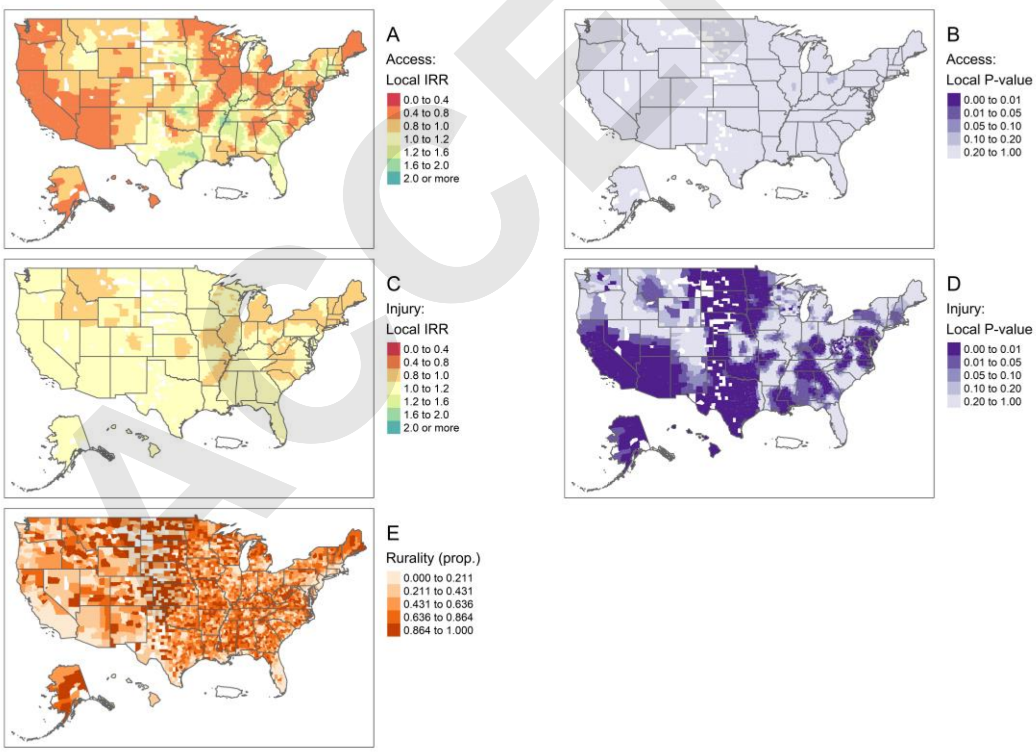


Figure A6: Rural Population (%)

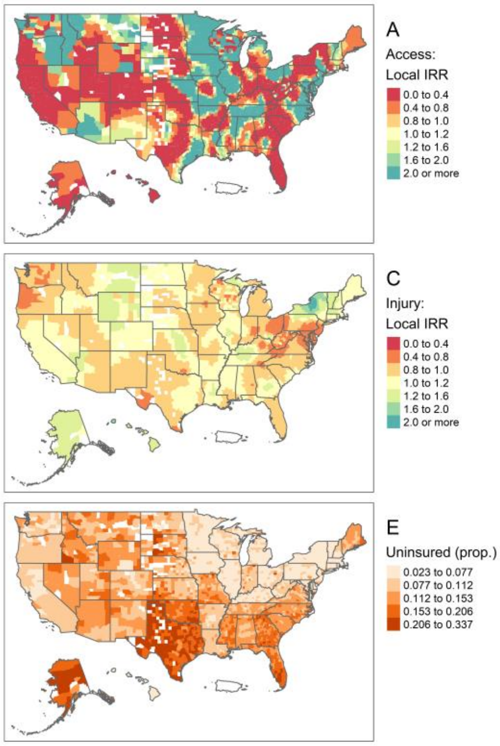
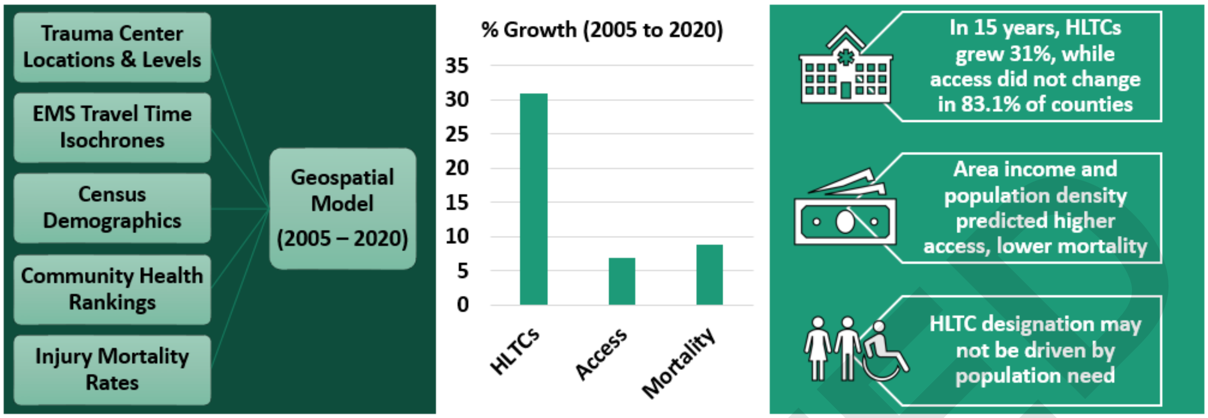


Figure A7: Uninsured Population (%)

Current Patterns of Trauma Center Proliferation Have Not Led to Proportionate Improvements in Access to Care or Mortality After Injury: An Ecologic Study



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