Proximity and Knowledge Spillovers:
Evidence from the Introduction of New Airline Routes

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Abstract: This paper examines the causal relationship between proximity and knowledge diffusion by estimating the elasticity of CBSA-pair level citations to variations in travel time induced by the introduction of new flight routes. The findings reveal that decreasing travel time between U.S. cities by 20% increases knowledge flow by 0.5%, which corresponds to an increase of over 15,000 citations at the aggregate level. Rather than boosting within-firm knowledge transfer, travel time reduction leads to a rise in knowledge spillovers primarily across firm boundaries, particularly among those that form joint ventures, have block holdings in each other, or form supply chain relationships. These effects are stronger among city pairs located farther away from each other, with higher absorptive capacity, in complex technology classes, and for newly developed technologies. Additional mechanism tests suggest that the most likely channel through which travel time reduction impacts knowledge spillover is by influencing the transfer of tacit knowledge via facilitating cross-CBSA inventor flow and information acquisition.

Keywords: Knowledge Spillovers, Tacit Knowledge, Patent Citation, Innovation, Travel Time, New Airline Routes

JEL classification: O30; O33; R4; L93

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1. Introduction

Knowledge creation is critical to economic growth (Romer 1990). In reality, however, access to knowledge is highly imperfect (Griliches 1957), directly contrasting a key assumption in Romer's seminal endogenous growth model, namely, "anyone engaged in research has free access to the entire stock of knowledge". In fact, knowledge is more likely to flow between individuals who are located more closely to each other.[1]

The notion that geographic proximity leads to more knowledge spillover has attracted much academic attention, as numerous studies find evidence consistent with this conjecture.[2] In this paper, we argue that the travel time between two physical locations is a more appropriate measure for proximity than geographic distance (Giroud 2013). Specifically, we exploit changes in travel time between metropolitan areas induced by the introduction of new flight routes to study whether and how proximity influences knowledge spillovers and impacts the volume and direction of future innovation. We combine the patent data from the United States Patent and Trademark Office (USPTO) with the airline data from the U.S. Department of Transportation (DOT) to assemble a panel data set of over 3 million Core Based Statistical Areas (CBSA) pair-year observations (corresponding to 923 unique CBSAs) between 1980 and 2010. We focus on patent citations to measure the flow of knowledge from the cited patent to the citing patent. The number of citations made by patents invented in one metropolitan area to patents invented in another metropolitan area provides a proxy for the volume of knowledge flowing from the latter to the former.[3]

Our baseline specification employs a (continuous treatment intensity) Difference-in-Differences (DiD) empirical methodology (De Chaisemartin and d'Haultfoeuille 2018, De Chaisemartin and d'Haultfoeuille 2020) to allow for the estimation of the elasticity of knowledge flow to travel time reduction. Our results show that a 20% reduction in travel time following the introduction of new flight routes increases the patent citation flow between two

[1] See Saxenian (1994) and Kerr and Kominers (2010) for studies on the success of Silicon Valley, and Zucker et al. (1998) and Zucker et al. (2002) for the study on the rise of biotechnology clusters.

[2] See, e.g., Thompson (2006), Agrawal et al. (2008), and Singh and Marx (2013).

[3] We recognize that patent citations represent only an imperfect measure of knowledge diffusion. First, our measure is a proxy for exchanging technological knowledge rather than for diffusions of basic scientific knowledge. The latter is more closely related to article citations, although it is not implausible that the two are positively correlated and are subject to similar forces in diffusion. Patent inventors face a legal requirement to cite all their prior arts, while they also have an economic incentive not to cite irrelevant prior patents to maximize their intellectual property rights for protection. In this sense, a patent citation is a more accurate measure of knowledge diffusion than article citations (Jaffe et al. 1993). Second, as Porter (1990) emphasizes, much knowledge sharing occurs between customers and suppliers, which may be captured more fully by input-output relationships than by these citations.

CBSAs by 0.5%. Alternative DID specification with a discrete shock variable yields qualitatively similar results.

Our stringent empirical specification overcomes several identification challenges. The first potential endogeneity issue is due to some underlying omitted variables at each CBSA-year level confounding our inference. In particular, local economic conditions at one CBSA might be the driving force behind both innovation activities and new airline routes linking it to other geographical areas. For example, the burgeoning biotech and healthcare industry in Boston might lead to more local investment, more innovative activities, and consequently more patents and citations. Meanwhile, realizing Boston's strong economic performance and future potential, airlines might foresee strong travel demands and launch new airline routes both *to* and *from* Boston. In this case, finding a positive treatment effect of time-reducing new flight routes on subsequent innovation could be a spurious outcome of an omitted shock in the Boston area. This problem is traditionally difficult to deal with because it is impossible for researchers to identify a comprehensive list of possible shocks. We circumvent this issue by including a complete set of citation-giving metropolitan area fixed effects by year and citation-receiving metropolitan area fixed effects by year, which together completely account for all local shocks at the citing CBSA as well as the cited CBSA, regardless of the shocks' origin, format, and magnitude. Such stringent specification is feasible as our observation is at the CBSA-pair year level, allowing us to exploit the variations in between-CBSA travel time for multiple CBSA pairs associated with a same citing CBSA or a same cited CBSA.

Another possibility is that some omitted shocks exist at the CBSA-pair level. For instance, Amazon has its first and second headquarters in Seattle, Washington, and Crystal City, Virginia, respectively. Given its sheer size, Amazon's presence and employment of a large number of people in both cities might simultaneously cause knowledge flow as well as direct flights connecting these two places to increase. Unfortunately, we cannot directly control for CBSA-pair fixed effects by year, as doing so would completely absorb our main independent variable, i.e., between-CBSA travel time. However, as a compromise, we alleviate this issue in several ways. First, we include CBSA-pair fixed effects, which would help account for time-invariant factors at the CBSA-pair level. For instance, many cities might have connections due to a variety of historical, economic, and political reasons. The CBSA-pair fixed effects are thus effective at controlling for these slow-moving connections. Second, when we estimate the dynamic effects of the introduction of new airline routes, only those travel time reductions that happen contemporaneously (i.e., in the same period t) or in the past, as opposed to future reductions in travel time, predict patent citations. This result helps alleviate the concern that some trends at the CBSA-pair level leading up to the travel time reduction are the root causes of our documented effects. Finally, in robustness checks, we re-estimate our regression model but only consider travel time reductions due to new hub openings and find similar results. Hub openings usually affect many routes related to an airport rather than just one specific metropolitan area pair. As a result, reductions in travel time due to hub openings are more likely to be exogenous at the *CBSA-pair* level because these decisions are often predetermined by individual airlines' existing infrastructure, routing systems, and optimization strategies within these firms (Giroud 2013).

After documenting the positive effect of travel time reduction on cross-region patent citations, our next set of analyses investigates the sources of this effect. We guide our exploration through the lens of within organizations and across organizations. First, we look at whether the increase in citations is mainly occurring in patent citation pairs where the citing patents and cited patents share one or more common assignee(s). This could happen when a single organization's different R&D centers cite each other. In addition, we also consider the case in which the same inventor moves across CBSA and cite herself when patenting again. However, the results consistently show that these do not seem to be where the increase in citations is taking place. Most of the increase in patent citations due to travel time reduction is across organizational boundaries without inventor overlap. Second, we consider inter-organizational patent citations. Because roughly 96% of all assigned patents are granted to corporations (Hall et al. 2001), we focus on patent citations that occur among firms with different linkages. We specifically consider three types of firm linkages: firms that form a joint venture; firms with block holdings in each other; and firms that are vertically connected along the supply chain. Our results show that knowledge diffusion in response to travel time reduction exists in each of the three groups. Taken together, these results suggest that a sizeable portion of the knowledge diffusion we have documented occurs outside of the firm boundary, reflecting "spillovers" to others.

We then take a closer look at how our documented effects vary in the cross-section. In particular, we consider attributes at the city level as well as the patent level. Several patterns are noteworthy. First, we find that knowledge diffusion between CBSA pairs that are farther away tends to benefit more from travel time reductions. Second, citation-making CBSAs with higher absorptive capacity (Cohen and Levinthal 1990) gain more knowledge diffusion from travel time reduction. Third, our results are the strongest among the most complex technology classes. Finally, we alternate the lengths of reference windows to count citations, and find that proximity is most effective in facilitating the diffusion of new knowledge (within 6 years). In contrast, the diffusion of dated knowledge is not responsive to travel time reduction. Both complex technologies and newly generated technologies are less likely to be well codified and more tacit in nature. The latter two results jointly suggest that it is mainly the tacit knowledge whose effective learnings are significantly facilitated by reduced travel time.

We also investigate the implications of reduced travel time on new knowledge creation as the advancements in the technological endeavor are enabled by the cumulativeness of knowledge when inventors "climb on the shoulders of giants". We find that better-connected CBSAs not only produce more new patents, but these new patents are also more impactful. Moreover, new patents produced in CBSA pairs that are better connected evolve towards a closer direction in the space of technological classes.

In the final part of this article, we provide auxiliary evidence that travel time reduction makes inventor communications and information acquisition more convenient which facilitates the transfer of tacit knowledge. First, we show that a reduction in travel time increases the flow of inventors. By tracking a same inventor' different patents over time, we find that reduced travel time significantly increases inventors' cross-CBSA relocation. Although this is only a very noisy and limited measure for inventors' cross-CBSA traveling, it partially accounts for the effects of travel time on patent citations. Second, we show that our results are stronger in the early half of our sample periods when convenient nonpersonal means of information transmission such as the Internet and video conferencing were not available (Agrawal and Goldfarb 2008, Giroud 2013, Panahi et al. 2013). Lastly, we discuss why our estimates based on patent citations, a usage of published documents, could potentially capture the diffusion of tacit knowledge.

Just as Polanyi (1967) puts it, "We know more than we can tell", tacit knowledge refers to knowledge that is hard to codify or information that one knows about but finds it hard to tell in a written format. In our setting, a large reduction in travel time increases the likelihood of inventors in the affected regions being physically together, exchanging important specific knowledge, experience, and know-how through demonstration, experiments, or informal story sharing. As previously mentioned, our main effects are the strongest in highly complex technological classes and among new knowledge, both of which are characterized by knowledge that is not well codified in nature.

Although the open publication of patents is intended for facilitating subsequent usage of prior inventions, the information disclosed in patents *alone* is usually insufficient for such purpose. Thus, a citation to a prior patent not only reflects the usage of documented contents in the patent, but also the usage of undocumented tacit knowledge embedded in it, for which convenient communications with relevant inventors are indispensable. As Dosi (1988) points out in his seminal work, even in a highly scientific and quantitative field such as mechanical engineering, tacit knowledge about "performance of previous generations of machines, their typical conditions of use, the productive requirements of the users" is important for knowledge generation, but it is not explicitly mentioned in any patent. Access to such know-how can only be transferred through face-to-face interactions or alternative means such as video and audio channels of communication that allow for close interactions with relevant inventors.

Our paper contributes to several strands of literature. This paper first builds on a voluminous literature on the determinants of knowledge transfer and innovation. Since the seminal work of Jaffe et al. (1993), economists have used patent citations to study how proximity influences knowledge spillovers (Thompson 2006, Agrawal et al. 2008, Singh and Marx 2013). To separate localized knowledge spillovers from spatial clustering of prior patents, researchers tend to match each actual cited patent with a control patent that comes from the same technological class and time period and examine whether proximity increases the probability of citation beyond what is predicted by the spatial distribution of technologies. The sizes and significances of these empirical estimates hinge critically on the degree of refinement of the technology class used for matching (Henderson et al. 2005, Thompson and Fox-Kean 2005). We contribute to this body of research by examining directly large variations in travel time and thus *actual* changes in physical proximity induced by airlines' introduction of new airline routes. Our stringent empirical specification effectively controls for time-varying local shocks and advances our understanding of proximity on knowledge spillover one step further towards a causal interpretation.

Another related literature studies firm-level innovation and proposes that many factors such as institutional investors (Luong et al. 2017), stock market liberalization (Moshirian et al. 2021), and firms' public status (Bernstein 2015) are important determinants. Relatedly, Manso (2011) provides a theoretical foundation for ways to motivate innovation. Specifically, he argues that compensation incentives such as stock options combined with long vesting periods, option repricing, etc. can be effectively used to motivate firm innovation. Baranchuk et al. (2014) offers some empirical evidence on the combination of incentive schemes that leads to better innovation for newly listed public firms. This paper joins the broad discussion but focuses on knowledge transfer in the form of innovation through spatially separated geographic areas. Our setting allows us to separate the influence of proximity on knowledge spillovers and the influence of knowledge spillovers on the spatial distribution of future innovation.

Thirdly, this paper also contributes to our understanding of knowledge diffusion across technology clusters. Given its importance to the industrial agglomeration (Marshall 1920, Feldman 1994, Audretsch and Feldman 1996, Ellison et al. 2010), the literature on knowledge diffusion has increasingly focused on its "localization", at an increasingly micro level, from the same Metropolitan Statistical Area (Jaffe et al. 1993), to the same zip code (Kerr and Kominers 2010), and to "blocks away" (Arzaghi and Henderson 2008). Much less attention has been paid to how knowledge diffuses (or fails to diffuse) across technology clusters. Most knowledge diffusion, as measured by patent citations, is not localized. Figure 1 shows that for patents applied between 1980 and 2010, fewer than 20% of backward references are those with the inventor addresses of the citation-making patent and the citation-receiving patent located in the same CBSA. This share decreased between 1980 and 1995 and stabilized afterwards. In contrast, cross-CBSAs patent references have always accounted for the bulk of patent references, which experienced a slight increase before 2000 and plateaued at around 60% since then. Figure 2 shows that the average distance between citation-making patents and citation-receiving patents within the U.S. increased considerably between 1980 and 2000, and has oscillated around 1,000 miles since 2000, possibly reflecting the joint effects of increased connectedness through travel and increased penetration of the commercial internet in the latter part of our sample period.

Finally, our paper relates to a strand of literature on how communication costs affect scientific collaboration, a special channel of knowledge diffusion. Agrawal and Goldfarb (2008) find that access to Bitnet increases the collaboration among professors from different universities. Using the expansion of Southwest Airlines as an exogenous change to flight fares, Catalini et al. (2020) find that lower travel costs increase scientific collaboration among university researchers. Chai and Freeman (2019) find that temporary collocation in the context of attending the same conference also increases the chance of collaboration. This strand of literature sheds light on understanding the diffusion of basic science originated from universities through collaboration. More broadly, our paper is also related to several studies that investigate how changes in travel time between a firm's headquarter and its branch locations impact branch-level business outcomes. Giroud (2013) finds that reduction in travel times between headquarter and manufacturing plants increases plant-level capital expenditure. Levine, Lin, Peng, and Xie (2020) find that shorter travel times between a bank's headquarter and branches increase branch-level lending to small businesses. Our paper shares the common theme that tacit knowledge transfer and face-to-face communication is an important mechanism for soft information acquisition that is often crucial for business decisions. At the same time, however, our results provide novel evidence of the impact of travel time reduction on knowledge diffusion across firm boundaries.

The remainder of this article is organized as follows. In Section 2 we introduce the data and discuss our empirical methodology. We present the empirical results in Section 3, and Section 4 concludes.

2. Data and Empirical Strategy

In this section, we discuss in detail the data sources and our empirical methodology. Section 2.1 discusses the data source and sample construction; Section 2.2 presents the analytical sample and summary statistics; Finally, Section 2.3 reviews the empirical specification.

2.1. Data and Sample

Airline Data. We obtain data on airline routes from the T-100 Domestic Segment Database for a period running from 1990 through 2010, and ER-586 Service segment data for a period running from 1977 through 1989. These two datasets are compiled from airline companies' filings of Form 41 with the U.S. Department of Transportation. All flights that have taken place between any two airports in the United States are reported. These databases provide monthly data for each airline and route (segment), including the origin and destination airports, flight duration, the number of departures scheduled, the number of departures performed, and the number of passengers.

Patent Data. We obtain USPTO patent citation data from the *PatentsView*[4]. We restrict our sample to the 2.38 million utility patents applied for from 1977 through 2010 and granted by 2014 that have at least one U.S. inventor. The *PatentsView* also provides inventor

[4] The *PatentsView* data are available for bulk download at https://patentsview.org/download/data-download-tables.

disambiguation and assignee disambiguation, allowing us to track inventor relocation, inventor self-citation, and assignee self-citation. We drop the 3,978 patents filed in Alaska, Hawaii, or U.S. territories and use inventor addresses to geolocate patents in counties in the contiguous U.S. For patents involving multiple U.S. inventors, we use the address of the first inventor. Patenting activities are highly concentrated in metropolitan areas. We drop counties that do not belong to any Core Based Statistical Area (CBSA) and focus on CBSA-to-CBSA knowledge flow.[5] This step removes only 1.4% of the patent sample.

Our final unit of observation is at CBSA-pair-year level. One noteworthy characteristic of our setting is that citations are directional. For example, citations from Chicago to Boston and citations from Boston to Chicago indicate knowledge flow in opposite directions. Thus, in any given year, Chicago-to-Boston and Boston-to-Chicago appear in data as two distinct CBSA pairs. We remove CBSA pairs that have no patent citations at all in the entire sample period. For CBSA pairs that have some patent citations in certain years but no citations in other years, we keep them for the entire sample period to make the data a balanced panel and fill in zero citations for those no-citation years. We do this because switching between zero citations and non-zero citations indicates a change in knowledge diffusion at the extensive margin. This leaves us with a balanced panel of 110,998 CBSA pairs that span the years running from 1977 through 2010.

2.2. Definitions of Variables and Summary Statistics

2.2.1 Measuring Travel-Time Change

To travel from any CBSA to another involves some combination of driving and flying. We can group the methods of traveling from CBSA i to CBSA j into four categories: (1) driving from i to j; (2) flying from i to j ; (3) driving from i to a nearby CBSA k and then flying from k to j; (4) driving to a nearby CBSA k, flying from k to CBSA h, and then driving from h to j. The flight section in (2), (3), and (4) could include direct or indirect flights with up to three legs. When flight routes between airports change, inventors who seek to minimize travel time may change their mode of travel across these four categories. In any given year,

[5] A Core Based Statistical Area (CBSA) is a geographic area defined by the Office of Management and Budget that consists of one or more counties (or equivalents) anchored by an urban center of at least 10,000 people plus adjacent counties that are socioeconomically tied to the urban center by commuting. In the contiguous United States, there are in total 925 CBSAs, covering 1,815 counties (or county equivalents) out of the 3,108 counties. See more details regarding the CBSA at https://www.census.gov/topics/housing/housing-patterns/about/core-based-statistical-areas.html

we compare travel time across all these categories to determine the optimal travel itinerary for each CBSA pair.

We use the geodetic distance in miles between the centroids of a CBSA pair and an average driving speed of sixty miles per hour to calculate a proxy for between-CBSA driving time. To calculate travel time by air between two CBSAs, we use the travel time between their airports. Some large CBSAs include more than one airport. For example, there are direct flights from LaGuardia Airport (LGA) in New York City to O'Hare International Airport (ORD) in Chicago, from Newark Liberty International Airport (EWR) to ORD, and from John F. Kennedy International Airport (JFK) to ORD, all connecting New York City with Chicago. In this situation, we use the shortest travel time between airport pairs as the travel time between CBSA pairs. Travel time between airports consists of the duration of the flight (ramp-to-ramp time), the time spent at airports, and the layover time for indirect flights. Flight duration per segment is obtained from T-100 and ER-586 data. The time spent at airports and layover times are unobservable. Following Giroud (2013), we assume that one hour is spent at the origin and destination airports combined, and that each layover takes one hour. To remove temporary flights from the sample, we restrict airline routes to those regularly operating with at least two passenger flights per week for 52 weeks a year. For new airline routes that were introduced in the middle of a year and then continued to operate in the following years, the first year of treatment is the first year when the new airline routes operated with at least two passenger flights per week for 52 weeks a year.

Note that we do not account for travel times from distinct locations within a CBSA to its airport (or to its centroid). The locations of major airports within a CBSA and within-CBSA road infrastructure are largely stable over our sample period (Agrawal et al. 2017). The distribution of the distances between inventor addresses to CBSA centroids or to the relevant airports is also largely stable over our sample period (See appendix Figure A1). We account for CBSA-year level characteristics such as the distance between inventors to airports using CBSA fixed effects by year, and our identification relies on CBSA-pair-year level variations. In other words, when we compare between-CBSA knowledge flow before and after changes in flight routes, average travel time from distinct locations within a CBSA to its major airports cancels out. It is possible that, after the introduction of travel-time-reducing flight routes, inventors who benefit from it to a greater extent would move closer to the affected airports. This scenario, if it occurs, is a result of the treatment rather than an endogeneity issue that hinders identification.

Among the 110,998 distinct CBSA pairs in the sample, a total of 17,407 (15.7%) distinct CBSA pairs experienced only one change in travel time, and 15,424 (13.9%) distinct CBSA pairs experienced multiple changes in travel time. In Table 1, we provide auxiliary information about the nature of these changes. There were 37,914 events of travel time reduction. The average travel time reduction across these events is 1 hour and 21 minutes, which amounts to a travel time reduction of 20%. There were 20,988 events of travel time increase. The average travel time increase is 1 hour and 16 minutes, about 24% of the size of the pre-change travel time.

Similar to Giroud (2013), we classify travel-time-reducing itinerary changes into five categories: (1)"Indirect to Direct", (2) "Indirect to Indirect", (3) "Direct to Direct", (4) "Direct to Indirect", and (5) "Road to Flight". "Indirect to Direct" and "Indirect to Indirect" are the two most common types of travel-time-reducing itinerary changes. These typically occur when the new optimal itinerary involves fewer stopovers. A "Direct to Direct" itinerary change reduces the between-CBSA travel time by flying from an airport closer to the origin CBSA or to an airport closer to the destination CBSA. For example, suppose the optimal itinerary to travel from CBSA i to CBSA j was originally to drive from i to a nearby CBSA k first, and then take a direct flight from k to j. The introduction of a new flight that directly connects CBSA i and CBSA j will save the driving time and reduce the total travel time. A "Direct to Indirect" itinerary change reduces travel time when the shorter drive time in the new "indirect" itinerary dominates the shorter flight time in the old "direct" itinerary. Lastly, the "Roads to Flight" category applies to pairs of CBSAs that are relatively close to each other (315 miles), compared to the average distance of 1060 miles between CBSA pairs that experienced travel time reduction.

2.2.2 Measuring Knowledge Flow

A backward patent citation signals knowledge flow from a citation-receiving patent to a citation-giving patent. We use the application year of the citation-giving patent to determine the timing of the knowledge flow because, relative to the grant date, the application date is closer to the occurrence of the invention activity (Henderson et al. 2005). Thus, the number of citations made by patents applied for in year t and invented in CBSA i to *prior* patents invented in CBSA j indicates the volume of knowledge diffusion from j to i in year t. In our main specifications, we use three-year backward citations as our dependent variable, i.e., the number of citations made by patents applied for in year t in CBSA i to patents applied for between year $t-3$ and year $t-1$ in CBSA j. Corresponding to the design of this dependent variable, the sample period used in the main specification runs from 1980 to 2010. In section 3.3 we also explore how the results vary when using a 6-year rolling window prior to t, a 10-year rolling window prior to t, or a fixed period between 1977 and 1985.

2.2.3 Summary Statistics

The results reported in Table 2 summarize the main variables in the regression analysis along with comparisons between CBSA pairs that eventually experienced travel time variations and those that never did. On average, the CBSA pairs that experienced travel time variations during our sample period are located 1,052 miles from each other, about 100 miles farther than the average distance between the CBSA pairs with constant travel times. This difference translates into about half an hour of additional travel time based on our calculations. Along with the greater distances and longer travel times, these "eventually treated" CBSA pairs have on average fewer between-CBSA patent citations, fewer patents in the citing CBSA, and fewer cumulated patents stock in the cited CBSA.

2.3. Empirical Methodology

The introduction of new airline routes that reduce travel time between two locations makes it easier for inventors from one location to travel to the other. This facilitates face-to-face interaction and knowledge diffusion from one location to the other and thus may in turn affect the development of new technologies. To examine the effects on knowledge diffusion, we estimate a continuous treatment intensity Difference-in-Differences (DiD) panel regression specification:

$$y_{ijt} = \beta \cdot \log\left(Travel\ Time_{ijt}\right) + \gamma' X_{ijt} + \lambda_{it} + \lambda_{jt} + \alpha_{ij} + \epsilon_{ijt}, \qquad (1)$$

where y_{ijt} measures the knowledge diffusion from CBSA j to CBSA i in year t. To deal with zero values, we use the $\log(x+1)$ transformation of the number of citations made by patents applied for in year t in CBSA i, and received by prior patents applied for between year $t-3$ and $t-1$ in CBSA j as the dependent variable in our baseline specification. In robustness checks, we also show that using the citation count directly as the dependent variable with a Poisson specification, and using inverse-hyperbolic transformed citation counts with an OLS specification lead to consistent results. λ_{it} are citing-CBSA fixed effects by year and λ_{jt} are cited-CBSA fixed effects by year. α_{ij} are CBSA-pair fixed effects. $Travel\ Time_{ijt}$ is a continuous variable that measures the travel time between CBSA i and CBSA j at time t.

The variations in $Travel\ Time_{ijt}$ are the result of changes in the airline routes network, as described in section 2.2.1. X_{ijt} is a vector of control variables, and ϵ_{ijt} is the error term. β thus estimates the effect of travel time on between-CBSA patent citations.

We adopt such a continuous treatment intensity DiD specification for two main reasons: First, travel time changes occurred in both directions. That is, both travel time increases and decreases took place. Specifically, during our sample, there are 37,914 travel time reductions and 20,988 travel time increases (at the CBSA-pair-year level). It seems appropriate to include both types of changes in order to estimate the elasticity of citations to variations in travel time. Second, travel changes were fairly frequent during our sample period, with a total of 17,407 (15.7%) distinct CBSA pairs experienced one change in travel time, and 15,424 (13.9%) distinct CBSA pairs experienced multiple changes in travel time. In other words, among CBSA pairs that experienced significant travel time changes, close to half[6] experienced more than one change over our sample period. The high incidence of multiple changes that happen within a relatively short time frame makes our setting meaningfully different from a typical discrete DiD setting that often involves for instance the passage of state-level legislatures. In section 3.2.1, we provide estimation based on discrete DiD design for a subset of CBSA pairs that only experienced one single travel time reduction and the results are consistent with our main results.[8]

Our identification relies on the exogenous variation in between-CBSA travel time. Admittedly, airlines' decisions to introduce new routes depend on economic, strategic, and political-economic factors. If there are omitted factors that are driving both the introduction of new airline routes and knowledge diffusion, any relationship between the two could be spurious because of the confounding effects of the omitted variables. By including cited-CBSA fixed effects by year λ_{jt} and citing-CBSA fixed effects by year λ_{it}, our specification accounts for time-varying shocks both at the cited CBSA level and at the citing CBSA level. In this way, we are making the comparison between different city pairs consisting of a same cited CBSA and multiple citing CBSAs, netting out the technology shocks at the cited CBSA.

To build more intuition, suppose Boston experiences a technology shock brought about by breakthroughs in gene editing, leading other regions to cite more of Boston's patents. Because of such productivity shocks and related economic boom, airlines might also introduce new flights to and from Boston. In this case, we will observe both an increase in patent

[6] 47%=15,424/(15,424+17,407)

citations to Boston and more flight connections to Boston even in the absence of any causal relationship between the two. Now consider the scenario when a time-reducing direct flight was introduced between Boston and San Diego, while Boston and Chicago had always been connected by direct flight and thus the travel time between them remained unchanged. Both San Diego and Chicago cite Boston more after the technology shock in Boston. Holding other things equal, if citations from San Diego to Boston increased to a greater degree than that from Chicago to Boston, then the difference between changes in the two pairwise citations is likely to be the result of the travel time reduction between San Diego and Boston. Thus, by controlling for cited-CBSA fixed effects by year, we can separate the effects of new airline routes from the effects of local shocks at the cited CBSA. We account for the shocks local to knowledge-absorbing CBSAs similarly with citing-CBSA fixed effects by year.

A remaining concern is that there could exist shocks that are specific to a CBSA pair. In the above example, one possibility is that because of Boston's booming healthcare industry, San Diego CBSA or other CBSAs in which there also exist a strong healthcare footprint start to have more patents being cited by Boston or to cite more patents in Boston. In the meantime, it is this same set of CBSAs that experiences an increase in the flow of travelers to and from Boston. Ideally, one could account for this by including a full set of CBSA-pair fixed effects by year, but doing so would also completely absorb our main explanatory variable. To address this issue, we adopt two empirical strategies. First, we examine whether our results appear at the "correct" time. If a new airline route is an endogenous outcome of a pre-existing location-pair shock, we would expect to find an "effect" even before the new airline route is introduced. Second, we re-estimate our results by regressing patent citations on changes in travel time that are directly due to the opening of a hub. Airport hubs are used mainly to concentrate passenger traffic and serve as layover airports to facilitate transferring them to their final destinations, which achieve economies of scale and lower operating costs (Berry et al. 1996). Airline route changes following the opening of a new hub are much less likely to be the result of CBSA-pair level shocks (Giroud 2013).[7]

3. Empirical Findings

3.1. Baseline Results: Proximity and Citations

[7] A list of hub openings in our sample period is available upon request.

We present our main results in Table 3. In column (1), we simply regress patent citations on *Log(Distance)*. We control for the number of newly applied patents in the citing CBSA, the patent stock in the cited CBSA, year fixed effects, citing-CBSA fixed effects, as well as cited-CBSA fixed effects. The results show a strong negative correlation between distance and knowledge flow. The purpose of this initial test is to show consistency with studies in the literature on localized knowledge diffusion. The results in column (1) are consistent with prior findings that geographic constraints play a significant role in influencing knowledge spillover. In column (2), we augment the specification in column (1) with *Log(Travel Time)*. While distance and travel time are positively correlated, when we include both in the same regression, the negative effects of travel time on knowledge diffusion dominate, while the coefficient of distance turns positive. This is indeed possible because, among regions with the same between-CBSA travel time, some CBSA pairs that are highly connected in innovative activities happen to be located far apart.[8] One example is biotechnology, for which the two biggest clusters – Boston and San Diego, crosses the contiguous United States diagonally.

Column (3) contains our baseline result, in which we estimate Equation (1). The results show a negative and statistically significant coefficient on *Log(Travel Time)*. In terms of economic magnitude, reducing the travel time between a given CBSA pair by 20% on average increases its knowledge flow by 0.5% (20% x 0.025). Note that this is a sizeable economic magnitude given the stringent specification employed. To put things in perspective, our sample contains 110,998 CBSA pairs spanning 31 years with an average citation of 0.91. With the average between-CBSA travel time at 6 hours, an average of 20% decrease (72 minutes) in travel time increases citations by 0.50%, which translates to 15,656 citations ($0.91 \times 3{,}440{,}938 \times 0.50\%$). In appendix Table A1, we re-run column (3) with the robust standard errors clustered at the CBSA-pair level and at the citing CBSA level, respectively. The coefficients of *Log(Travel Time)* remain statistically significant.

In column (4) we investigate whether our results appear at the "correct" time. Besides contemporaneous travel time, we also control for the between-CBSA travel time one year before the focal year, $Log(Travel\,Time)_{t-1}$, and that one year after the focal year, $Log(Travel\,Time)_{t+1}$. A significant coefficient of $Log(Travel\,Time)_{t+1}$ would indicate that

[8] See innovation cluster maps at https://www.clustermapping.us/region. The source of the map is the U.S. Cluster Mapping Project, Institute for Strategy and Competitiveness, Harvard Business School.

future travel times "affect" current knowledge diffusion, suggesting that knowledge diffusion changes before travel time *actually* changes, thereby casting doubt on the statement that reduced travel time stimulates knowledge diffusion. Reassuringly, we find that the coefficient of $Log(Travel\,Time)_{t+1}$ is statistically insignificant. In contrast, the coefficient of $Log(Travel\,Time)_{t-1}$ is statistically significant and close to the coefficient of $Log(Travel\,Time)$ in size, suggesting a lasting effect. In other words, if travel time was reduced last year, it remains facilitating knowledge diffusion this year.

3.2. Robustness Checks

In this section, we conduct a battery of robustness tests to examine whether the documented results are sensitive to a discrete difference-in-differences specification, redefining travel time changes to those due to hub openings, and alternative empirical specifications. These results are presented in Tables A2 to A3 of appendix.

3.2.1. Discrete Difference-in-Differences

For comparison with the literature (Giroud 2013) and to show how events of significant drops in between-CBSA travel time affect knowledge diffusion, in Table A2 we restrict our sample to CBSA pairs that have experienced no more than one reduction in travel time and recode our travel time variable as a discrete shock. Specifically, we define Dm (Post Travel Time Reduction) as an indicator variable that is equal to one if the travel time between two CBSAs decreases by more than 1.5 hours as a result of a new flight route introduction, and zero otherwise. In column (1) we show that the coefficient on Dm (Post Travel Time Reduction) is positive and statistically significant. This is consistent with our baseline results: reducing travel time boosts between-CBSA knowledge diffusion.

Following the standard tests for pretends and dynamic treatment effects which are common among applications of DiD method with two-way fixed effects model, in column (2) we replace Post Travel Time Reduction Dummy with six different dummies. Travel Time Reduction Year (-3), Travel Time Reduction Year (-2), and Travel Time Reduction Year (-1) are dummies that equal one if a CBSA pair will experience a major travel time reduction (i.e., 1.5 hours or more in reduction) in three years from now, two years from now, and one year from now, respectively. Travel Time Reduction Year (0) is a dummy that equals one in the year when a CBSA pair experience a major travel time reduction. In a similar vein, Travel Time Reduction Year (1) and Travel Time Reduction Year (2) are dummies that equal one if a CBSA pair experiences a major travel time reduction one year ago and two years ago, respectively. Finally, Travel Time Reduction Year (3+) is a dummy that equals one if a CBSA pair experiences a major travel reduction more than three years ago. The period prior to three years before the travel reduction shock is used as the reference group.

The goal of the treatment dynamics test is to ensure there are no trends that already occur before the actual treatment takes effect. In particular, if direct flight routes are introduced as a response to underlying economic booms and increases in innovative activities, then we should expect to see an “effect” of the travel time reduction prior to the actual introduction of the direct flights. The results in column (2) of Table A2 show that the coefficients on Travel Time Reduction Year (-3), Time Reduction Year (-2), and Travel Time Reduction Year (-1) are small in economic magnitude and statistically insignificant, indicating that there are no pre-trend treatment effects. We plot these coefficients and their confidence intervals in Figure 3. The effects are present in the year of treatment and get bigger in later years after treatment. Recall that our measure of knowledge diffusion is the number of citations made by patents applied in t to prior patents applied between t-3 and t-1. Only by year t+3, the pool of patent stock to be cited are all applied for after the travel-time-reducing event occurred in year t. Consistent with this design, the treatment effects get much bigger after three years post-treatment.

3.2.2. Hub Openings

In this section, we show that our results are robust when we consider only travel-time reductions that reflect new hub openings. Most hub openings date back to the 1980s. Before the Airline Deregulation Act of October 1978, airlines were mandated by the federal government to fly directly between pairs of small markets. Following deregulation in the 1980s, airlines began competing for strategic hub locations, switching from the point-to-point system to the hub-and-spoke system (Borenstein 1992, Cook and Goodwin 2008). Changes in airline routes caused by hub openings are less likely to be driven by shocks at the CBSA-pair level.

We define a CBSA pair as *Hub Treated* when the CBSA pair experiences a travel time change involving airline routes that are introduced in the same year when the origin, the destination, or any connecting airport becomes a new hub. In Panel A of Table A3 in the appendix, we regress on *Log(Travel Time)* and the interaction between *Log(Travel Time)* and *Hub Treated* in column (1). We find that the coefficient on *Log(Travel Time)* remains negative and significant. Interestingly, the coefficient on the interaction term *Hub Treated * Log(Travel Time)* is also negative and significant at the 10% level. This result indicates that travel time reductions that are related to hub openings tend to have a bigger impact on patent citations, which is economically intuitive as hub openings generally involve the overhaul of existing infrastructures and often are accompanied by significant efficiency improvements and travel time reductions. In column (2), we estimate our baseline specification on CBSA-pairs that are ever affected by hub openings. Note that this is a much smaller sample, with only roughly 6% of the number of observations in the baseline regression. Even in this very small sample and with our stringent fixed effects specification, we find a negative and significant impact of travel time on patent citations. Consistent with the result in (1), knowledge diffusion is more responsive to travel time in hub-treated CBSA pairs. Finally, in column (3), we experiment with yet another empirical option whereby we define the travel time to be the actual travel time only for hub-treated CBSA pairs, but set it as the 1980 initial travel time value for all other pairs. By removing those travel time reductions that are unrelated to hub openings, this alternative empirical specification is more conservative but provides an arguably cleaner estimate of the effect of travel time on patent citations. Once again, we continue to see a negative and significant coefficient on this redefined travel time variable.

3.2.3. Alternative Specifications

The pattern of our results is also not sensitive to the $\log(x + 1)$ transformation. In Panel B of Table A3 in the appendix, we investigate whether our results are sensitive to alternative empirical functional forms. In columns (1) through (3), we use the OLS model with inverse hyperbolic transformed citation counts as the dependent variable, the Poisson model with citation counts as the dependent variable, and the OLS model with citation counts as the dependent variable. All the results are qualitatively consistent and quantitative comparable with our baseline estimates.

3.3. Heterogeneity

We next study how the effects vary in the cross-section. We first examine how the effects vary depending on the connection between the knowledge-absorbing entity (citation maker) and the knowledge-diffusing entity (citation receiver). We find that travel time reduction mainly facilitates knowledge spillovers across organizational boundaries. We then show how the effects vary by the between-CBSA distances, by the absorptive capacity of the citing CBSAs, by the technology complexity of the knowledge to be diffused (the cited patents), and by the freshness of the knowledge to be diffused. The latter two heterogeneity patterns suggest that the diffusion of knowledge that is more complex and less well-codified is more responsive to travel time.

3.3.1. Sources of Patent Citations

In this section, we examine how the effects of travel time on knowledge-diffusion vary depending on the connection between the knowledge-absorbing entity (citation maker) and the knowledge diffusing entity (citation receiver). In Table 4 column (1), we first replicate our baseline result from Table 3 for ease of comparison. In column (2), we use the between-CBSA inventor self-citations as the dependent variable. A patent citation is counted as an inventor self-citation when a same inventor appears both on the citing patent and on the cited patent. This scenario could occur when the inventor relocates to a different CBSA and cites her own prior patents when applying for new patents. However, inventor self-citations only account for about 3.2% of citations, so they are unlikely to be the main factor contributing to our findings. Moreover, while shorter travel time is associated with more inventor self-citations, the coefficient is insignificant.

In column (3) we use the between-CBSA *same-assignee* citations as the dependent variable. Less than 2% of patents in the sample are assigned to more than one assignee. A patent citation is counted as a *same*-assignee citation when the citing patent and the cited patent have any overlap in assignees. We also make use of the assignee-to-public-firm match constructed by Kogan et al. (2017) to identify additional patent citations where the assignee of the citing patent and the assignee of the cited patent belong to a same public firm. We count these additional citations together with the same-assignee citations as the *same-firm* citations, and use it as the dependent variable in column (4). Again we get a negative but insignificant coefficient of *Log(Travel Time)*, suggesting that knowledge diffusion within organizational boundaries is not responsive to variations in travel time. Given the pre-existing within-organization channels for communication (Alcácer and Zhao 2012), one potential reason for this is that there is limited margin that additional reduction in travel time can contribute to.[9]

[9] The lack of significance for within-firm knowledge diffusion could be due to the fact that within-firm knowledge diffusion across CBSAs is relatively rare. The majority of intra-firm knowledge diffusion occur within the same CBSA instead of between CBSA pairs. While there are patent citations in 13.36% of the observations at the CBSA pair-year level, within-firm patent citations occur only in 1.48% of the sample. Therefore, travel time reduction could still be a highly important channel of within-firm knowledge diffusion across CBSAs, but is unfortunately not captured by our empirical setting.

For the dependent variable in column (5), we exclude the inventor self-citations and same-firm citations. The coefficient of *Log(Travel Time)* is negative, significant, and larger in magnitude compared to our baseline in column (1), which indicates that travel time reduction mainly facilitates knowledge diffusion across organizational boundaries. Such knowledge diffusion is indeed knowledge "spillovers" in the sense that they generate positive externalities to entities beyond their original inventors or owners.

Next, we consider how the effects of travel time on cross-organizational knowledge spillovers would be mediated if there are some linkages between these organizations. Given that more than 96% of all assigned patents are granted to corporations (Hall, Jaffe, and Trajtenberg, 2001), we consider three types of firm linkages: firms that form a joint venture; firms with block holdings in each other; and firms that are vertically connected along the supply chain.

We obtain data on joint ventures and mergers and acquisitions from the Securities Data Company (SDC) Platinum™. The data on vertical customers is from Compustat Segment – Customer file. Starting from 1997, the Securities and Exchange Commission requires that all public firms disclose major customers to which they sell 10% or more of their output. This data allows us to capture major supplier-customer linkages between public firms. In column (6), we use "Joint Venture" citations as the dependent variable. It includes all patent citation pairs where both the citing patents and the cited patents are linked to some publicly listed firms (PERMNO) and the two firms have had joint venture deals in or prior to the year of citation. "M&A citations" and "Vertical Customers Citations" in columns (7) and (8) are defined correspondingly. Note that only when both the citing patents and the cited patents are assigned to publicly listed firms, we can identify these linkages. These by no means provide complete coverage for all the between-firm linkages. Only 7.3% of the patent citations are identified as "Joint Venture" citations, 1.2% are identified as "M&A citations", and 1.5% are identified as "Vertical Customer" citations.[10] Although these citation counts are at about the same scale as same-inventor or same-assignee citations, nevertheless, *Log(Travel Time)* has a significant and negative coefficient. When compared to the mean of the dependent variable, the relative sizes of the coefficients in column (6) to column (8) are bigger than that in our baseline column (1).

[10] Calculated based on the summary statistics provided in table 4. For example, 0.061/0.831=7.3%.

Taken jointly, these patterns suggest that within-firm knowledge diffusion is not responsive to travel time variations. In contrast, travel time reduction mainly facilitates knowledge spillovers across organizational boundaries,[11] and these effects are magnified when there are some pre-existing inter-organizational linkages such as joint venture, mutual block holding, or vertical supplier-customer relationship.

3.3.2. Geographic Distance

Panel A of Table 5 examines how our main effect varies with the distance between CBSA-pairs. We conjecture that the farther away CBSAs are from each other before the travel time reduction, the more affected the CBSAs are when travel time is reduced. This is intuitive as it does not take much time to travel between CBSA pairs that are located close to each other regardless of the travel time change.

To test this hypothesis, we divide our sample into four subsamples based on the distance between CBSA pairs and re-estimate our baseline regression in each distance quartile. We find that the main effects are mostly present in the top quartile and the 50^{th} – 75^{th} percentile, as evident in the large and negative coefficients. In contrast, the effect of travel time on citations is small in magnitude and statistically insignificant in the lowest distance quartile (col. 1) and 25^{th} – 50^{th} percentile (col. 2).

3.3.3. Absorptive Capacity

We next follow a similar strategy and split the sample into quartiles of "absorption capacity" of the citing CBSAs. The rationale for this approach is the more innovative a CBSA is, the more capable inventors there are to absorb new knowledge (Cohen and Levinthal 1990). Specifically, we use the cumulative number of patents applied during the fixed window between 1977 and 1985 to proxy for the "absorptive capacity" of a CBSA. We do not use contemporaneous patent counts for such a proxy out of the concern that reduced travel time may influence the quantity of innovation and thus change the composition of the four subsamples.[12] As is shown in Panel B of Table 5, effects of travel-time reduction on knowledge diffusion are driven mainly by the citing CBSAs in the top quartile of absorptive capacity. For the citing CBSAs in the second quartile of absorptive capacity, the coefficient of travel

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[11] These results expand and build on prior studies such as Giroud (2013) and Levine et al. (2020) that focus on the impact of travel time reductions within the firm boundaries impact business decisions at the individual branch level by enabling less costly information acquisition by the headquarter. Our results suggest that the impact of travel time reductions seems to also go beyond firm boundaries.

[12] Using contemporaneous patent counts to proxy for "absorptive capacity" of a CBSA and splitting the sample accordingly generates similar results.

time drops by more than half and is not statistically different from zero. This is not surprising, as the spatial distribution of innovative activities is highly concentrated.[13]

3.3.4. Technological Complexity of Cited Patents

The third dimension along which we study the variation of our documented effect is the complexity of the technology class of the citation-receiving patents. The idea behind this cross-sectional test is that if travel time reduction leads to higher citations by lowering the cost of information acquisition and tacit knowledge transfer, the effect should then be the strongest for cited patents that are highly complicated in nature. It is reasonable to expect that these complex patents are the ones that need inventors to meet at one physical location to discuss and exchange ideas, stories, as well as other related know-how that pertain to the specific invention.

To this end, we classify citation-receiving patents into four quartiles of technology complexity (Broekel 2019)[14] and count the CBSA-pair-year level number of citations to these four sets of patents separately. The results of this exercise are reported in Panel C of Table 5. Consistent with our conjecture, the effect of travel time reduction on knowledge spillover is robust in all four quartiles of technological complexity, but is the largest in the top quartile.

3.3.5. Reference Windows

We have thus far focused on the backward citation within three years. In Panel D of Table 5, we present results exploiting alternative time windows of reference. The dependent variables in columns (1) through (3) are the number of citations to prior patents in 3-year, 6-year, and 10-year rolling reference windows[15], respectively. We also consider a fixed reference window in column (4), i.e., looking at citations to the patent stock applied for between 1977 and 1985 as the dependent variable. We find that the coefficient on travel time monotonically decreases from column (1) to column (4), both in terms of economic magnitude and statistical significance. This is consistent with that newly generated knowledge is less likely to be well codified and more tacit in nature for which effective learning relies more on face-to-face

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[13] The first quartile of citing CBSAs account for 74.2% of all the patents applied for between 1977 and 1985. This figure drops to 15.1% for the second quartile, 7.1% for the third quartile, and 3.5% for the bottom quartile.

[14] Broekel (2019) construct and provide a measure for the technology complexity of patents based on the co-appearance network of Cooperative Patent Classes (CPCs) among European Patents between 1980 and 2015. Thus, this measure of technology complexity is exogenous to the spatial distribution of patents and the knowledge diffusion pattern in the United States.

[15] The sample periods corresponding to these dependent variables are from 1983 to 2010, from 1987 to 2010, and from 1986 to 2010, respectively.

communications. In contrast, dated knowledge is more mature and better codified, so that a reduction in travel time does not significantly change its transfer.

We also perform our analysis by technological classes and find that, in technological classes which rely on recent technological developments to a greater extent, travel time reduction has a greater effect on knowledge diffusion. In technological classes which make a higher share of backward references to dated prior patents, travel time reduction has a smaller effect on knowledge diffusion. We present this pattern in appendix Figure A2. This pattern is also consistent with a tacit-knowledge interpretation. In technology areas that are more well-developed and more mature, pre-existing knowledge and technologies tend to be well-codified (Pisano and Shih 2012). In technology areas where the frontier shifts more quickly, technological know-how is not yet codified and more tacit in nature. Knowledge diffusion in these areas relies heavily on direct interpersonal interaction (Zucker et al. 1998) and thus is potentially affected to a greater extent by travel time reduction.

3.4. The Volume and Direction of New Knowledge Creation

So far, our results show that reduced travel time leads to higher between-CBSA knowledge spillovers. Studies have shown that localized knowledge spillovers drive the agglomeration of innovation (Ellison et al. 2010), and local infrastructure enhances local knowledge creation by facilitating knowledge spillovers (Agrawal et al. 2017). Much less is known about whether the effects of knowledge spillovers on knowledge creation hold over a wider geographic scale and across technology clusters. In this section, we investigate how increased knowledge spillovers induced by travel-time reduction affect the quantity, significance, and direction of future innovation.

In column (1) of Table 6, we show that reduced travel time is positively associated with a greater number of patents at knowledge-receiving locations, a finding that is consistent with the notion that increasing knowledge flow is likely to increase innovation activity. To gauge the quality or the impact of new patents, in column (2), we employ the logged number of patents at knowledge-receiving CBSAs weighted by the number of forward citations they received as the dependent variable and find a larger effect of travel time. More directly, we also find that travel-time reduction significantly increases the number of high-impact patents as defined by those ranking top 25% (column 3) among patents applied for in the same year based on their total forward citations garnered by 2020.

Finally, we investigate how increased knowledge spillovers induced by travel-time reduction affect the technological direction of innovation. Following Jaffe (1986), MacGarvie

(2006), and Forman and van Zeebroeck (2015), we use the inner product of the patent-class vectors between two CBSAs to measure the between-CBSA similarity of technological direction. Specifically, with the citing CBSA (the knowledge recipient) denoted by i and the cited CBSA (the knowledge source) denoted by j:

$$TechDirSim_{ijt} = \frac{\Sigma_{c=1}^{\mathrm{M}} P_{ict} \cdot P_{jct}}{\sqrt{\Sigma_{c=1}^{\mathrm{M}} P_{ict}^2} \cdot \sqrt{\Sigma_{c=1}^{\mathrm{M}} P_{jct}^2}}, \tag{1}$$

where $P_{lc\cdot}$ $(l = i, j)$ denotes the number of patents in CBSA l, $c = 1,2, \ldots, M$ indicates the M distinct patent technological classes[16], and t denotes the patents application year. By design, $TechDirSim_{ijt}$ is a number ranging between zero and one. When it takes the value of zero, it indicates that the technological strengths of the two CBSAs are orthogonal. When it takes the value of one, the technological strengths of two CBSAs are perfectly aligned. In column (4) of Table 6 we find that a reduction in travel time significantly increases the between-CBSA similarity of technological direction of newly applied patents. That is, a reduction in travel time steers the evolution of the technology strengths in the two CBSAs towards a more similar direction. This last finding suggests that not only that the spatial distribution of technologies affect where inventors source knowledge, the pattern of knowledge diffusion also affects the spatial distribution of technologies in turn.

3.5. Potential Mechanisms and Further Discussions

Results from previous sections (i.e., 3.3.3 and 3.3.4) show that travel-time reduction facilitates particularly the diffusion of more complex and more recent and presumably less well-codified knowledge, both of which suggest that tacit knowledge transfer is probably an important mechanism of the documented effect. This is economically intuitive because reduced travel time makes face-to-face interactions easier, allowing inventors to get together through formal or informal social settings to share stories, knowhows, and experiences and ultimately leading to more transfer of tacit knowledge. We now investigate three distinct yet non-mutually exclusive aspects of innovation that provide some corroborative evidence to support this interpretation. First, we examine whether a reduction in travel time influences the inventor relocation and inventor collaboration. Second, we study whether our results are stronger when convenient nonpersonal means of information transmission through information technologies were unavailable. Lastly, we use two specific patents to illustrate

[16] We use the section codes of the International Patent Classes (IPC). For patents with more than one IPCs, we use the main technological class only.

why our estimates based on patent citations, a usage of published documents, could indeed capture the diffusion of tacit knowledge.

3.5.1 Inventor Relocation and Inventor Collaboration

Non-codifiable technological knowledge is non-severable from the workers who possess them (Sørensen 1996), and inventor mobility is an important channel through which such knowledge transfers across organizational and geographical boundaries. The frequent job mobility and knowledge spillovers associated with it contributed to the rise of the Silicon Valley (Saxenian 1996). Beyond the protection of intellectual property provided by the patent system, firms also resort to noncompete agreements to retain inventors so as to avoid knowledge leakage to competitors (Marx et al. 2009, Marx 2011).

Reduced travel time between a CBSA pair makes it easier for inventors in one CBSA to seek job opportunities in the other. When an inventor moves to a new CBSA, the inventor not only cites the patents local to her old CBSA when she applies for patents from the new CBSA, but also interacts with other inventors in the new CBSA and transfers to them the tacit knowledge from her old CBSA. The inventor may also absorb tacit knowledge in the new CBSA and transfer it back to the old CBSA as she maintains interactions with inventors there (Almeida and Kogut 1999, Møen 2000, Agrawal et al. 2006, Singh and Agrawal 2011). All these would increase between-CBSA patent citations.

Using name-disambiguated patent data from PatentsView, we are able to track inventor relocation. When an inventor appears on multiple patents with addresses in different CBSAs, we identify an incidence of inventor relocation (Marx et al. 2009). We use the application year of the subsequent patent as the year when inventor relocation occurs.[17] The distribution of the between-CBSA inventor relocation is highly skewed. Only about 5% of our CBSA-pair-year level observations have non-zero inventor relocation. In Table 7 column (1), we find a negative coefficient on *Log(Travel Time)*, which suggests that reduced travel time leads to an increased probability of between-CBSA inventor relocation. This coefficient is significant at the 1% level. In column (2), we regress the between-CBSA citations on both the *Log(Travel Time)* and a dummy capturing between-CBSA inventor relocation. As expected, between-CBSA inventor relocation is significantly positively associated with between-CBSA patent citations. The size of the coefficient of *Log(Travel Time)* declines

[17] Using the application year of the prior patent, or the midpoint between the application year of the prior patent and the subsequent patent leads to qualitatively the same result.

slightly from -0.25 in the baseline result to -0.24, indicating that between-CBSA inventor relocation partially accounts for the effects of reduced travel time on patent citations, albeit the effect being small.

Several reasons might explain the seemingly small change in the coefficient of *Log(Travel Time)* between columns (1) and (2). First, our measure of inventor relocation is unfortunately quite noisy due to the inaccurate timing for when the relocation occurs. Second, only a small part of between-CBSA traveling and interactions will eventually turn into job relocation. Moreover, in order to be captured by the patent database, these scientists and engineers will have to have changed jobs between-CBSA, have contributed to knowledge spillovers, and will patent again. This stringent requirement means that only a very small proportion of inventors is captured by our empirical specification. Taken together, our results support the conjecture that reduced travel time increases between-CBSA knowledge transfer by making it easier for an inventor to travel and interact with other inventors. In addition, the economic magnitude documented should be interpreted as an underestimate of the actual effect of inventor relocation.

The second potential channel we investigate is whether reduced communication costs influence between-CBSA collaboration (Agrawal and Goldfarb 2008, Catalini et al. 2020). We count each pair of inventors who locate in different CBSAs and appear on a same patent as an incidence of between-CBSA collaboration. The results in Table 7 column (3) show that when we regress an indicator variable that captures between-CBSA collaboration on *Log(Travel Time)*, the coefficient on travel time is insignificant and small in size though negative as predicted. In column (4) we regress between-CBSA patent citations on both travel time and a dummy indicating the existence of between-CBSA collaboration. While the existence of between-CBSA collaboration significantly and positively increases patent citations, adding it to the baseline regression does not affect the coefficient of travel time. Though this result may appear to contradict the literature at first sight, upon close inspection, however, an important difference exists between our setting and prior literature on scientists' collaboration. Namely, existing studies on how travel costs influence collaboration (Boudreau et al. 2017, Chai and Freeman 2019, Catalini et al. 2020) are almost exclusively based on academic collaboration which forms more "organically" and spontaneously. In our setting, the formation of an inventor team is likely to be constrained by firms' organizational structure, as multi-locational firms may have other within-firm channels for knowledge transfer (Alcácer and Zhao 2012) that are not sensitive to travel time changes. Moreover, firms might have policies on R&D team formation and collaborative relationships, which differ from a freestyle collaboration in the academic setting.

In summary, while both inventor relocation and between-CBSA collaboration have positive effects on patent citations, reduced travel time is likely to increase between-CBSA knowledge diffusion through increasing inventor traveling and circulation. Within-firm collaboration does not appear to be responsive to travel time reduction, possibly because there already exist strong ties within multi-location firms that connects inventors. These findings are also consistent with our earlier results (i.e., Table 4) that reduced travel time mainly facilitates between-CBSA knowledge spillovers across organizational boundaries rather than within organizations.

3.5.2 Effects Before and After the Rise of the Internet

In the latter half of our sample period, information technologies (IT) and Internet adoption revolutionized the way people communicate with each other. Prior studies have shown that IT and Internet adoption increased both the diffusion of explicit knowledge through facilitating document searching and the diffusion of tacit knowledge through facilitating interpersonal communications (Forman and van Zeebroeck 2019). IT and the wide availability of fast Internet may substitute some face-to-face interaction that can only be achieved by traveling to the same physical location, thus making travel time reduction less important in knowledge diffusion. To test this conjecture, we split our sample by 1995, the year when the commercial Internet began to diffuse (Giroud 2013, Forman and van Zeebroeck 2019), into two time periods of about the same lengths: 1980-1995 (16 years) and 1996–2010 (15 years). In Table 8 we show that travel time has a negative and significant effect on patent citations in the early half of our sample period (Column 1), but an insignificant effect in the latter half which happens to correspond to the rise of the information technology. This pattern is consistent with Giroud (2003), who also find a dampened effect of travel time reduction on communications between headquarter and plants for the period after 1995.

To more directly test whether the lack of effects of travel time on knowledge diffusion is related to the rise of the Internet, we investigate how the availability of commercial Internet affects the effects of travel time. Specifically, we obtain the number of high-speed Internet service providers by ZIP codes by year from Form 477 data[18]. This data was collected

[18] https://www.fcc.gov/form-477-data-zip-codes-number-high-speed-service-providers

annually starting from 1999 until 2008.[19] We average[20] this zip-year-level number at the CBSA-year level. For each year, we use the lower number of the two, one at the citing CBSA and one at the cited CBSA, to measure *dyadic internet availability* at the CBSA-pair-year level. The rationale for this measurement is that, even if there is commercial Internet available in one CBSA but not in the other CBSA, the CBSA pair still does not benefit from the lower communication costs brought about by the Internet.

In Table 8 column (3), we first report our baseline regressions for this subsample between 1999 and 2008. In column (4), we include the *Log(travel time)*, *dyadic internet availability*, as well as the interaction between the two variables. Several patterns are noteworthy: First, the main effect of travel time on citations during this period remains negative and significant. In particular, the size of the coefficient is close to our baseline results. It indicates that, when at least one of the two CBSAs of a pair does not have any high-speed internet provider, travel time reduction significantly increases between-CBSA knowledge diffusion during the latter sample period just as it does in the earlier period. Second, the coefficient of *dyadic internet availability* is positive and significant. That is, holding travel time constant, increasing the number of high-speed internet providers increases between-CBSA knowledge diffusion. Finally, the interaction between travel time and *dyadic internet availability* is positive, suggesting that the longer the travel time, the bigger the effects of the Internet on knowledge diffusion.

To shed further light on how various levels of dyadic Internet availability between CBSA pairs impact knowledge diffusion, we further decompose the availability variable into separate indicators: *Dm(Dyadic Internet Availability* $\in [0,1)$*)*, *Dm(Dyadic Internet Availability* $\in [1,2)$*)*, *Dm(Dyadic Internet Availability* $\in [2,3)$*)*, and *Dm(Dyadic Internet Availability* ≥ 3*)*. For instance, *Dm(Dyadic Internet Availability* $\in [0,1)$*)* is an indicator variable that takes the value of one if neither of the two CBSAs of a given CBSA pair has one or more internet providers per zips-code on average, and zero otherwise. *Dm(Dyadic Internet Availability* $\in [1,2)$*)* is an indicator variable that takes the value of one if both the two CBSAs of a given CBSA pair has at least one but no more than two internet providers per zips-code on average, and zero otherwise. The other three dummy variables are defined analogously. Figure A3

[19] The data is available up to 2008 due to the saturated coverage (up to 96% by 2007, see Atasoy 2013).
[20] For zip codes with between one to three high-speed internet service providers, the data do not disclose the specific number for confidentiality protection. In this case, we fill the zip-year observation with 1.5 providers. For zip codes that do not appear in the form 477 data in a year, we fill the zip-year observation with zero provider.

provides the distribution of the Dyadic Internet Availability. Evidently, the distribution is highly skewed to the right, with a large number of CBSA pairs having one to three average Internet Service Providers (ISP) and a small number of CBSA pairs having greater than five ISPs.

In Column (5), we re-estimate the interactive effects between travel time and Internet availability on knowledge diffusion using the newly created binary variables. Several results stand out: First, the coefficient estimates for the four interactions increase monotonically, from -0.022 for *Log (Travel Time) X Dm(Dyadic Internet Availability ∈[0,1))*, to 0.041 for *Log (Travel Time) X Dm(Dyadic Internet Availability ≥3)).* This monotonic pattern suggests that physical, face-to-face interaction remains highly important for knowledge diffusion when alternative channels of communication enabled by Broadband Internet are unavailable, but its importance significantly declines when such alternatives become readily available. Second, the coefficient of -0.022 for the first interaction *(Log (Travel Time) X Dm(Dyadic Internet Availability ∈[0,1))).* Not only is this coefficient statistically significant at the 5% level, the magnitude is also almost the same as the coefficient in column (1) (i.e., -0.023). This suggests that, in the later sample period (i.e., 1999-2008), for CBSA pairs that are poorly connected by the Internet, travel time bears almost the same level of importance for knowledge diffusion as in the earlier period (i.e., 1980 to 1998). In contrast, the coefficient on the interaction term *Log (Travel Time) X Dm(Dyadic Internet Availability ≥3))* is statistically significant and positive. This implies that the longer the travel time, the larger the effects of Internet penetration on knowledge diffusion, which possibly reflects the notion that CBSA pairs that are more distant in terms of travel time have more under-explored opportunities for knowledge exchange and the introduction of the Internet enables such "catching up".

Taken together, these results point to a strong substitution effect between face-to-face meetings as dictated by travel time and alternative methods of communication that allow for both visual and audio interaction. Though we do not think such substitutability is 100%, i.e., there are certain aspects of knowledge transfer that rely on tacit knowledge (our focus for the next section), informal social interaction, and perhaps relationship building, technology-enabled new methods of communication such as Zoom/Teams meetings provide a timely and crucial alternative when face-to-face interactions are rendered impossible.

Thinking beyond our results, during the initial onset of the recent Covid-19 pandemic, businesses, schools, governments, and research institutions in the U.S. and globally saw a sudden imposed termination of face-to-face communication. Work-from-home became almost the only option for continued operations for many organizations, for-profit and nonprofit alike. In fact, several studies (e.g., Bai, Brynjolfsson, Jin, Steffen, and Wan 2022; Oikonomou, Pierri, and Timmer, 2023) document the superior performance of companies with work-from-home capabilities relative to their peers during the pandemic. Our findings corroborate these studies by suggesting that newly emerging technologies might continue to play an increasingly significant role in allowing for effective, essential communication while face-to-face interactions retain their special role in facilitating relationship building and tacit knowledge transfer.

3.5.3 Tacit Knowledge

Tacit knowledge has long been regarded as those elements of knowledge, insight, and so on that individuals have which are ill-defined, uncodified, unpublished, which they themselves cannot fully express, and which differ from person to person, but which may to some significant degree be shared by innovators and colleagues who have a common experience (Polanyi 1967). Our results so far suggest that it is the transfer of tacit knowledge that mostly responds to travel time reduction. First, as previously mentioned in Table 5, our main effects are the strongest in highly complex technological classes. This result is consistent with the notion that specific and tacit knowledge serves as a complement to public knowledge in science-based fields, particularly those that are complex in nature (Dosi 1988). Second, the citations to new technologies are more responsive to travel time reduction, whereas the citations to dated technologies are not. This is consistent with the notion that mature technologies are better codified while fresh technologies contain more tacit contents (Pisano and Shih 2012). Lastly, travel time reduction increases knowledge diffusion by facilitating inventor flow when Internet-enabled substitutes for face-to-face interactions were unavailable (e.g., Giroud 2013, Agrawal and Goldfarb 2008, and Panahi et al. 2013).

Although patent citations reflect the usage of published documents, they also capture the diffusion of tacit knowledge. The patent system requires open publication of patents to inform inventors what are protected and facilitate latter usage of prior inventions. Yet, modern patents often lack transparency in information disclosed. We illustrate this idea using two examples. First, take the “Electromagnetic Windshield Wiper System” (patent number: US 10,899,267 B2) in appendix B1 as an example, the patent includes a detailed description of the mechanical layout of each physical component of the system by including a graphic illustration and explanation of the functions and locations of each part. However, detailed answers to questions such as “what angle do electromagnets need to point at”, “the required strength level for the spring used in the actuator”, “the power that is needed for optimized electromagnetic field”, or “at what speed does this system work/fail” is not provided or required in the patent application. But one can easily imagine that in order to build on this proposed technology, any future work citing this patent needs to have the answers to the aforementioned questions. Because these answers are only available after repeated experiments and optimal reconfiguration, this tacit knowledge can only be transferred through face-to-face communications or alternative means that allow for close interactions via video and audio conferencing.

Another example is the “Active Materials for Lithium-Ion Batteries” (patent number: US 2012/0280435 A1), which proposes a new active material that was previously unused in forming a cathode of a lithium battery (included in appendix B2). The patent contains a detailed description of the general procedure for generating such a cathode (Figures 1 and 2 of the patent), but remains vague on many fronts. For instance, in talking about the underlying material for the cathode, the patent deliberately uses molecular formulas that are obscure. Specifically, the patent talks about $Li_zNi_{1-x-y}Mn_xCo_yO_2$ as a potential material but does not reveal the values of x and y that would make this substance chemically feasible and stable as well as optimal for the purpose of a cathode. Vague languages such as “in certain embodiments” are used throughout the patent description. It is likely that the patent inventors have no intention of sharing their “secret ingredient” with the general public, and this valuable information is only available by talking with or interacting closely with the inventors who have run numerous experiments to figure out the optimal substance(s).

Taken together, we believe that patent citations correspond to the diffusion of tacit knowledge at least to a certain degree. The reduced travel time makes face-to-face interactions easier, making it less costly for inventors to get together through formal or informal social settings to share stories, knowhows, and experiences, leading to higher citations between affected CBSA pairs.

4. Conclusion

In this paper, we estimate the elasticity of patent citations to between-CBSA travel time between CBSAs to study how proximity causally influences knowledge diffusion and in turn affects the volume and direction of future innovation. We find that a 20% reduction in travel time owing to the introduction of new flight routes increases knowledge flow by 0.5%, which corresponds to an increase of over 15,000 citations at the aggregate level. Better connected CBSAs generate more impactful new patents, and also develop more in technology areas where its "neighboring" CBSAs in terms of travel time instead of geographical distance are active in.

We find that the increases in citations resulting from travel time reduction are mainly knowledge spillovers across organizational boundaries. The effects are particularly strong when the knowledge-absorbing entity (citation maker) and the knowledge-diffusing entity (citation receiver) are connected through relationships such as joint ventures, block holdings, and vertically related supplier-customers. We also find that the increases in citations are more pronounced among city pairs located farther away from each other, with higher absorptive capacity, in more complex technology classes. Moreover, citations to dated prior knowledge are not responsive to these travel time reductions while that to recently developed technologies do. These results suggest that the effective learnings of tacit knowledge are more responsive to travel time reduction. When we investigate the mechanism, we find evidence that our results are primarily driven by increased inventor flow and likely tacit knowledge transfer due to more convenient information acquisition.

Overall, this study expands our understanding of knowledge diffusion across metropolitan areas in the U.S. through the lens of travel time reduction that results from the introduction of new airline routes. Our findings also underscore the changing dynamics of knowledge diffusion through technological advancement and highlight important avenues for further research designed to provide more effective policy suggestions for promoting knowledge diffusion and innovation.

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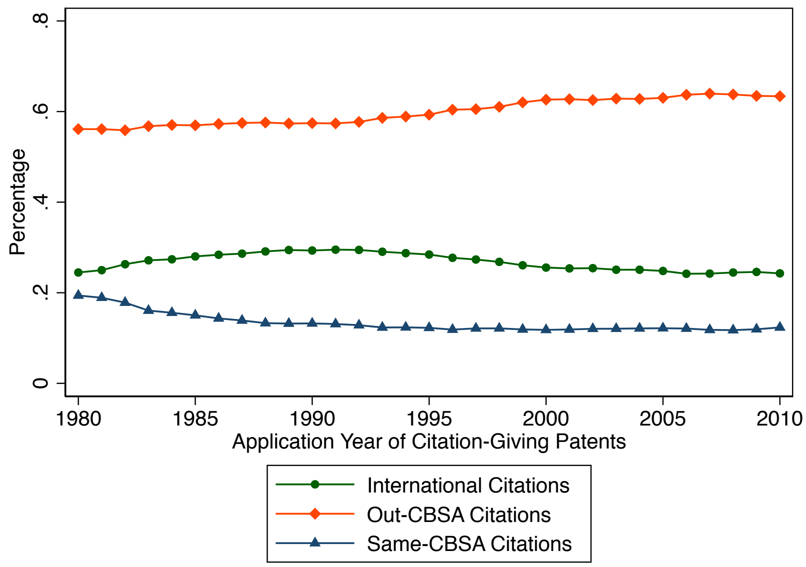
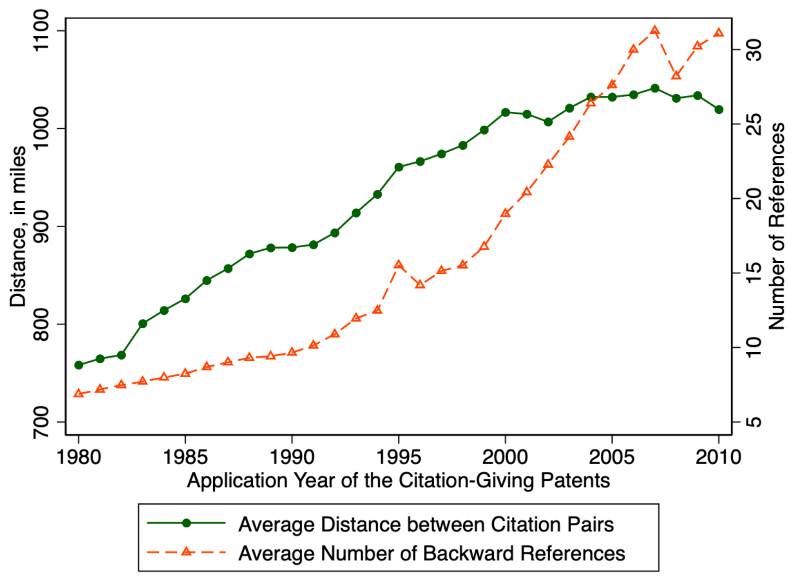
Figure 1: Patent Citations by Locations



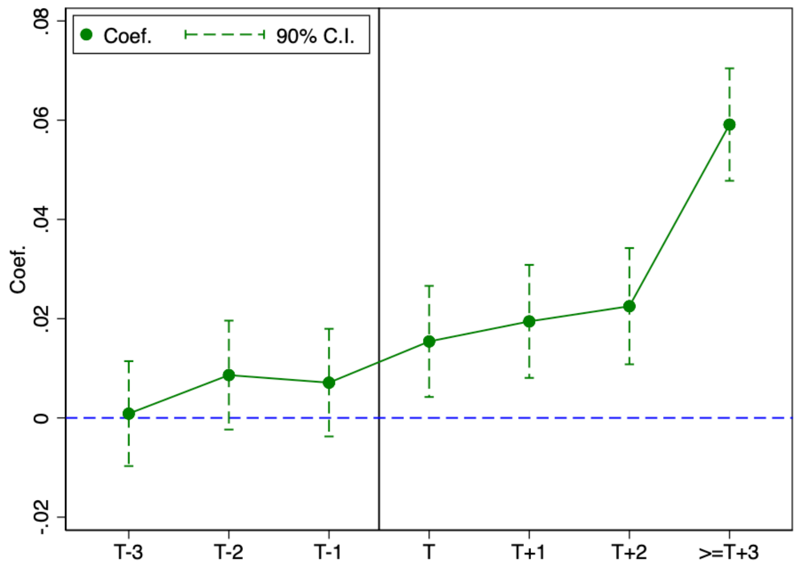
Notes: The reported statistics are based on the USPTO patent citations which satisfy the following requirements: (1) the citation-giving patents have at least one inventor in a U.S. CBSA, (2) the citation-giving patents are applied for during 1980 – 2010 and granted by 2014, and the citation-receiving patents are applied for during 1976 – 2010 and granted by 2014.

Figure 2. Pairwise Distance Between Citations



Notes. When calculating the average number of backward references, the sample of citation-giving patents is restricted to the USPTO patents with at least one U.S. inventor. When calculating the pairwise distance in miles between citations, both the citation-giving patents (citing patents) and the citation-receiving patents (cited patents) are restricted to the USPTO patents with at least one U.S. inventor. Citations to or from patents invented in foreign countries are not considered.

Figure 3: Dynamic Effects of New Airline Routes



Notes. We use the log (number of three-year citations+1) as the dependent variable and a sample of CBSA pairs that experienced no more than one time of reduction in travel time. All years of the relevant CBSA pairs are used in the regression. The period before three years prior to the reduction in travel time is used as the reference group and its coefficient is omitted. The period in and after the third year post the reduction in travel time is grouped into the last period. The coefficients are estimated based on a two-way fixed effects model, with CBSA pair fixed effects and year fixed effects controlled for. Robust standard errors clustered at the CBSA-pair level.

Table 1. Travel Time Changes

	Type of Travel Time Change						
	Travel Time Reduction						Travel Time Increase
	Indirect to Direct	Indirect to Indirect	Direct to Direct	Direct to Indirect	Roads to Flight	All	
Number of Changes	13,115	12,942	5,742	2,008	4,076	37,914	20,988
Distance (in miles)	1112.7	1322.7	825.5	1207.4	315.3	1059.5	928.9
	(590.5)	(561.6)	(489.4)	(579.)	(70.1)	(613.9)	(601.5)
Travel time before	6.51	7.96	5.57	7.79	5.17	6.77	5.19
(in hours)	(1.5)	(1.5)	(1.4)	(1.6)	(1.1)	(1.8)	(1.8)
Travel time after	5.13	6.66	4.42	6.42	3.75	5.46	6.43
(in hours)	(1.6)	(1.4)	(1.3)	(1.5)	(1.1)	(1.8)	(1.8)
Δ travel time (in hours)	-1.41	-1.33	-1.17	-1.38	-1.45	-1.35	1.25
Δ travel time (%)	-21.6%	-16.7%	-21.0%	-17.8%	-27.9%	-19.9%	24.2%

Notes. A total of 17,407 (15.7%) distinct CBSA pairs experienced only one change in travel time, and 15,424 (13.9%) distinct CBSA pairs experienced multiple changes in travel time. The total number of changes is bigger than the number of distinct CBSA pairs that experienced some changes in travel time. A "Direct to Direct" itinerary change reduces the between-CBSA travel time by flying from an airport closer to the origin CBSA or to an airport closer to the destination CBSA. A "Direct to Indirect" itinerary change reduces travel time when the shorter drive time in the new "indirect" itinerary dominates the shorter flight time in the old "direct" itinerary. The sample period is from 1980 and 2010.

Table 2. Summary Statistics

Subsamples:	Never Treated	Eventually Treated
Number of Observations	2,349,521	1,091,417
Distance between CBSA (in miles)	945.75	1051.68
	(669.08)	(615.25)
One-Way Travel Time between CBSA (in hours)	5.44	6.00
	(2.08)	(1.82)
Number of 3-Year Patent Citations*	0.92	0.90
	(16.87)	(17.53)
Number of Patents at Citing CBSA**	378.53	333.00
	(971.57)	(857.86)
Number of 3-Year Cumulated Patents at Cited CBSA***	1465.92	1295.51
	(3761.81)	(3341.88)

Notes. The sample period is from 1980 to 2010. Each observation is a CBSA-pair-year cell. Note that citations are directional. For example, citations from Chicago to Boston and citations from Boston to Chicago indicate knowledge flow in opposite directions. Thus, in any given year, Chicago-to-Boston and Boston-to-Chicago appear in data as two distinct CBSA pairs. *The number of citations made by patents applied for in year t in the citing CBSA, and received by patents applied for between year $t-3$ and $t-1$ in the cited CBSA. **The number of patents applied for in year t in the citing CBSA. ***The number of cumulated patents applied for between year $t-3$ and $t-1$ in the cited CBSA.

Table 3. Reduction in Travel Time Facilitates Knowledge Diffusion

Dependent Variable	Log(Number of 3-year Citations+1)			
	(1)	(2)	(3)	(4)
Log (Distance)	-0.057***	0.036***		
	(0.002)	(0.004)		
Log (Travel Time)		-0.179***	-0.025***	-0.014*
		(0.007)	(0.006)	(0.007)
Log (Travel Time)$_{t-1}$				-0.012*
				(0.007)
Log (Travel Time)$_{t+1}$				-0.005
				(0.007)
Log (New Patents in Citing-CBSA+1)	0.096***	0.096***		
	(0.001)	(0.001)		
Log (Patent Stock in Cited-CBSA+1)	0.088***	0.087***		
	(0.001)	(0.001)		
Year FE	Y	Y		
Citing-CBSA FE	Y	Y		
Cited-CBSA FE	Y	Y		
CBSA-pair FE			Y	Y
Citing-CBSA X Year FE			Y	Y
Cited-CBSA X Year FE			Y	Y
Observations	3,440,938	3,440,938	3,440,938	2,908,823
R-squared	0.262	0.264	0.678	0.631

Notes. The reported estimates from (1) to (3) are based on a balanced panel from 1980 to 2010. Each observation is a CBSA-pair-year unit. For an observation in year t with CBSA i as the citing CBSA and CBSA j as the cited CBSA, the dependent variable is the $\log(x+1)$ transformation of the number of citations made by patents applied for in year t in CBSA i, and received by prior patents applied for between year $t-3$ and $t-1$ in CBSA j. The Patent Counts in Citing-CBSA is the number of patents applied for (and latter granted) in CBSA i in year t. The Patent Stock in Cited-CBSA is the number of patents applied for in CBSA j between year $t-3$ and $t-1$. In column (4) we report how the contemporaneous travel time, the travel time one year before, and the travel time one year after affect current knowledge diffusion respectively. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 4. Heterogeneity - Sources of Citations

Dep. Var.	Log(Number of 3-Year Citations+1)							
Relationship between citing patent and cited patent:	Total	Same Inventor	Same Assignee	Same Firm	Other	Joint Venture	Merge & Acquisitions	Vertical Customers
Mean	0.908	0.029	0.066	0.070	0.831	0.061	0.010	0.015
(St. Dev.)	(17.06)	(1.659)	(2.790)	(2.899)	(14.89)	(2.599)	(0.669)	(0.789)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log(Travel Time)	-0.025***	-0.003	-0.003	-0.003	-0.028***	-0.008**	-0.004**	-0.007***
	(0.006)	(0.002)	(0.003)	(0.003)	(0.006)	(0.003)	(0.002)	(0.002)
CBSA-pair FE	Y	Y	Y	Y	Y	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Observations	3,440,938	3,440,938	3,440,938	3,440,938	3,440,938	3,440,938	3,440,938	3,440,938
R-squared	0.678	0.372	0.460	0.469	0.676	0.473	0.347	0.385

Notes. We make use of the assignee disambiguation and inventor disambiguation from PatentsView to track assignee and inventor across different patents. And we use the match by Kogan et al. (2017) to link patents to publicly listed firms. In column (2), "same inventor" citations include all patent citation pairs where citing patent and cited patent share any inventor. In column (3), "same assignee" citations include all patent citation pairs where citing patent and cited patent share any common assignee. In column (4), "same firm" citations include all same-assignee citations and those whose citing patent and cited patent share a common PERMNO of a publicly listed firm. In column (5), "Other" indicates citation pairs that do not fall into any category found from column (2) to column (4). In column (6) "Joint Venture" citations include all patent citation pairs where both the citing patents and the cited patents are linked to some publicly listed firms (PERMNO) and the two firms have had joint venture deals in or prior to the year of the application year of the citing patents. In columns (7) and (8), "M&A citations" and "Vertical Customers Citations" are defined correspondingly. The sample period ranges from 1980 to 2010. Each observation is a CBSA-pair-year unit. In all specifications, we take log $(x + 1)$ transformation for the number of citations to prior patents in 3-year rolling reference windows as the dependent variable. CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year are always controlled for. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 5. Heterogeneity – Distance, Absorptive Capacity, Technology Complexity, and Reference Windows

Dependent Variable	Log (Number of 3-Year Citations+1)			
Panel A:	*Quartiles of Distance*			
	P0-P25	P25-P50	P50-P75	P75-P100
	(1)	(2)	(3)	(4)
Log (Travel Time)	-0.006	-0.013	-0.076***	-0.074***
	(0.009)	(0.011)	(0.016)	(0.024)
Observations	858,731	859,072	858,669	857,305
R-squared	0.690	0.644	0.662	0.740
Panel B:	*Quartiles of Absorptive Capacity of Citing-CBSA*			
	P0-P25	P25-P50	P50-P75	P75-P100
	(1)	(2)	(3)	(4)
Log (Travel Time)	0.004	-0.003	-0.018*	-0.045***
	(0.006)	(0.010)	(0.010)	(0.014)
Observations	836,752	837,355	838,085	842,084
R-squared	0.210	0.399	0.612	0.807
Panel C:	*Quartiles of the Technology Complexity of Cited Patents*			
	P0-P25	P25-P50	P50-P75	P75-P100
	(1)	(2)	(3)	(4)
Log (Travel Time)	-0.012***	-0.013***	-0.014***	-0.022***
	(0.004)	(0.004)	(0.004)	(0.004)
Observations	3,440,938	3,440,938	3,440,938	3,440,938
R-squared	0.536	0.601	0.598	0.592
Panel D:	*Alternative Reference Windows*			
	3-year	6-year	10-year	Prior to 1985
Mean	0.908	2.458	4.782	1.154
Std. Dev.	(17.06)	(42.67)	(76.36)	(11.91)
	(1)	(2)	(3)	(4)
Log (Travel Time)	-0.025***	-0.022***	-0.014	-0.002
	(0.006)	(0.008)	(0.010)	(0.006)
Observations	3,440,938	3,107,944	2,663,952	2,774,950
R-squared	0.678	0.742	0.784	0.755
CBSA-pair FE	Y	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y	Y

Notes. The sample period ranges from 1980 to 2010. Each observation is a CBSA-pair-year unit. For Panel A we split the sample into four quartiles according to the between-CBSA distance. For Panel B, we use cumulated patents applied for during the fixed window between 1977 and 1985 to proxy for the "absorptive capacity" of a citing CBSA and split the sample into four quartiles accordingly. For Panel C, we classify citation-receiving patents into four quartiles of technology complexity and count the CBSA-pair-year level number of citations to these four sets of patents separately. For Panel D, we use three-year citations (col. 1), six-year citations (col. 2), ten-year citations (col. 3), and citations to patents applied for between 1977 and 1985 (col. 4) as dependent variables. The sample periods corresponding to these dependent variables are from 1980 to 2010 (col. 1), from 1983 to 2010 (col. 2), from 1987 to 2010 (col. 3), and from 1986 to 2010 (col. 4), respectively. In all specifications, we take log $(x + 1)$ transformation for the number of citations to prior patents in 3-year rolling reference windows as the dependent variable. CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year are always controlled for. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 6. The Effects of Travel Time on the Volume and the Direction of New Knowledge Creation

Dependent Variable	Log (Number of Patents at the Knowledge-Receiving CBSA+1)	Log (Citation Weighted Number of Patents at the Knowledge-Receiving CBSA+1)	Log(Number of Star Patents – Top 25 %+1)	Between-CBSA Similarity of Technological Direction
	(1)	(2)	(3)	（4）
Log (Travel Time)	-0.269***	-0.338***	-0.278***	-0.005**
	(0.046)	(0.054)	(0.048)	(0.002)
Citing-CBSA FE	Y	Y	Y	
CBSA-pair FE	Y	Y	Y	Y
Citing-CBSA X Year FE				Y
Cited-CBSA X Year FE	Y	Y	Y	Y
Observations	3,440,938	3,440,938	3,440,938	3,278,027
R-squared	0.961	0.935	0.939	0.703

Notes. The reported estimates are based on a balanced panel from 1980 to 2010. Each observation is a CBSA-pair-year unit. The dependent variable used in column (1) is the $\log(x + 1)$ transformed number of patents at the knowledge-receiving CBSA. In column (2), we weigh the number of patents at each knowledge-receiving CBSA using the total number of forward citations these patents garnered by 2010 and then use its $\log(x + 1)$ transformation as the dependent variable. In column (3), we use the $\log(x + 1)$ transformed number of high-impact patents at the knowledge-receiving CBSA as the dependent variables. High-impact patents are defined as those ranking top 25% among patents applied for in the same year based on their total forward citations garnered by 2010. In column (4), the dependent variable is the inner product of the patent-class vectors between two CBSAs for patents newly applied for per year. Travel Time in Hours indicates the one-way travel time between CBSAs. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 7. Inventors' Cross-CBSA Relocation and Collaboration

Dependent Variable	Dm(Inventor Relocation)	Log (Number of Citations+1)	Dm(Between-CBSA Collaboration)	Log (Number of Citations+1)	Log (Number of Citations+1)
	(1)	(2)	(3)	(4)	(5)
Log (Travel Time)	-0.010***	-0.024***	-0.001	-0.025***	-0.024***
	(0.003)	(0.006)	(0.004)	(0.006)	(0.006)
Dm(Inventor Relocation)		0.121***			0.109***
		(0.002)			(0.002)
Dm(Between-CBSA Collaboration)				0.119***	0.109***
				(0.002)	(0.002)
CBSA-pair FE	Y	Y	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y	Y	Y
Observations	3,440,938	3,440,938	3,440,938	3,440,938	3,440,938
R-squared	0.364	0.679	0.446	0.680	0.681

Notes. Dm(Inventor Relocation) equals to one when we observe at least one inventor relocation between a CBSA pair in a given year and zero otherwise. To identify inventor relocation, we make use of the inventor disambiguation provided by PatentsView, track a same inventor who appears on multiple patents with different inventor addresses, and use the application year of the subsequent patent as the year when the relocation occurs. Results are similar when we use the application year of the former patent, or use the midpoint between the former patent and the subsequent patent as the year of inventor relocation. Dm(Between-CBSA Collaboration) equals to one when we observe at least one patent with inventors from both CBSAs of a CBSA pair in a given year. While some 42.8% of distinct CBSA pairs have ever had inventor collaboration and 43.3% have ever experienced inventor relocation, both variables take non-zero values in only about 5% of our CBSA-pair-year level observations. In all specifications, CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year are controlled for. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 8. Effects by Period and Internet Penetration

Dependent Variable	Log (Number of Three-Year Citations+1)				
Sample Years	1980-1995	1996-2010	1999-2008		
	(1)	(2)	(3)	(4)	(5)
Log (Travel Time)	-0.023***	0.007	0.019*	-0.026**	
	(0.006)	(0.009)	(0.011)	(0.011)	
Log(Dyadic Internet Availability+1)				0.072***	
				(0.007)	
Log (Travel Time) *X* *Log(Dyadic Internet Availability+1)*				0.034***	
				(0.002)	
Log (Travel Time) *X*					
Dm(*Dyadic Internet Availability* ∈ [0,1))					-0.022**
					(0.011)
Dm(*Dyadic Internet Availability* ∈ [1,2))					-0.009
					(0.011)
Dm(*Dyadic Internet Availability* ∈ [2,3))					0.019*
					(0.011)
Dm(*Dyadic Internet Availability* ≥ 3)					0.041***
					(0.011)
CBSA-pair FE	Y	Y	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y	Y	Y
Observations	1,775,968	1,664,970	1,109,980	1,109,980	1,109,980
R-squared	0.667	0.750	0.773	0.773	0.773

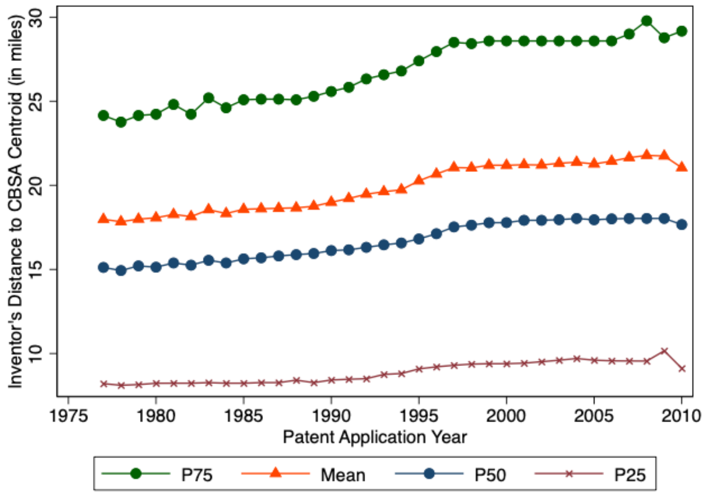
Notes. In column (1) we use the period of 16 years between 1980 and 1995. In column (2) we use the period between 1996 and 2010. In column (3), column (4), and column (5) we use the period between 1999 and 2008, when the data on the zip code level number of commercial internet providers are available from Form 477 (Downloaded at https://www.fcc.gov/form-477-data-zip-codes-number-high-speed-service-providers). *Dm(Dyadic Internet Availability ∈[0,1))* is an indicator variable that takes the value of one if neither of the two CBSAs of a given CBSA pair has one or more internet providers per zips-code on average, and zero otherwise. *Dm(Dyadic Internet Availability ∈[1,2))* is an indicator variable that takes the value of one if the two CBSAs of a given CBSA pair both have at least one internet providers but neither has more than two internet providers per zips-code on average, and zero otherwise. The other indicator variables for internet availability are defined analogously. We average the zip-code level number of internet service companies at the CBSA level, and take the lower number of service providers of the two CBSAs of each CBSA pair as the measure of *dyadic internet availability* at the CBSA-pair-year level. In all specifications, CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year are controlled for. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Online Appendix for "Proximity and Knowledge Spillovers: Evidence from the Introduction of New Airline Routes"

Online Appendix A contains supplementary figures and tables. Online Appendix B contains two actual patent documents. The first patent is "Electromagnetic Windshield Wiper System" (patent number: US 10,899,267 B2) as Appendix B1; The second patent is "Active Materials for Lithium-Ion Batteries" (patent number: US 2012/0280435 A1) as Appendix B2.

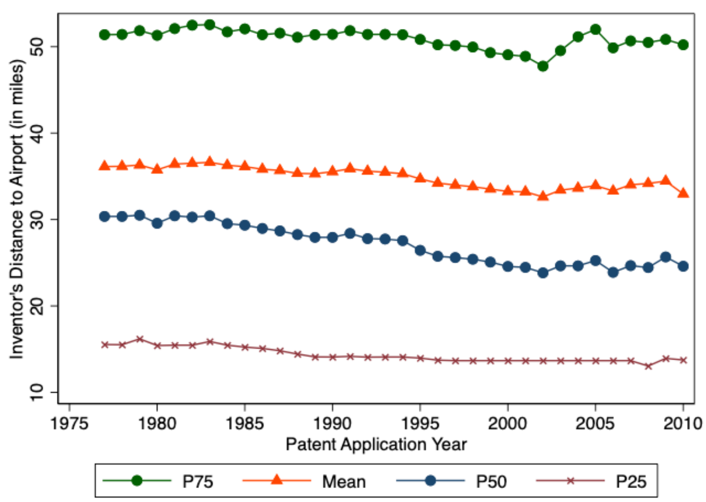
Online Appendix A

Figure A1. Inventors' Spatial Distribution Within CBSAs
(A) Inventors' Distances to CBSA Centroids



Notes. The distance from inventors to the centroid of their CBSAs increased only slightly over the sample period. The average distance increased from 18 miles or so in 1977 to 21 miles in 2010, a 3-mile difference. The 75th percentile increased by less than 5 miles.

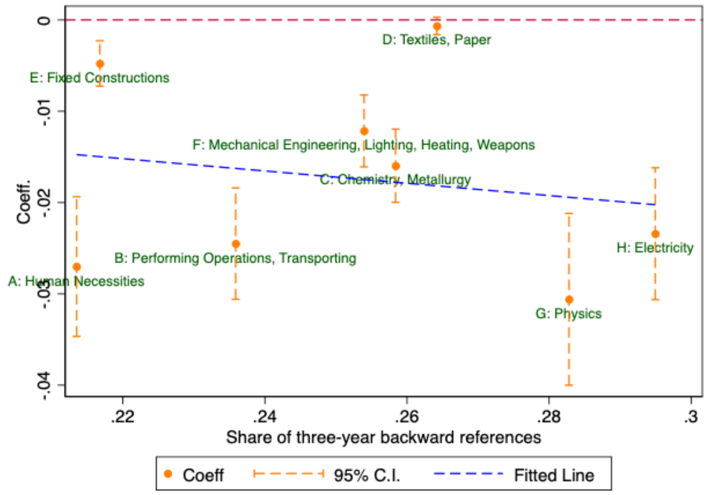
(B) Inventors' Distances to Airports



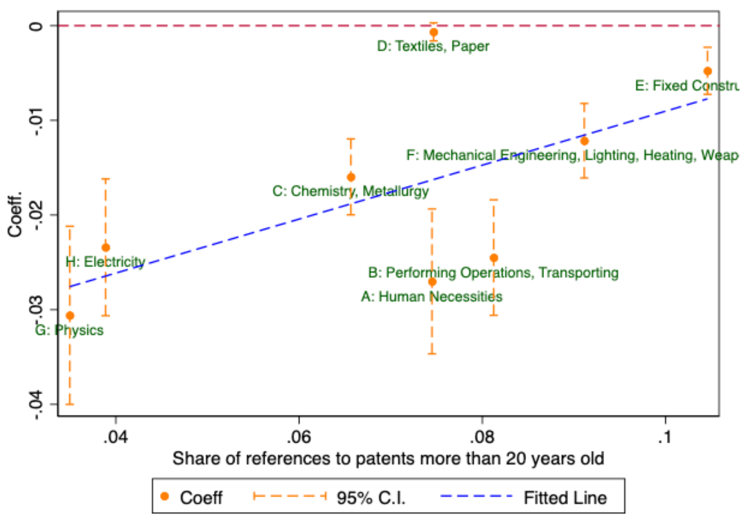
Notes. The distance from inventors to the airports of their CBSAs decreased slightly over the sample period. The average distance decreased from 36 miles in 1977 to 32 miles in 2010, a 4-mile difference. The 75th percentile decreased by about 1 mile.

Figure A2. Travel Time and Knowledge Diffusion, by Technology Class

(A)

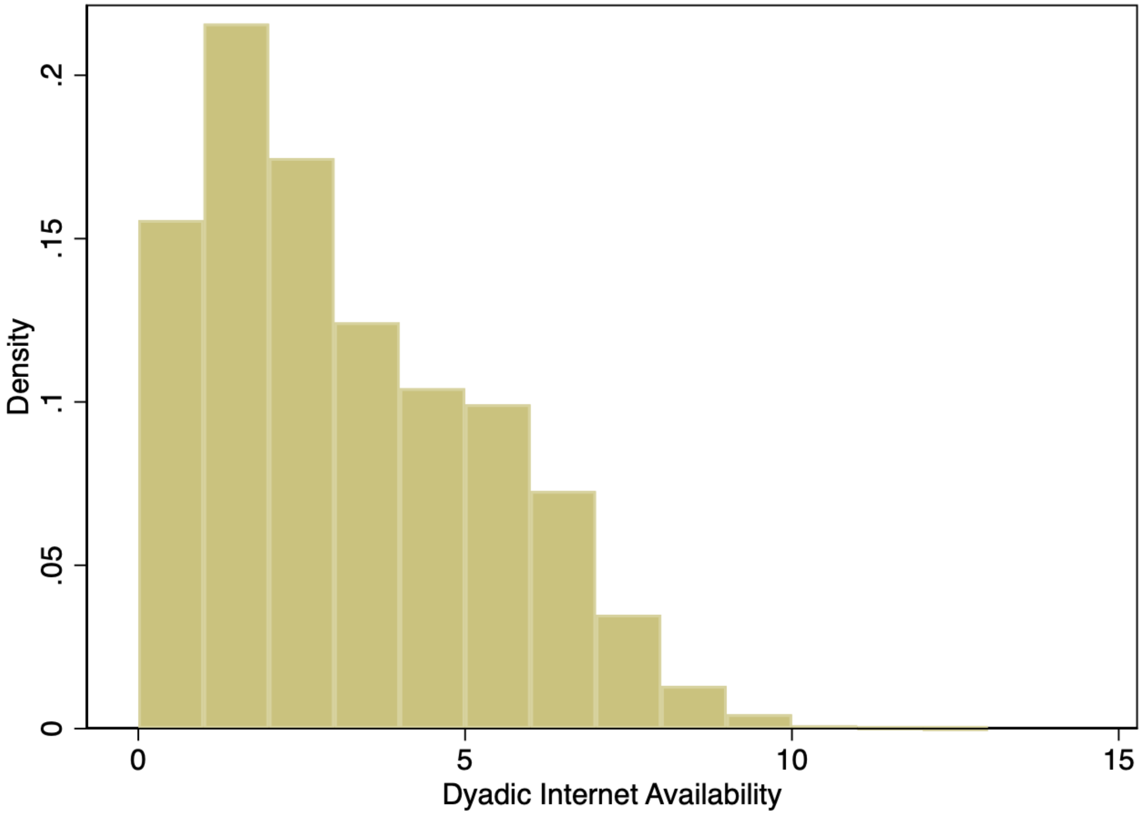


(B)



Notes. Each point is derived from a separate regression with the sample restricted to citations made by patents of the labeled technology class. The dependent variable is the log $(x + 1)$ transformation for the number of citations to prior patents in 3-year rolling reference windows as the dependent variable. Control variables include between-CBSA technological proximity, CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year. Robust standard errors are clustered at the CBSA-pair level. The vertical axis indicates the coefficient of log (Travel Time). Figures 4(A) and 4(B) present the same set of regression coefficients. The horizontal axis in Figure 4(A) indicates the share of backward references a patent class makes to prior patents that were applied for within three years previously. The horizontal axis in Figure 4(B) indicates the share of backward references a patent class makes to prior patents that were applied for more than 20 years previously.

Figure A3: The Distribution of the Dyadic Internet Availability.



Notes: We average the zip-code level number of internet service companies at the CBSA level, and take the lower number of service providers of the two CBSAs of each CBSA pair as the measure of *dyadic internet availability* at the CBSA-pair-year level.

Table A1: Estimation Using Alternative Clustered Standard Errors

Dependent Variable	Log (Number of 3-year Citations+1)		
Standard Errors Clustered At:	CBSA Pair	Citing CBSA	Cited CBSA
	(1)	(2)	(3)
Log (Travel Time)	-0.025***	-0.025***	-0.025***
	(0.006)	(0.007)	(0.006)
CBSA-pair FE	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y
Observations	3,440,938	3,440,938	3,440,938
R-squared	0.678	0.678	0.678

Notes. The reported estimates from (1) to (3) are based on a balanced panel from 1980 to 2010. Each observation is a CBSA-pair-year unit. For an observation in year t with CBSA i as the citing CBSA and CBSA j as the cited CBSA, the dependent variable is the log $(x + 1)$ transformation of the number of citations made by patents applied for in year t in CBSA i, and received by prior patents applied for between year $t - 3$ and t in CBSA j. Statistical significances are indicated by: *** p<0.01, ** p<0.05, * p<0.1.

Table A2. Discrete Difference-in-Differences

Dependent Variable	Log(Number of 3-year Citations+1)	
	(1)	(2)
Dm (Post Travel Time Reduction)	0.046***	
	(0.006)	
Travel Time Reduction Year (-3)		0.001
		(0.006)
Travel Time Reduction Year (-2)		0.009
		(0.007)
Travel Time Reduction Year (-1)		0.007
		(0.007)
Travel Time Reduction Year (0)		0.015**
		(0.007)
Travel Time Reduction Year (1)		0.019***
		(0.007)
Travel Time Reduction Year (2)		0.023***
		(0.007)
Travel Time Reduction Year (3+)		0.059***
		(0.007)
CBSA-pair FE	Y	Y
Year FE	N	Y
Citing-CBSA X Year FE	Y	N
Cited-CBSA X Year FE	Y	N
Observations	2,588,996	2,588,996
R-squared	0.633	0.633

Notes. We restrict the sample to CBSA pairs that have experienced no more than one reduction in travel time. Dm (Post Travel Time Reduction) equals one after the travel time decreased by more than 1.5 hours as a result of new flight routes and zero otherwise. In column (2), we replace Dm (Post Travel Time Reduction) with six different dummies: Travel Time Reduction Year (-3), Travel Time Reduction Year (-2), Travel Time Reduction Year (-1), Travel Time Reduction Year (0), Travel Time Reduction Year (1), Travel Time Reduction Year (2), Travel Time Reduction Year (3+), where Travel Time Reduction Year (-3) is a dummy that equals one if a CBSA pair will experience a major travel time reduction (i.e., 1.5 hours or more in reduction) in three years. Travel Time Reduction Year (-2) is a dummy that equals one if a CBSA pair will experience a major travel time reduction two years from now. Travel Time Reduction Year (-1) is a dummy that equals one if a CBSA pair will experience a major travel time reduction one year from now. Travel Time Reduction Year (0) is a dummy that equals one in the year when a CBSA pair experience a major travel time reduction. In a similar vein, Travel Time Reduction Year (1) and Travel Time Reduction Year (2) are dummies that equal one if a CBSA-pair experiences a major travel time reduction one year ago and two years ago, respectively. Finally, Travel Time Reduction Year (3+) is a dummy that equals one if a CBSA pair experiences a major travel reduction more than three years ago. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A3: Robustness Checks

Panel A: Hub Openings			
Dependent Variable	Log (Number of 3-Year Citations+1)		
Sample	Full	Ever Hub Treated	Full
	(1)	(2)	(3)
Log (Travel Time)	-0.021***	-0.061***	-0.047***
	(0.006)	(0.023)	(0.017)
Hub Treated * Log (Travel Time)	-0.029*		
	(0.018)		
Observations	3,440,938	211,203	3,440,938
R-squared	0.676	0.726	0.676

Panel B: Alternative Specifications			
Model	OLS	Poisson	OLS
	3-Year Number of Citations		
Dependent Variable	Inverse Hyperbolic Transformed	Count	Count
	(1)	(2)	(3)
Log (Travel Time)	-0.031***	-0.202***	-1.260***
	(0.008)	(0.048)	(0.434)
Observations	3,440,938	3,440,938	3,440,938
R-squared	0.665	NA	0.504
CBSA-pair FE	Y	Y	Y
Citing-CBSA X Year FE	Y	Y	Y
Cited-CBSA X Year FE	Y	Y	Y

Notes. In Panel A, Hub Treated is a dummy indicating that a change in travel time involves airline routes that are introduced in the same year when the origin, destination, or any connecting airport becomes a new hub. In column (3) of panel A, Log(Travel Time) is redefined to be the actual travel time only for Hub-Treated pairs, and to be the 1980 initial travel time for all other pairs. In Panel B column (1), we take the inverse hyperbolic transformation for the number of 3-year citations as the dependent variable. In columns (2) and (3) of Panel B, we use the number of 3-year citations as the dependent variable directly without any transformation. Column (2) presents the result of a Poisson specification and column (3) presents the result of an OLS specification. In all specifications, CBSA-pair fixed effects, citing-CBSA fixed effects by year, and cited-CBSA fixed effects by year are controlled for. Robust standard errors clustered at the CBSA-pair level are shown in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

US010889267B2

(12) **United States Patent**
Clift et al.

(10) **Patent No.: US 10,889,267 B2**
(45) **Date of Patent: Jan. 12, 2021**

(54) **ELECTROMAGNETIC WINDSHIELD WIPER SYSTEM**

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(73) Assignee: **Tesla, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 129 days.

(21) Appl. No.: **16/291,186**

(22) Filed: **Mar. 4, 2019**

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Related U.S. Application Data

(60) Provisional application No. 62/638,516, filed on Mar. 5, 2018.

(51) **Int. Cl.**

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B60S 1/08	(2006.01)
B60S 1/16	(2006.01)
H02K 11/33	(2016.01)
B60R 16/023	(2006.01)
B60S 1/04	(2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***B60S 1/0807*** (2013.01); ***B60S 1/0818*** (2013.01); ***B60S 1/16*** (2013.01); ***B60S 1/44*** (2013.01); ***H02K 11/33*** (2016.01); *B60R 16/0231* (2013.01); *B60S 1/0402* (2013.01); *B60S 1/06* (2013.01); *B60S 1/3411* (2013.01); *B60S 1/3418* (2013.01); *B60S 1/3463* (2013.01)

(58) **Field of Classification Search**

CPC B60S 1/0807; B60S 1/0818; B60S 1/44; H02K 11/33; H02K 11/215; H02K 29/08

See application file for complete search history.

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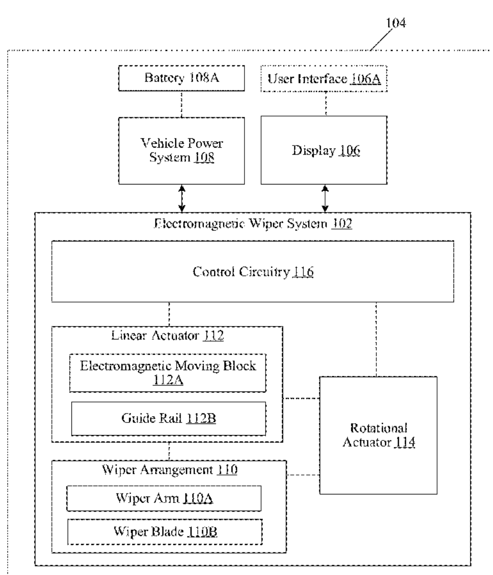
Primary Examiner — Thai T Dinh

(74) *Attorney, Agent, or Firm* — Knohhe, Martens, Olson & Bear, LLP

(57) **ABSTRACT**

An electromagnetic wiper system for a windshield of a vehicle includes a linear actuator, a wiper-arrangement, and control circuitry. The linear actuator includes at least one guide rail having permanent magnets and an electromagnetic moving block. The electromagnetic moving block includes at least one perforation that surrounds the at least one guide rail and at least one electromagnetic coil that surrounds the at least one perforation. The wiper-arrangement includes a wiper arm and a wiper blade, wherein at least the wiper arm is coupled to the electromagnetic moving block. The control circuitry controls a linear motion of the electromagnetic moving block along the at least one guide rail to steer the wiper arm that is coupled to the electromagnetic moving block back and forth across a length of the windshield to the windshield, wherein the electromagnetic moving block induces minimal friction during the linear motion.

20 Claims, 4 Drawing Sheets



(51) **Int. Cl.**

B60S 1/34	(2006.01)
B60S 1/06	(2006.01)

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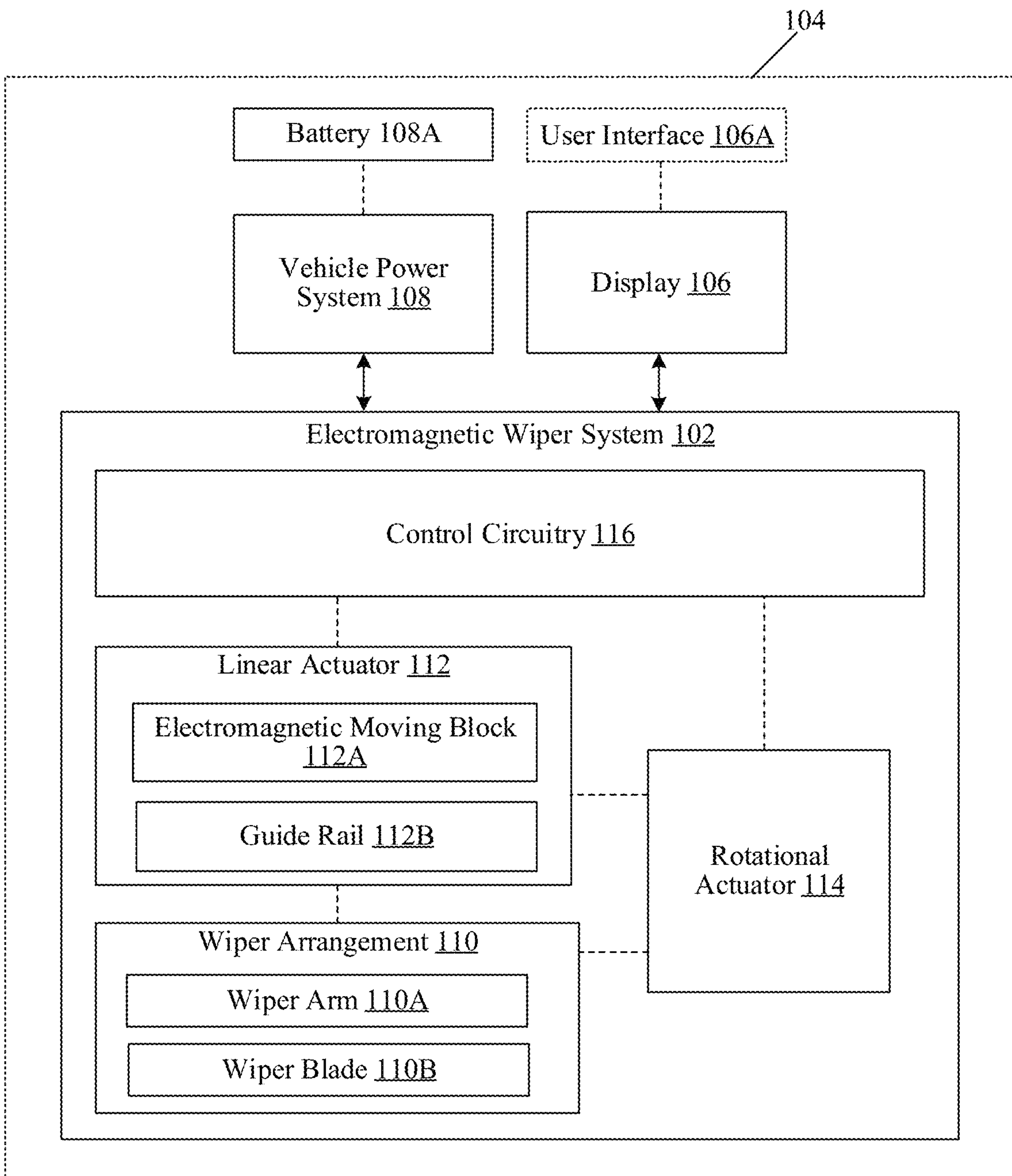

104
Battery 108A
User Interface 106A
Vehicle Power System 108
Display 106
Electromagnetic Wiper System 102
Control Circuitry 116
Linear Actuator 112
Electromagnetic Moving Block 112A
Guide Rail 112B
Rotational Actuator 114
Wiper Arrangement 110
Wiper Arm 110A
Wiper Blade 110B

FIG. 1A

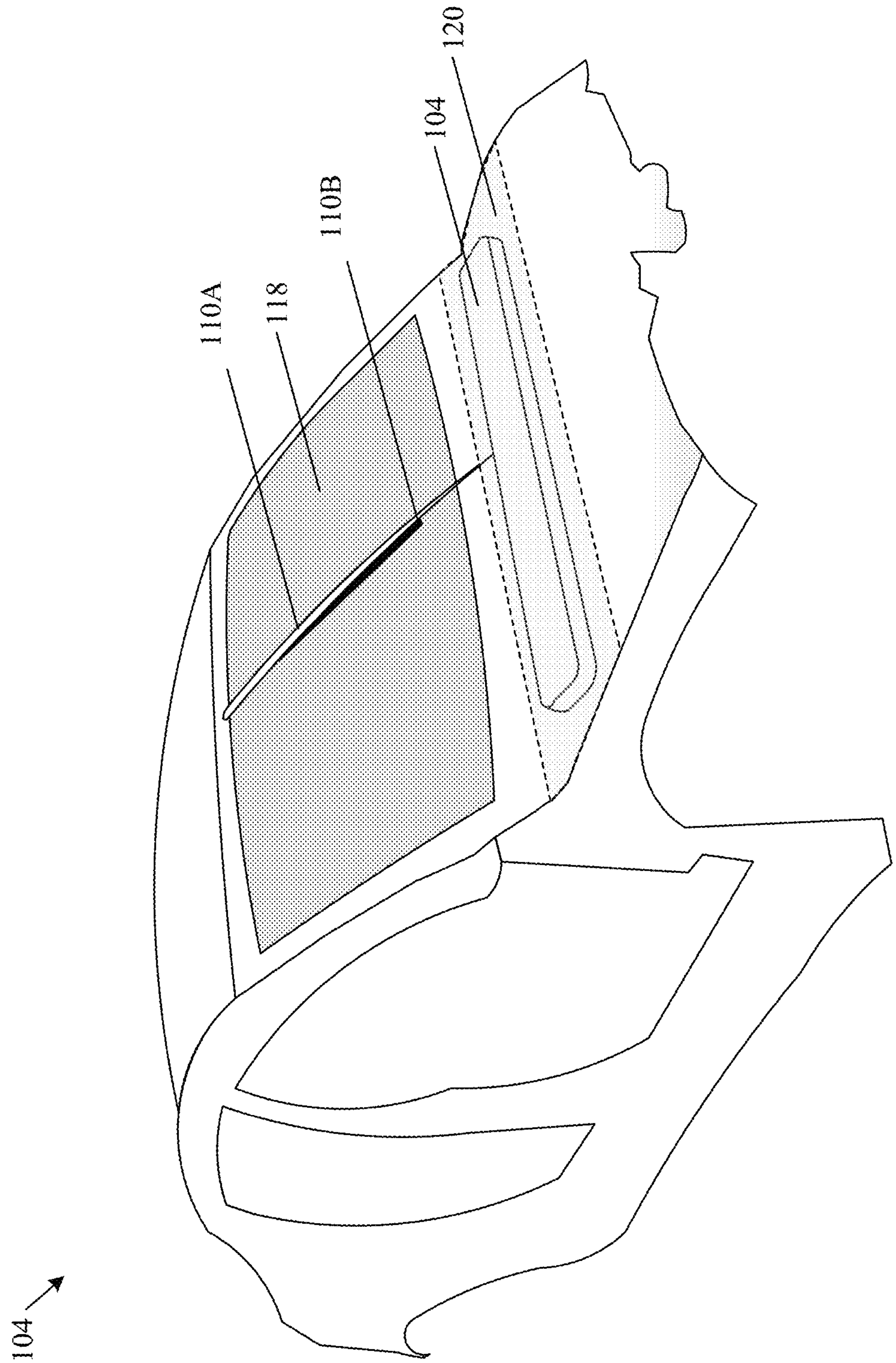
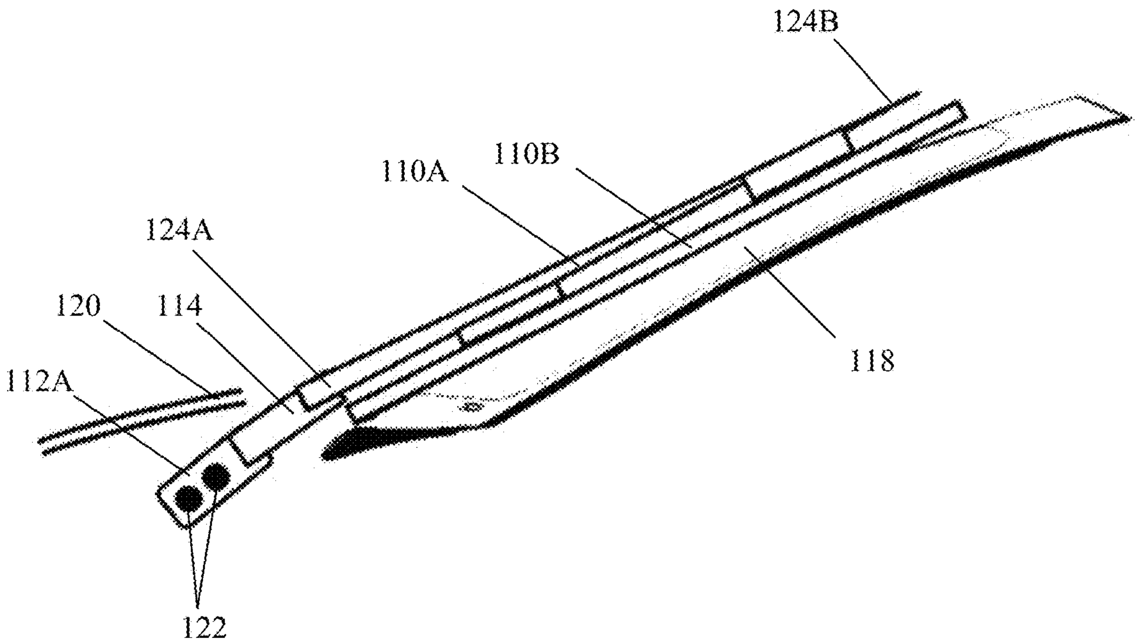


FIG. 1B


124B
110A
110B
124A
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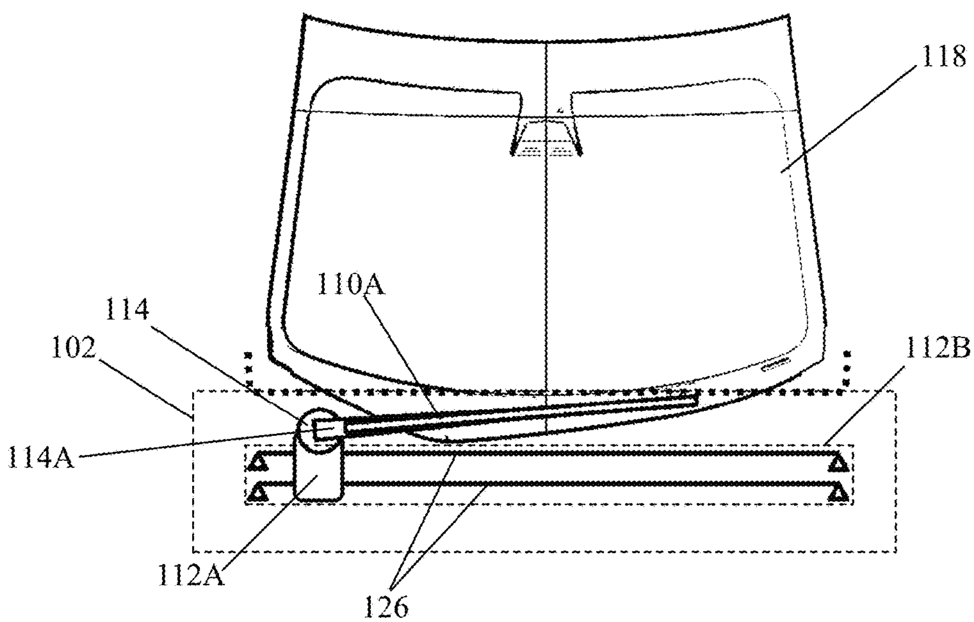
114
112A
118
122

FIG. 1C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110A
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112B
114A
112A
126

FIG. 1D

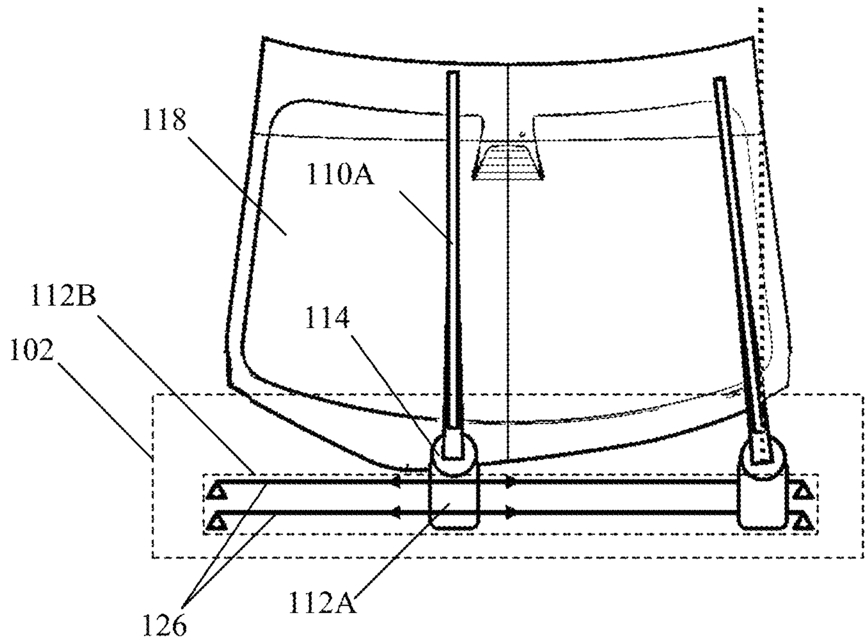

FIG. 1E

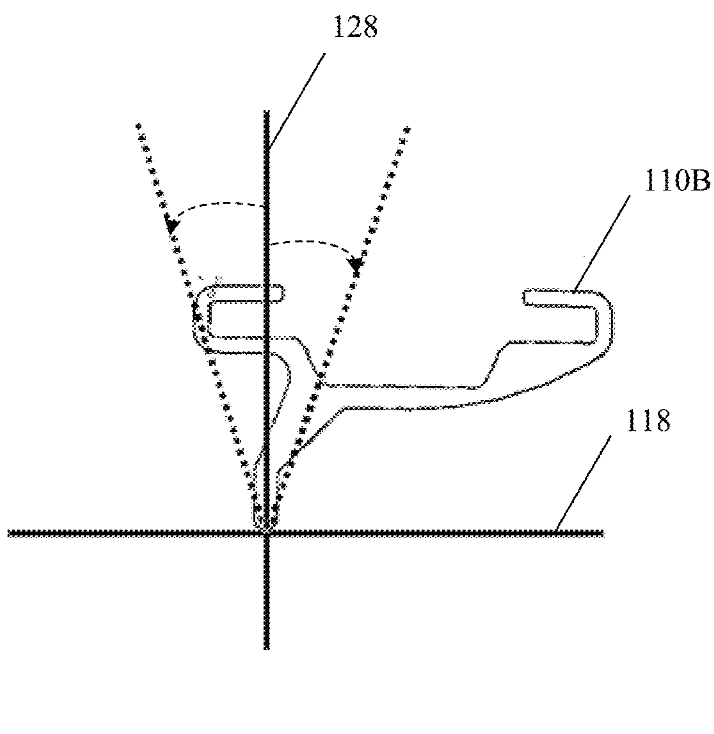

FIG. 1F

ELECTROMAGNETIC WINDSHIELD WIPER SYSTEM

CROSS REFERENCE TO RELATED PATENTS

The present U.S. Utility Patent Applications claims priority pursuant to 35 U.S.C. § 119(e) to U.S. Provisional Application No. 62/638,516, entitled "ELECTROMAGNETIC WINDSHIELD WIPER SYSTEM", filed Mar. 5, 2018, which is hereby incorporated herein by reference in its entirety and made part of the present U.S. Utility Patent Applications for all purposes.

FIELD

Various embodiments of the disclosure relate to a windshield wiper system. More specifically, various embodiments of the disclosure relate to an electromagnetic windshield wiper system that exhibits power efficiency and produces minimal friction during operation.

BACKGROUND

Advancements in the field of windshield cleaning systems and ergonomic vehicle design have led to an increase in the demand for windshield wiper systems that are not only visually appealing but are also effective in cleaning the windshields of a vehicle. In certain scenarios, a driver or in-vehicle cameras (e.g., in case of assisted and autonomous driving) require an unobstructed field-of-view of the path ahead from inside of a vehicle. Conventional windshield wiper systems that use multiple wiper blades usually have a cluttered design and do not sufficiently clear the windshield, which may hamper the unobstructed field-of-view of the path ahead.

In some conventional wiper systems, electrical motors are used to move one or more wiper blades to clean a windshield of a vehicle. The electrical motors include many mechanical components, such as gears and bearings, to slide the wiper blades. However, such sliding motion of the mechanical components creates significant friction resulting in the need for additional power to be supplied by the in-vehicle battery, which decreases vehicle range. Further, the gears and bearings of the conventional systems are susceptible to rust and wear, which may lead to poor and in-efficient cleaning of windshields. Such corrosion and system deterioration is especially true in geographical areas subject to harsh weather conditions, like significant rainfall or snowfall. When these systems corrode accident risk increases, and may result in driver-assist or autonomous-driving functionality being rendered inoperable.

In addition, as the curvature of windshields becomes more complex, conventional wiper systems have difficulty adapting to varying surface profiles and thus affecting their ability to effectively clean windshield contaminants. For example, conventional systems are not capable of effectively cleaning a windshield that curves around a driver, that is the windshield provides a view directly in front of the driver but also to the left and to the right. Further, conventional wiper systems have varying influence from aerodynamic effects as they traverse from the bottom of the windshield to the top and vice-versa, due to airflow vector changes.

Further limitations and disadvantages of conventional and traditional approaches will become apparent to one skilled in the art by comparing the described systems with some aspects of the present disclosure, as set forth in the remainder of the present application and with reference to the drawings. Hence, there is need for a new windshield wiper system that overcomes the aforementioned drawbacks.

SUMMARY

An electromagnetic windshield wiper system for a vehicle is substantially shown in, and/or described in connection with, at least one of the figures, as set forth more completely in the claims.

This and other features and their advantages of the present disclosure may be appreciated from a review of the following detailed description of the present disclosure, along with the accompanying figures in which like reference numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a block diagram that illustrates an exemplary electromagnetic wiper system, in accordance with an embodiment of the present disclosure.

FIG. **1**B illustrates the electromagnetic wiper system of FIG. **1**A installed in a vehicle as a modular component of the vehicle, in accordance with an embodiment of the present disclosure.

FIGS. **1**C to **1**E collectively illustrate different operative states of the exemplary electromagnetic wiper system of FIG. **1**A, in accordance with an embodiment of the present disclosure.

FIG. **1**F illustrates an extent of the angle of attack of a wiper arm of the exemplary electromagnetic wiper system of FIG. **1**A with respect to a reference axis, in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

The following described implementations may be found in the disclosed electromagnetic wiper system for a vehicle. The disclosed electromagnetic wiper system may have a modular architecture that can be readily installed in a vehicle. The electromagnetic wiper system includes a wiper-arrangement that may include a wiper arm and a wiper blade. The wiper arm and the wiper blade may be attached to each other, and thus, form a linear mono wiper in an uncluttered design.

The disclosed electromagnetic wiper system may further include a linear actuator that may include a guide rail and an electromagnetic moving block. The guide rail may include a plurality of permanent magnet bars that may be disposed horizontally along a curvature of the windshield of the vehicle. The electromagnetic moving block may act as an electromagnetic train, and may include a plurality of perforations and at least an electromagnetic coil that surrounds the plurality of perforations in the electromagnetic moving block. The disclosed electromagnetic wiper system may further include control circuitry that controls the linear motion of the electromagnetic moving block through the plurality of permanent magnet bars. The linear motion of the electromagnetic moving block through the plurality of permanent magnet bars may be controlled to steer the wiper arm that may be coupled to the electromagnetic moving block, back and forth across the entire length of the windshield to wipe a defined region, for example, the entire transparent area (i.e., near cent percent area) of the windshield. The plurality of permanent magnet bars may pass through the plurality of perforations surrounded by the electromagnetic coil in the electromagnetic moving block. This may result in minimal friction during the linear motion of the electromagnetic moving block. Alternatively stated, the disclosed electromagnetic wiper system may utilize the current carrying electromagnetic coil in the electromagnetic moving block to generate a magnetic induction-based electrodynamic force to steer the wiper arm, and is thereby able to efficiently and effectively minimize friction that otherwise may exist between the moving elements of a conventional wiper system.

In accordance with an embodiment, when not in operation, the control circuitry causes the linear mono wiper to be stowed beneath the hood of the vehicle. This improves the aerodynamic performance of the vehicle during operation, especially at high speeds, and reduces exposure to environmental damage, like direct sun exposure. In contrast to conventional wiper systems that do not apply a constant force on the windshield, the control circuitry according to the present disclosure adjust the inclination angle and/or angle of attack of the wiper arm with respect to a reference axis during the linear motion of the electromagnetic moving block. Such adjustment of the extent of inclination of the wiper arm may enable effective cleaning of the windshield and improve washer spray performance. As a result of the uncluttered design and almost frictionless movement of the electromagnetic moving block, the disclosed electromagnetic wiper system improved the field-of-view of the path for drivers, driver-assist functions, and autonomous-driving functions.

FIG. **1**A is a block diagram that illustrates an exemplary electromagnetic wiper system, in accordance with an embodiment of the present disclosure. As shown in FIG. **1**A an electromagnetic wiper system **102** is part of a vehicle **104**. Vehicle **104** also includes a display **106**, a user interface **106**A for the display **106**, a vehicle power system **108**, and a battery **108**A (or a battery-pack) for the vehicle power system **108** in the vehicle **104**. As shown in FIG. **1**A, the electromagnetic wiper system **102** includes a wiper arrangement **110**, a linear actuator **112**, a rotational actuator **114**, and control circuitry **116** that is communicatively coupled to the linear actuator **112** and the rotational actuator **114**. The wiper arrangement **110** includes a wiper arm **110**A and a wiper blade **110**B. The linear actuator **112** may further include an electromagnetic moving block **112**A and a guide rail **112**B.

In described embodiments, the electromagnetic wiper system **102** is a magnetic induction based windshield wiper system. The electromagnetic wiper system **102** may have a modular architecture. The electromagnetic wiper system **102** may be pre-formed as a sub-assembled module and subsequently installed into vehicle **104**, thereby reducing the installation time during general assembly of components into vehicle **104**. An exemplary embodiment of the electromagnetic wiper system **102** is shown in FIG. **1**B. The control circuitry **116** of the electromagnetic wiper system **102** may control the linear actuator **112** and the rotational actuator **114** to steer the wiper arrangement **110** across the entire length of a windshield of the vehicle **104**.

Vehicle **104** may be an electric vehicle, a hybrid vehicle, a vehicle with driver-assist capabilities, and/or a vehicle with autonomous-drive capabilities. In embodiments, the vehicle **104** may be an air-borne vehicle, a water-borne vehicle, or a hybrid of an air-borne, or a land-borne vehicle.

The display **106** may include suitable logic, circuitry, interfaces, and/or code that renders various types of information and controls via the user interface (UI) **106**A.

UI **106**A may be a customized graphical user interface (GUI) that displays the various types of information, controls, or settings to operate the electromagnetic wiper system **102**. The electromagnetic wiper system **102** may also be controlled or operated by a hardware control button or a wiper switch provided in the vehicle **104**. The display **106** may be a touch screen that receives an input from the one or more occupants of the vehicle **104**. Examples of the display **106** include, but are not limited to a display of the infotainment head unit, a projection-based display, a see-through display, and/or an electro-chromic display.

The vehicle power system **108** may regulate the charging and the power output of the battery **108**A to various electric circuits and the loads of the vehicle **104**, such as the electromagnetic wiper system **102** and the display **106**. In accordance with an embodiment, the vehicle power system **108** may include power electronics. The vehicle power system **108** may be communicatively connected to the control circuitry **116** to receive control signals from the control circuitry **116** (or an electronic control unit (ECU)) to modulate the current and power distribution for different operational components of the electromagnetic wiper system **102**. The control circuitry **116** control a plurality of operational parameters of the electromagnetic wiper system **102** based on the adaptive modulation of the power and current to the different operational components of the electromagnetic wiper system **102**. Exemplary parameters include, but are not limited to, the velocity of the electromagnetic moving block **112**A, the angle of inclination of a wiper arm of the wiper arrangement **110** (or a change in the angle of inclination), the movement frequency of the wiper arm **110**A, and the frequency that any washer fluid is released from a spray washer unit (not shown) and the duration of any such release.

The battery **108**A may be a rechargeable source of electric power for one or more electric circuits or loads (not shown), such as the electromagnetic wiper system **102** and the display **106** of the vehicle **104**. In some embodiments, instead of a single battery, a battery pack has a plurality of batteries arranged in a planar or non-planar array to power the vehicle **104**.

Although not shown, the vehicle **104** may include an in-vehicle network, which provides communication channels and ports for communication between various control units, components, and/or systems of the vehicle **104**, such as communication ports for exchanging data among the display **106**, the control circuitry **116** of the electromagnetic wiper system **102**, and other associated circuitry in the vehicle **104**. The in-vehicle network may facilitate access control and/or communication between the control circuitry **116** and other ECUs, such as a telematics control unit (TCU) of the vehicle **104**. Various devices or components in the vehicle **104** may connect to the in-vehicle network, in accordance with various wired and wireless communication protocols. Examples of the wired and wireless communication protocols for the in-vehicle network may include, but are not limited to, a vehicle area network (VAN), a CAN bus, Domestic Digital Bus (D2B), Time-Triggered Protocol (TTP), FlexRay, IEEE 1394, Carrier Sense Multiple Access With Collision Detection (CSMA/CD) based data communication protocol, Inter-Integrated Circuit (I^2C), Inter Equipment Bus (IEBus), Society of Automotive Engineers (SAE) J1708, SAE J1939, International Organization for Standardization (ISO) 11992, ISO 11783, Media Oriented Systems Transport (MOST), MOST25, MOST50, MOST150, Plastic optical fiber (POF), Power-line communication (PLC), Serial Peripheral Interface (SPI) bus, and/or Local Interconnect Network (LIN).

The wiper arrangement **110** includes the wiper arm **110**A and the wiper blade **110**B. The wiper arm **110**A may be attached with the wiper blade **110**B along a length of the wiper blade **110**B to form a linear mono wiper providing an uncluttered design to the electromagnetic wiper system **102**. At least one end of the wiper arm **110**A may be coupled to the electromagnetic moving block **112**A, and the other end may be a free end (i.e., not coupled to any structure), as shown, for example, in FIG. **1**B. An example of the wiper arrangement **110** is shown and described in FIG. **1**C.

As shown in FIG. **1**C, the linear actuator **112** includes moving components that exhibit translational motion, for example the electromagnetic moving block **112**A, and stationary (or affixed) components, for example, the guide rail **112**B. The assembly of the electromagnetic moving block **112**A and the guide rail **112**B collectively move the wiper arm **110**A of the wiper arrangement **110** in a linear motion along the length of a windshield of the vehicle **104**. In embodiments, the linear actuator **112** is a linear motor, such as a linear inductor motion. In embodiments, the linear actuator **112** has mechanical components that convert the rotation of a motor shaft into a linear motion of the electromagnetic moving block **112**A.

The rotational actuator **114** may have a fixed portion (e.g., a coupler) to connect to the electromagnetic moving block **112**A. The rotational actuator **114** may include a shaft that attach to one end of the wiper arm **110**A. Based on control signals from the control circuitry **116**, the wiper arrangement **110** may be stowed and/or and the specific wiping angle may be set. For example, the shaft of the rotational actuator **114** may rotate to stow the wiper arrangement **110** and/or set or change the wiping angle. Rotational actuator **114** may be a stepper motor, servo motor, digital-servo motor, or another motor. An example of the rotational actuator **114** is shown and described in FIGS. **1**C and **1**D.

As shown in FIGS. **1**D and **1**E, the control circuitry **116** controls the linear motion of the electromagnetic moving block **112**A along the guide rail **112**B to allow steering of the wiper arm **110**A coupled to the electromagnetic moving block **112**A. The control circuitry **116** may also control other components of the electromagnetic wiper system **102**, such as the linear actuator **112**, a washer spray, and the rotational actuator **114**. The control circuitry **116** may include, but is not limited to including, a microcontroller, an Application-Specific Integrated Circuit (ASIC) processor, a microcontroller, a state machine, and/or other processors or control circuits.

During operation, a trigger signal (or instruction) may be received at the control circuitry **116** of the electromagnetic wiper system **102** to initiate operation of the electromagnetic wiper system **102**. Based on the received trigger signal, the control circuitry **116** may generate and transmit control signals (or control instructions) to the vehicle power system **108**, to provide power specific to the linear actuator **112**, the rotational actuator **114**, or a spray washer attached with the wiper arrangement **110**. The trigger signal may be received at the control circuitry **116** based on a user input. For example, a driver of the vehicle **104** may switch "ON" the wiper switch or select a UI control on the UI **106**A via the display **106**, to start the operation of the electromagnetic wiper system **102**. In embodiments, the trigger signal is generated without human interaction with the vehicle **104**, based on the one or more in-vehicle sensors, such as an in-vehicle camera, an in-vehicle radar, an in-vehicle moisture sensor, and/or in-vehicle camera or sensors coupled to a neural network that determines the presence of rain or another condition requiring clearing of the windshield. In embodiments, vehicle sensors (such as a camera or radar) capture a field-of-view through a defined region of the windshield. The sensors may detect a weather condition. Examples of the different weather conditions include, but are not limited to, snow fall, rain, wind, humid, smoke, fog, or arid weather condition. In some implementations, a degree of a weather condition may be further detected, for example, heavy rain fall, light snowfall, strong dirt carrying winds, and the like, which may impact visibility. The sensors may generate real time or near-real time trigger signals for auto-activation and controlled operations of the electromagnetic wiper system **102**.

FIG. **1**B illustrates the electromagnetic wiper system of FIG. **1**A installed in a vehicle as a modular component of the vehicle, in accordance with an embodiment of the present disclosure. As show in FIG. **1**B, vehicle **104** is fitted with the electromagnetic wiper system **102** as a modular component. FIG. **1**B also shows a windshield **118** and a hood **120** that may be raised to provide a compartment that stows the wiper arrangement **110** when not in operation. The wiper arm **110**A may be attached with the wiper blade **110**B to form a mono wiper blade of the wiper arrangement **110**. In embodiments, the control circuitry **116** is embedded within the chassis of the electromagnetic wiper system **102**. In embodiments, the control circuitry **116** or one or more features of the control circuitry **116** is implemented in an ECU of vehicle **104**.

FIGS. **1**C to **1**E collectively illustrate different operative states of the exemplary electromagnetic wiper system of FIG. **1**A, in accordance with an embodiment of the present disclosure. As shown in FIG. **1**C, wiper blade **110**B is attached to the wiper arm **110**A along a length of the wiper arm **110**A. The wiper blade **110**B may be in contact with the windshield **118** to physically wipe a defined region of the windshield **118**. FIG. **1**C also shows the positioning of the electromagnetic moving block **112**A of the linear actuator **112** and the rotational actuator **114** below the hood **120** of the vehicle **104**.

In accordance with an embodiment, the electromagnetic moving block **112**A includes a plurality of perforations **122**. The electromagnetic moving block **112**A may be also referred to an electromagnetic train. The electromagnetic moving block **112**A may be mounted on the guide rail **112**B such that the guide rail **112**B passes through the plurality of perforations **122**. The guide rail **112**B may be one or a plurality of permanent magnet bars. The number of perforations in the electromagnetic moving block **112**A may be equal to the number of permanent magnet bars. At least one electromagnetic coil may be provided within the electromagnetic moving block **112**A to surround the plurality of perforations **122** in the electromagnetic moving block **112**A.

In accordance with an embodiment, one end, such as a first end **124**A, of the wiper arm **110**A is coupled to the electromagnetic moving block **112**A and the other end, such as a second end **124**B, may be a free end, as shown. In some embodiments, the first end **124**A of the wiper arm **110**A is coupled to the rotational actuator **114**, which in turn is coupled to the electromagnetic moving block **112**A.

FIG. **1**D illustrates the electromagnetic wiper system **102** with the wiper arm **110**A in a stowed mode. Also shown is the guide rail **112**B that includes a plurality of permanent magnet bars **126** disposed horizontally along a curvature of the windshield **118** of the vehicle **104**. In an embodiment, the guide rail **112**B is affixed to a chassis of the electromagnetic wiper system **102**. The chassis may be further affixed to the body of the vehicle **104**. The electromagnetic moving block **112**A may be mounted on the guide rail **112**B such that the plurality of permanent magnet bars **126** of the guide rail **112**B pass through the plurality of perforations **122** present in the electromagnetic moving block **112**A. The control circuitry **116** may direct rotational actuator **114** to stow components of the wiper arrangement **110**, such as the wiper arm **110**A under the hood **120** of the vehicle **104**.

In accordance with an embodiment, the rotational actuator **114** includes a shaft **114**A. The shaft **114**A may be attached to the first end **124**A of the wiper arm **110**A and the control circuitry **116** may control the rotation of the shaft **114**A. Using the rotational actuator **114** the control circuitry **116** may send signals to stow the wiper arrangement **110** and set specific attack angles for wiping the windshield **118**. The attack angle is the angle of the wiper arm **110**A with respect to the windshield **118**. In other embodiments, the wiper arm **110**A is rotated without the use of the rotational actuator **114**. For example, the wiper arm **110**A is rotated by applying differential forces on the electromagnetic moving block **112**A by the plurality of permanent magnet bars **126**.

As shown in FIG. **1**E, the control circuitry **116** may control a linear motion of the electromagnetic moving block **112**A through the plurality of permanent magnet bars **126** to steer the wiper arm **110**A coupled to the electromagnetic moving block **112**A, back and forth across a length of the windshield **118** to wipe a defined region of the windshield **118**.

In embodiments, the guide rail **112**B includes straight permanent magnet bars disposed along the entire length of the windshield **118**. In such embodiments, the wiper arrangement **110**, including the wiper arm **110**A, moves in a straight line along the length of the windshield **118** of the vehicle **104**. In embodiments, the guide rail **112**B includes a plurality of curved permanent magnet bars (not shown) parallel to the curvature of the windshield **118**. In such embodiments, the wiper arrangement **110**, including the wiper arm **110**A, moves along the curvature of the windshield **118**. In other embodiments, the curved permanent magnet bars have a different curvature compared to the curvature of the windshield **118**. In embodiments, the control circuitry **116** controls the attack angle of the wiper arm **110**A to ensure that the wiper arm stays in contact with the windshield **118**. In other embodiments, a mechanical part, such as a spring, maintains the wiper arm **110**A in contact with windshield **118**.

In accordance with an embodiment, in response to the received trigger signal, the control circuitry **116** of the electromagnetic wiper system **102** positions the wiper arm **110**A, including the wiper blade **110**B attached to the wiper arm **110**A, at a specific inclination angle, for example, an inclination angle of approximately "90°" (i.e., an upright position) with respect to a longitudinal axis of the windshield **118**. The wiper arm **110**A may be positioned at the specific inclination angle from a previous position of the wiper arm **110**A, for example, an inclination angle near "0°" (e.g., in the stowed mode). The positioning of the wiper arm **110**A at the specific inclination angle with respect to the longitudinal axis may be done by use of the rotational actuator **114**. Based on the received trigger signal, the rotational actuator **114** may rotate the shaft **114**A. Then, the control circuitry **116** may cause an electrodynamic force to be induced to move the electromagnetic moving block **112**A through the plurality of permanent magnet bars **126** in a linear motion. Using this electrodynamic force produces minimal friction compared to conventional systems. To reduce friction, an air gap between the electromagnetic moving block **112**A and the permanent magnet bars **126** may be created. Alternatively, oil or grease may be placed in the plurality of perforations **122** to reduce friction.

In embodiments, the control circuitry **116** may be further control a spray fluid that may be used to clean the windshield **118**. To improve cleaning, a consistent blade force of the wiper blade **110**B on the windshield **118** may be maintained throughout the back and forth movement of the wiper arm **110**A.

FIG. **1**F illustrates an extent of the angle of attack of a wiper arm of the exemplary electromagnetic wiper system of FIG. **1**A with respect to a reference axis, in accordance with an embodiment of the present disclosure. With reference to FIG. **1**F, there is shown a reference axis **128**, which is perpendicular to the linear motion of the electromagnetic moving block **112**A and may be considered to be parallel to at least a portion of the windshield **118**. The control circuitry **116** may adjust the angle of attack and/or the inclination angle of the wiper arm **110**A with respect to the reference axis **128** during the linear motion of the electromagnetic moving block **112**A.

The angle of attack for the wiper arm **110**A (or wiper blade **110**B) may be adjusted within a range (for example, "−6° to +6°" with respect to the reference axis **128**). The inclination angle and angle of attack may be adjusted based on a defined criteria, such as a weather condition, a type of deposit (for example, soil, water, or snow) accumulated on the windshield **118**, a priority setting to first wipe a driver-sensitive region of the windshield **118**, or other defined conditions that may facilitate the wiper arm **110**A to clear the desired area of the windshield **118**, such as a maximum area, the area in front of the certain sensors, or another area of the windshield **118**. The inclination angle may also be adjusted to define the coverage area for wiping.

The rotational actuator **114** may be an operational component of the electromagnetic wiper system **102** that performs the angular displacement of the wiper arm **110**A. At a given time, the wiper arm **110**A may be inclined at a specific inclination angle with respect to the reference axis **128**. For example, in a non-operational state, the wiper arm **110**A may be inclined at "0 degree" or near "0" degree inclination angle beneath the hood **120** of the vehicle **104**. In operational state, the wiper arm **110**A may be inclined at a specific inclination angle, such as "90 degrees" (±6 degrees) with respect to the reference axis **128**. After the specific inclination angle is set as per the defined criteria for the wiper arm **110**A, the linear actuator **112** may be activated to move the wiper arm **110**A along the length of the windshield **118**. The control circuitry **116** may control the supply of current/power to the electromagnetic coil within the electromagnetic moving block **112**A, to induce a time-varying/moving magnetic field within the electromagnetic moving block **112**A. As a result of the design, and almost frictionless movement of the electromagnetic moving block, the disclosed electromagnetic wiper system **102** is more power efficient that traditional systems, while also providing an unobstructed field-of-view for sensors and/or drivers of the vehicle **104**. This may facilitate drivers, driver-assist functionality, and/or autonomous-driving functionality to make precise and quick decisions. Both the inclination angle and the angle of attack may be adjusted over time based upon operational conditions and/or linear position of the electromagnetic moving block **112**A.

While the present disclosure has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the present disclosure. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the present disclosure without departing from its scope. Therefore, it is intended that the present disclosure not be limited to the particular embodiment disclosed, but that the present disclosure will include all embodiments that fall within the scope of the appended claims. Equivalent elements, materials, processes or steps may be substituted for those representatively illustrated and described herein. Moreover, certain features of the disclosure may be utilized independently of the use of other features, all as would be apparent to one skilled in the art after having the benefit of this description of the disclosure.

As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having" or any contextual variants thereof, are intended to cover a non-exclusive inclusion. For example, a process, product, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements, but may include other elements not expressly listed or inherent to such process, product, article, or apparatus. Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition "A or B" is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B is true (or present).

Although the steps, operations, or computations may be presented in a specific order, this order may be changed in different embodiments. In some embodiments, to the extent multiple steps are shown as sequential in this specification, some combination of such steps in alternative embodiments may be performed at the same time. The sequence of operations described herein can be interrupted, suspended, reversed, or otherwise controlled by another process. It will also be appreciated that one or more of the elements depicted in the drawings/figures can also be implemented in a more separated or integrated manner, or even removed or rendered as inoperable in certain cases, as is useful in accordance with a particular application.

What is claimed is:

1. An electromagnetic wiper system for a windshield of a vehicle, comprising:

a linear actuator that includes a guide rail and an electromagnetic moving block, wherein the guide rail includes a plurality of permanent magnet bars disposed horizontally along a curvature of the windshield of the vehicle, and wherein the electromagnetic moving block includes a plurality of perforations and at least an electromagnetic coil that surrounds the plurality of perforations in the electromagnetic moving block;

a wiper-arrangement including a wiper arm and a wiper blade, wherein at least the wiper arm is coupled to the electromagnetic moving block; and

a control circuitry that controls a linear motion of the electromagnetic moving block through the plurality of permanent magnet bars to steer the wiper arm that is coupled to the electromagnetic moving block, back and forth across a length of the windshield to wipe a defined region of the windshield, wherein the plurality of permanent magnet bars passes through the plurality of perforations surrounded by the electromagnetic coil in the electromagnetic moving block to induce a minimal friction that is less than a defined threshold friction value during the linear motion.

2. The electromagnetic wiper system according to claim **1**, wherein the wiper blade is attached to the wiper arm along a length of the wiper arm such that the wiper blade is in contact to the windshield to wipe the defined region of the windshield across the length of the windshield based on the linear motion of the electromagnetic moving block.

3. The electromagnetic wiper system according to claim **1**, further comprising a rotational actuator coupled to the electromagnetic moving block of the linear actuator, wherein the control circuitry is configured to stow, using the rotational actuator, the wiper-arrangement beneath a hood of the vehicle by adjusting an inclination angle of the wiper arm with respect to a reference axis.

4. The electromagnetic wiper system according to claim **1**, wherein the control circuitry is further configured to adjust an angle of attack of the wiper arm with respect to a reference axis during the linear motion.

5. The electromagnetic wiper system according to claim **4**, wherein the control circuitry is further configured to adjust the angle of attack of the wiper arm with respect to a reference axis during the linear motion based upon a detected weather condition.

6. The electromagnetic wiper system according to claim **1**, wherein the control circuitry is further configured to adjust an angle of inclination of the wiper arm with respect to a reference axis during the linear motion.

7. The electromagnetic wiper system according to claim **1**, wherein the control circuitry is further configured to communicatively couple to at least one other control unit of the vehicle via an in-vehicle network.

8. The electromagnetic wiper system according to claim **7**, wherein the control circuitry is further configured to:

communicatively couple to at least one other control unit of the vehicle via an in-vehicle network;

receive detected weather condition from another control unit; and

operate the electromagnetic wiper system based upon the detected weather condition.

9. The electromagnetic wiper system according to claim **1**, wherein the plurality of permanent magnet bars are curved to substantially match the curvature of the windshield of the vehicle.

10. The electromagnetic wiper system according to claim **1**, wherein the control circuitry is configured to cause the electromagnetic wiper system to first wipe a driver-sensitive region of the windshield.

11. An electromagnetic wiper system for a windshield of a vehicle, comprising:

a linear actuator that includes at least one guide rail and an electromagnetic moving block, wherein the at least one guide rail includes a plurality of permanent magnet bars disposed horizontally along a curvature of the windshield of the vehicle, and wherein the electromagnetic moving block includes at least one perforation that surrounds the at least one guide rail and at least one electromagnetic coil that surrounds the at least one perforation;

a wiper-arrangement including a wiper arm and a wiper blade, wherein at least the wiper arm is coupled to the electromagnetic moving block; and

a control circuitry that controls a linear motion of the electromagnetic moving block along the at least one guide rail to steer the wiper arm that is coupled to the electromagnetic moving block back and forth across a length of the windshield to the windshield, wherein the electromagnetic moving block induces a minimal friction that is less than a defined threshold friction value during the linear motion.

12. The electromagnetic wiper system according to claim **11**, wherein the wiper blade is attached to the wiper arm along a length of the wiper arm such that the wiper blade is in contact to the windshield to wipe a defined region of the windshield across the length of the windshield based on the linear motion of the electromagnetic moving block.

13. The electromagnetic wiper system according to claim **11**, further comprising a rotational actuator coupled to the electromagnetic moving block of the linear actuator, wherein the control circuitry is configured to stow, using the rotational actuator, the wiper-arrangement beneath a hood of the vehicle by adjusting an inclination angle of the wiper arm with respect to a reference axis.

14. The electromagnetic wiper system according to claim **11**, wherein the control circuitry is further configured to adjust an angle of attack of the wiper arm with respect to a reference axis during the linear motion.

15. The electromagnetic wiper system according to claim **14**, wherein the control circuitry is further configured to adjust the angle of attack of the wiper arm with respect to a reference axis during the linear motion based upon a detected weather condition.

16. The electromagnetic wiper system according to claim **11**, wherein the control circuitry is further configured to adjust an angle of inclination of the wiper arm with respect to a reference axis during the linear motion.

17. The electromagnetic wiper system according to claim **11**, wherein the control circuitry is further configured to communicatively couple to at least one other control unit of the vehicle via an in-vehicle network.

18. The electromagnetic wiper system according to claim **17**, wherein the control circuitry is further configured to:

communicatively couple to at least one other control unit of the vehicle via an in-vehicle network;

receive detected weather condition from another control unit; and

operate the electromagnetic wiper system based upon the detected weather condition.

19. The electromagnetic wiper system according to claim **11**, wherein the plurality of permanent magnet bars are curved to substantially match the curvature of the windshield of the vehicle.

20. The electromagnetic wiper system according to claim **11**, wherein the control circuitry is configured to cause the electromagnetic wiper system to first wipe a driver-sensitive region of the windshield.

* * * * *

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(54) **ACTIVE MATERIALS FOR LITHIUM-ION BATTERIES**

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(57) **ABSTRACT**

Methods for forming a cathode active material comprise sintering flakes formed from a nickel, manganese, cobalt and lithium-containing slurry to form the cathode material having the formula $Li_2Ni_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number greater than or equal to about 0.8 and less than 1. Lithium-ion batteries having cathode active materials formed according to methods of embodiments of the invention are provided.

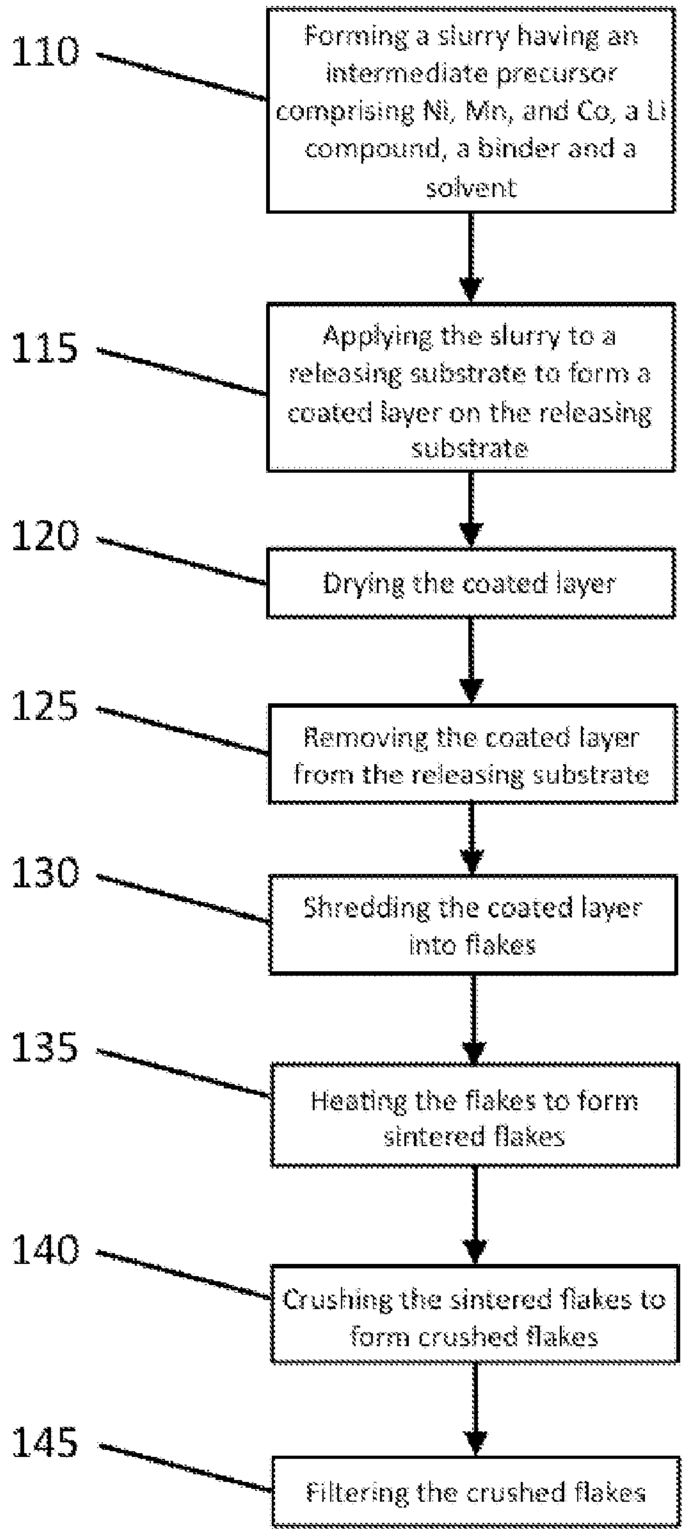
110
Forming a slurry having an intermediate precursor comprising Ni, Mn, and Co, a Li compound, a binder and a solvent
115
Applying the slurry to a releasing substrate to form a coated layer on the releasing substrate
120
Drying the coated layer
125
Removing the coated layer from the releasing substrate
130
Shredding the coated layer into flakes
135
Heating the flakes to form sintered flakes
140
Crushing the sintered flakes to form crushed flakes
145
Filtering the crushed flakes

FIG. 1

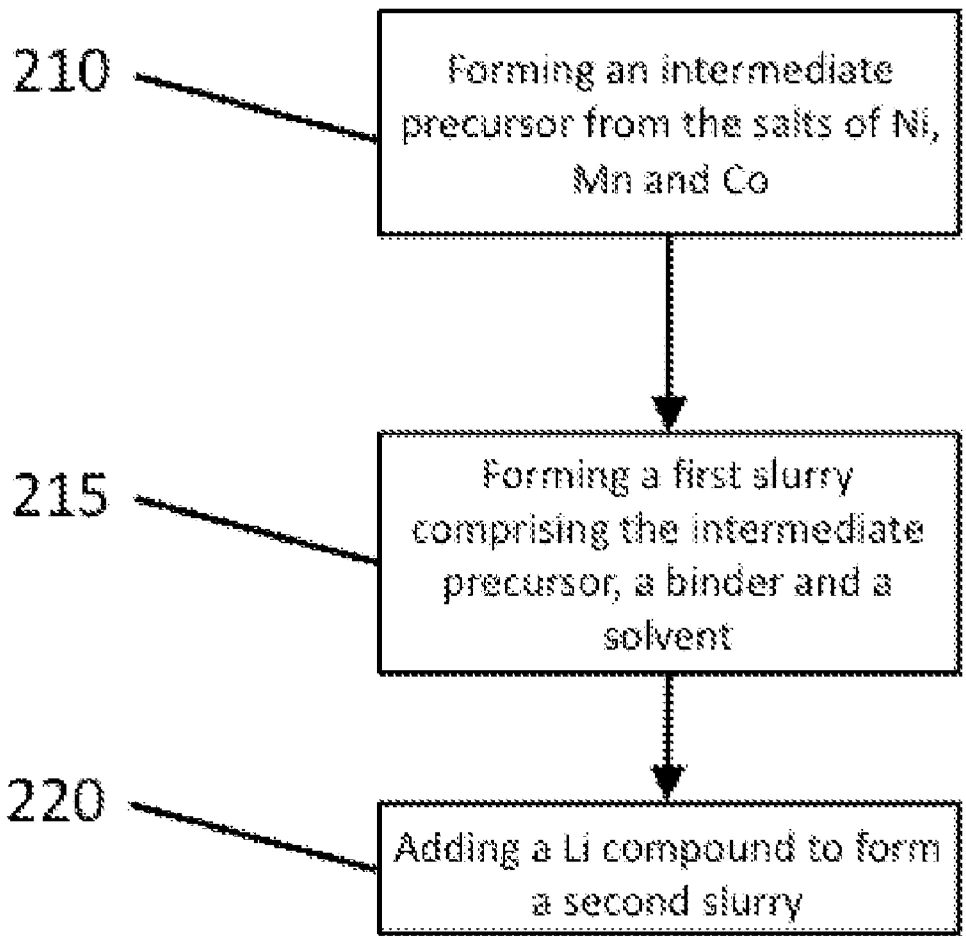
210
Forming an intermediate precursor from the salts of Ni, Mn and Co
215
Forming a first slurry comprising the intermediate precursor, a binder and a solvent
220
Adding a Li compound to form a second slurry

FIG. 2

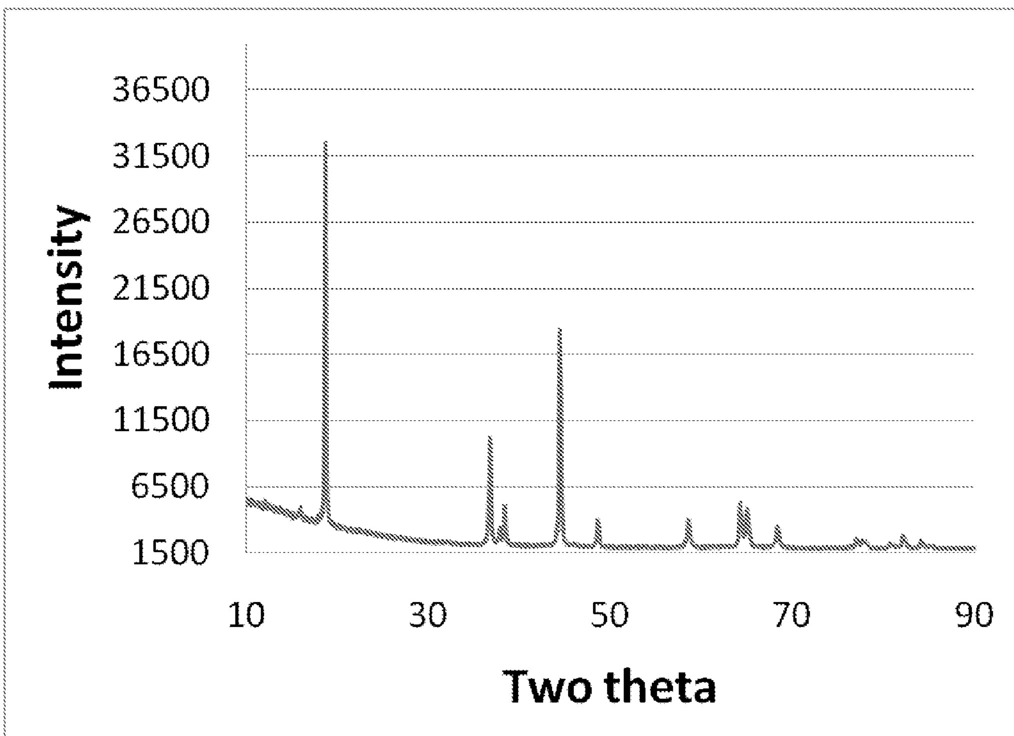
36500
31500
26500
21500
16500
11500
6500
1500
Intensity
10
30
50
70
90
Two theta

FIG. 3

ACTIVE MATERIALS FOR LITHIUM-ION BATTERIES

FIELD OF THE INVENTION

[0001] The invention generally relates to lithium-ion batteries, more particularly to lithium transition metal oxide materials for use as positive electrodes or cathode materials of lithium-ion batteries.

BACKGROUND OF THE INVENTION

[0002] Lithium-ion batteries typically include an anode, an electrolyte and a cathode that contains lithium in the form of a lithium-transition metal oxide. Examples of transition metal oxides that have been used include cobalt dioxide, nickel dioxide, and manganese dioxide. These materials, however, lack high initial capacity, high thermal stability and preferable capacity retention after repeated charge-discharge cycles.

[0003] Li transition metal oxides have been used in most of commercial lithium-ion batteries as cathode materials. The traditional cathode material is typically formed of $LiCoO_2$, which may be used in portable electronic devices, such as cell phones, laptop computers and digital cameras. The recent thrust in the development of lithium-ion batteries has been to develop high performance, safe and low-cost batteries for electric vehicles and grid storage. The cathode materials, which may be referred to as the active materials in lithium-ion batteries, may critically contribute to battery performance and cost. Research has been focused on developing cathode materials beyond those comprising $LiCoO_2$.

[0004] Further, in certain lithium mixed metal oxide materials containing Ni, Mn and Co, after the first (1^{st}) cycle the mixed metal oxides may have a relatively high irreversible capacity loss. Although these oxides may have high capacity, high thermal stability and lower cost due to less Co (in relation to the Co content in $LiCoO_2$), the high irreversible capacity loss is undesirable. For instance, after the first cycle the mixed metal oxides may have an irreversible capacity loss exceeding 10%. Such high irreversible loss has been shown research work, such as, for example, Wilcox et al., "Structure and Electrochemistry of $LiNi_{1/3}Co_{1/3-y}M_yMn_{1/3}O_2$ (M=Ti, Al, Fe) Positive Electrode Materials," *Journal of The Electrochemical Society*, Vol 156, p. A195 (2009). A high 1st cycle irreversible capacity loss may increase the cost of batteries and hinder the design and production of high capacity batteries.

[0005] There is therefore a need in the art for improved cathode materials for use in lithium-ion batteries.

SUMMARY OF THE INVENTION

[0006] According to certain prior art methods, use of flakes of metal oxide as cathode active materials may give rise to very high power batteries, which may maintain high energy. See, e.g., U.S. Pat. Nos. 6,337,156 and 6,682,849 to Narang et al.

[0007] Active material flakes may be formed via sintering "green" flakes that include agglomerates of smaller primary particles. These flakes are often characterized as being in a "green" state prior to sintering. The sintering may occur in a heating apparatus, such as an oven or furnace, so as to bring about the physical joining of the primary particles and provide inter-particle connectivity. For example, primary particles of lithium nickel manganese cobalt oxide (NMC) active material may be sintered under various conditions, which result in the physical joining of active material particles, thus forming higher order flakes.

[0008] Generally, flake sintering (also "sintering" herein) is a heat treatment that is in addition to the heat treatment for the fabrication of the NMC of the primary particles. Furthermore, flake sintering requires longer times and/or higher temperature as compared to the conditions for fabricating the NMC of the primary particles, which increases the cost, time and risk of degradation of materials via lithium loss.

[0009] In embodiments of the invention, alternative processes to make the flake materials for Li-ion batteries are provided. These processes include: use of precursor compounds, that is, nickel, cobalt and manganese salts (e.g., carbonates, nitrates, sulfates) via a co-precipitation synthesis route to prepare a NiMnCo intermediate precursor; mixing the intermediate precursor with appropriate stoichiometry of lithium compound (for example, lithium carbonate) and a binder in a certain solvent; coating the slurry on a releasing substrate to form a green flake; and sintering the green flake to fabricate the lithium nickel manganese cobalt oxide (also "NMC" herein), the cathode active material. In embodiments, the advantages of this alternative synthesis process include reduced cost due to one less heat treatment process and lower sintering temperature and shorter time; increased capacity by ~3% due to better control of Li content in the flakes and lower mixing between Li and Ni sites at lower sintering temperature; and improved flake morphology with smaller primary particle size and internal pores.

[0010] In an aspect of the invention, methods for forming positive electrode or cathode materials for use in lithium-ion batteries are provided.

[0011] In embodiments of the invention, methods for forming a cathode active material comprise sintering flakes formed from a nickel, manganese, cobalt and lithium-containing slurry to form the cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number between about 0.8 and 1.

[0012] In other embodiments of the invention, methods for producing a cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein $0 \leqq x \leqq 1$, $0 \leqq y \leqq 1$ and $0.8 \leqq z < 1$, comprise mixing a nickel (Ni) salt, manganese (Mn) salt and cobalt (Co) salt to form an intermediate precursor. The intermediate precursor may be mixed with a lithium (Li) compound, a binder and a solvent to form a slurry. A releasing substrate (also "substrate" herein) may be coated with the slurry to form a coated layer on the releasing substrate. In an embodiment, the coated layer may be dried and separated from the releasing substrate. Flakes may then be formed from the dried coated layer; the flakes may be subsequently sintered (or calcined). In an embodiment, the flakes may be crushed and filtered to form the cathode material.

[0013] In yet other embodiments of the invention, methods for forming lithium nickel manganese cobalt oxide (NMC) particles comprise forming a slurry comprising a Li compound, a binder, a solvent and an intermediate precursor having nickel (Ni), manganese (Mn) and cobalt (Co). A substrate may be coated with the slurry to form a coated layer on the substrate. The coated layer may then be dried to separate the coated layer from the substrate. The coated layer may then be shredded into green flakes. The green flakes may then be heated to form sintered flakes. The sintered flakes may be subsequently crushed to form the NMC particles. The NMC particles may be used as cathode active materials in lithium-ion batteries.

[0014] In still other embodiments of the invention, methods for producing a cathode active material comprise mixing salts of nickel (Ni), manganese (Mn) and cobalt (Co) to form an intermediate precursor; mixing the intermediate precursor with a binder and a solvent to form a slurry; applying the slurry on a releasing substrate to form green flakes; and sintering the green flakes to form the cathode active material.

[0015] In another aspect of the invention, cathode active materials for use in lithium-ion batteries are provided. In embodiments of the invention, cathode active materials having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number greater than or equal to about 0 and less than or equal to 1, 'y' is a number greater than or equal to about 0 and less than or equal to 1, and 'z' is a number greater than or equal to about 0.8 and less than 1, are provided

[0016] In yet another aspect of the invention, lithium-ion batteries having cathode active materials are provided. In embodiments of the invention, lithium-ion batteries having cathode active materials comprising $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number less than about 1, are provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The invention will be better understood from the Detailed Description of the Invention and from the appended drawings, which are meant to illustrate and not to limit the invention.

[0018] FIG. **1** shows a flowchart for forming a cathode active material for use in a lithium-ion battery, in accordance with an embodiment of the invention;

[0019] FIG. **2** shows a flowchart for forming a slurry for use in forming a cathode active material, in accordance with an embodiment of the invention; and

[0020] FIG. **3** shows a powder x-ray diffraction (XRD) pattern of $Li_{0.81}(Ni_{0.34}Mn_{0.33}Co_{0.33})O_2$, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The invention provides compositions and methods of manufacturing lithium-based (or lithium-containing) cathode materials for use in lithium-ion batteries. Cathode materials provided in accordance with the invention may comprise mixed metal oxides having a first (1st) cycle irreversible capacity loss lower than prior art materials. Such cathode materials (or alternatively, positive electrode materials herein) may advantageously maintain more charge after a first charge-discharge cycle. In various embodiments, cathode active materials may be capable of providing a first cycle irreversible capacity loss less than or equal to about 10%, or less than or equal to about 5%, or less than or equal to about 3%.

[0022] In embodiments of the invention, cathode materials (also "cathode active materials" herein) are provided having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number between about 0.8 and 1.3. In some embodiments, 'z' is a number less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.90, or less than or equal to about 0.85, or less than or equal to about 0.8. In an embodiment, 'z' is a number less than about 1 and greater than or equal to about 0.8.

[0023] In preferable embodiments of the invention, a lithium-based cathode material having the general formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$ is provided. In an embodiment, the 3a sites in the crystallographic structure (R3m) are only partially occupied while maintaining the α-$NaFeO_2$ (O3) type of crystal structure. Preferably the lithium atoms of the as-sintered cathode material have only about 80% occupancy of the 3a sites, and the cation mixing between Li and Ni ions is less than about 5 molar %.

[0024] Lithium-based cathode materials of various embodiments of the invention are based on unexpected results. Prior art references have taught away from a lithium-based cathode material having a low lithium content when a Ni-containing oxide (such as NMC) is used in the cathode material. This could be due to cation mixing between Li and Ni in the cathode material. See, e.g., Journal of The Electrochemical Society, Vol. 149, p. A1114; Solid State Ionics, Volume 176, Issues 5-6, p.463; U.S. Patent No. 7,494,744. Cation mixing may be detrimental to the capacity of a cathode. In contrast to prior art lithium-based cathode materials, the low lithium content in lithium-based cathode materials of various embodiments of the invention provides for lower total lithium in a lithium-ion battery incorporating cathode materials of embodiments of the invention without compromising battery (or cathode) capacity, energy and power, as compared to prior art lithium mixed metal oxide materials.

[0025] In addition, the low lithium content in lithium-based cathode materials may reduce the first cycle irreversibility. In various embodiments of the invention, cathode active materials may be prepared from a slurry comprising nickel (Ni), manganese (Mn), cobalt (Co), lithium (Li), a binder and a solvent. In embodiments, Ni, Mn, Co and Li may be provided by way of one or more salts of the constituent elements. The slurry may then be applied to a releasing substrate (also "substrate" herein), dried, separated from the substrate and shredded into green flakes. The green flakes may be subsequently heated to sinter the flakes in to particles comprising cathode materials of embodiments of the invention. By forming cathode materials in such "bottoms-up" fashion (i.e., from a slurry comprising the constituent elements of the cathode active material), fewer heating steps are employed, leading to savings in processing costs. In addition, lower sintering temperatures and heating times during sintering may be employed. Use of lower sintering temperatures may minimize the mixing between Li and Ni sites, thus reducing, if not eliminating problems associated with cation mixing. Cathode active materials formed according to methods of embodiments of the invention may also benefit from improved flake morphology with adjustable particle sizes and internal pores.

[0026] In certain embodiment, the primary particle sizes may be similar. In an embodiment, primary particle sizes may be about 0.2 µm. In an embodiment, the sizes of agglomerates of the primary particles (secondary particles) may vary from about 0.5 µm to about 20 µm. In an embodiment, 6 µm particles may be used in flake formation processes of various embodiments of the invention. In such a case, the sintering temperature may be limited to temperatures above about 1000° C. Methods of embodiments of the invention and the uses of smaller particle sizes may advantageously open up the range of processing conditions, particularly at lower sintering temperatures, providing for achieving optimized flake processes and materials.

[0027] For the lithium ion cells made of the lithium-based NMC material of embodiments of the invention, the lithium content of the cathode may be less than the lithium content of current lithium-rich NMC cathodes. In some cases, the lithium content may be 5% less, or 10% less, or 15% less, 20% less than the lithium content of current lithium-rich NMC cathodes. In some embodiments, for a cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' and 'y' are numbers between 0 and 1, and 'z' is a number less than about 1, a fully discharged cell may have a lithium content ('z') of about 0.75, while a fully charged cell having a voltage of about 4.2 V may have a lithium content ('z') as low as about 0.2. A lower lithium content ('z') may advantageously provide for safer cells. Under overcharging (abusive) conditions, for a cell that is charged to about 5 V, for example, the low lithium cell may have significantly less lithium metal formed than NMC cathode materials available in the art.

[0028] The terms "calcining" and "sintering", as used herein, refer to heating a solid material to a temperature below its melting point. Calcining (or calcination) may be used to drive off volatile, chemically combined components, or to thermally induce phase transfer and decomposition. Sintering may be used to promote interparticle atomic diffusion to form interparticle connectivity.

Methods for Forming Cathode Active Materials

[0029] In an aspect of the invention, methods for forming cathode materials for use in lithium-ion batteries are provided. In embodiments, methods for forming a cathode material may comprise sintering flakes formed from a nickel, manganese, cobalt and lithium-containing slurry to form the cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number between about 0.8 and 1.3. In various embodiments, 'z' may be less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.90, or less than or equal to about 0.85, or less than or equal to about 0.8.

[0030] In embodiments of the invention, a first slurry comprising a Li compound (or Li-containing compound), a binder, a solvent and an intermediate precursor comprising Ni, Mn and Co may be formed by first forming an intermediate precursor comprising Ni, Mn and Co. The intermediate precursor may be a salt comprising Ni, Mn and Co. In an embodiment, the intermediate precursor may be $(Ni_{1-x-y}Co_xMn_y)CO_3$, wherein 'x' is a number between about 0 and 1 and 'y' is a number between about 0 and 1. The intermediate precursor may be formed by co-precipitating salts of Ni, Mn and Co. The intermediate precursor may then be mixed with the binder and solvent to form a second slurry. The Li compound (e.g., a lithium-containing salt, such as Li_2CO_3) may then be added to the second slurry to form the first slurry. Alternatively, the Li compound may be mixed with the intermediate precursor prior to mixing the intermediate precursor with the binder and the solvent. The lithium compound may be a lithium salt. A mixture comprising the Li compound and the intermediate may then be combined with the binder and the solvent to form the first slurry. In such a case, formation of the second slurry may not be necessary. The first slurry thus formed is capable of providing cathode materials having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number between about 0.8 and 1.3. In some embodiments, 'z' may be less than about 1.

[0031] In certain embodiments, upon forming the intermediate precursor, the intermediate precursor may be dried prior to combining with a lithium compound, a binder and a solvent. In an embodiment, prior to combining the intermediate precursor with the lithium compound, the binder and the solvent, the intermediate precursor may be dried (in vacuum or air) at a temperature greater than or equal to about 50° C., or greater than or equal to about 100° C., for a time period greater than or equal to about 30 minutes, or greater than or equal to about 60 minutes, or greater than or equal to about 5 hours, or greater than or equal to about 10 hours.

[0032] In certain embodiments, prior to forming a slurry, the intermediate precursor may be mixed with a lithium compound and heated in vacuum or air. In an embodiment, the intermediate precursor may be mixed with the lithium compound and heated at a temperature greater than or equal to about 400° C., or greater than or equal to about 500° C., for a time period greater than or equal to about 10 minutes, or greater than or equal to about 30 minutes. This forms a mixture comprising Ni, Mn, Co and Li, which may subsequently be combined with a binder and a solvent to form the slurry.

[0033] The slurry may then be used to form a flake comprising $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein $0 \leqq x \leqq 1$, $0 \leqq y \leqq 1$ and $0.8 \leqq z \leqq 1.3$. In certain embodiments, 'z' is a number less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.9, or less than or equal to about 0.85, or less than or equal to about 0.8. In an embodiment, 'z' is a number less than about 1 and greater than or equal to about 0.8. In embodiments, the slurry may be applied to a releasing substrate to form a coated layer. The coated layer may then be dried. The dried coated layer may then be removed from the releasing substrate and shredded or broken into green flakes. The green flakes may then be heated (sintered) to form one or more sintered flakes. The one or more sintered flakes may be larger than the flakes prior to sintering. The one or more sintered flakes may then be crushed into smaller pieces and employed for use as cathode active materials.

[0034] Flakes formed in accordance with this aspect of the invention may vary in size depending on various conditions. As known to those of skill in the field, these flakes may be observed through SEM photographs to study and determine the actual flake sizes on a mass (or number) average basis. It is preferable to classify or categorize the flakes or elongated structures herein according to their sizes with conventional separation systems and methodologies.

[0035] Reference will now be made to the figures, wherein like numerals refer to like parts throughout. It will be appreciated that the figures are not necessarily drawn to scale.

[0036] With reference to FIG. **1**, a method for producing a cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein $0 \leqq x \leqq 1$, $0 \leqq y \leqq 1$ and $0.8 \leqq z \leqq 1.3$, is provided. In certain embodiments, 'z' is a number less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.9, or less than or equal to about 0.85, or less than or equal to about 0.8. In an embodiment, 'z' is a number less than about 1 and greater than or equal to about 0.8. In step 110, the method comprises forming a slurry having an intermediate precursor, a lithium compound, a binder and a solvent. In a preferable embodiment, the intermediate precursor comprises nickel (Ni), manganese (Mn) and cobalt (Co). In an embodiment, the intermediate precursor is formed via co-precipitation synthesis of salts of Ni, Mn and Co. In an embodiment, the intermediate precursor may be formed by co-precipitating one or more salts of Ni, one or more salts of

Mn and one or more salts of Co. The one or more of salts of Ni, Mn and Co may be selected from the group consisting of nitrates, chlorides, sulfates and acetates. In some cases, multiple salts may be used to provide Ni, Mn or Co. For example, $NiNO_3$ and $NiSO_4$ may be used to provide Ni during the co-precipitation synthesis of the intermediate precursor.

[0037] During formation of the intermediate precursor, the quantity (or amount) of Ni, Mn and Co in solution is selected so as to yield a cathode material having a desirable composition, i.e., 'x' and 'y' in $Li_zNi_{1-x-y}Mn_xCo_yO_2$ are selected as desired. The amount of Ni, Mn and Co in solution may be controlled by the amount (or relative proportion) of Ni salts, Mn salts and Co salts used to form the intermediate precursor. In addition, the amount of the lithium compound added to the slurry is selected so as to yield a desirable lithium composition ('z') in the $Li_zNi_{1-x-y}Mn_xCo_yO_2$ cathode material. In certain embodiments, the amount of lithium compound added is such that 'z' is a number less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.9, or less than or equal to about 0.85, or less than or equal to about 0.8. In an embodiment, 'z' is a number less than about 1 and greater than or equal to about 0.8.

[0038] The binder may include one or more of gelatin, cellulose, cellulose derivatives, polyvinylpyrrolidone (PVP), polyvinyl acetate (PVA), starch, sucrose and polyethylene glycol. In a preferable embodiment, the binder is PVP. The solvent for forming the slurry may include one or more of water and alcohols, such as, e.g., methanol, ethanol, propanol (e.g., isopropanol) and butanol. In a preferable embodiment, the solvent for forming the slurry is isopropanol (isopropyl alcohol). The Li compound may include a lithium-containing salt. In an embodiment, the Li compound may include one or more of lithium carbonate, lithium hydroxide, lithium nitrate and lithium acetate. In a preferable embodiment, the Li compound is lithium carbonate.

[0039] In an alternative embodiment, the intermediate precursor may be mixed with the Li compound prior to forming the slurry. In such a case, the slurry may be formed by bringing a mixture having the Li compound and the intermediate precursor in contact with the binder and the solvent.

[0040] It will be appreciated that methods for forming the slurry may include mixing the intermediate precursor, the Li compound, the binder and the solvent in a mixing apparatus. In some cases, the binder may be added after mixing the Li compound, the intermediate precursor and the solvent. In other cases, the Li compound may be added after mixing the intermediate precursor, the solvent and the binder.

[0041] With continued reference to FIG. **1**, in step **115**, a releasing substrate (also "substrate" herein) is coated with the slurry to form a coated layer on the substrate. In such a case, the slurry may be applied to the releasing substrate via various means, such as, e.g., using a brush, a "doctor blade", or an industrial coating machine, for example, a reverse roll or comma bar coater to coat the releasing substrate with the slurry. In an embodiment, the releasing substrate is a polymeric material, such as, e.g., plastic. In some cases, the releasing substrate may include a layer of a polymeric material over a supporting material, such as wood or metal (e.g., aluminum). For instance, the releasing substrate may be an aluminum block coated with plastic.

[0042] Next, in step **120**, the coated layer is dried and separated from the releasing substrate. In an embodiment, the coated layer may be dried in air at room temperature (about 25° C.). In another embodiment, the coated layer may be dried in air via the application of heat. In such a case, one or more of convective, radiative or conductive heating methods may be employed to dry the coated layer. For instance, air having a temperature greater than 25° C. may be directed over the coated layer. In an embodiment, as the releasing substrate dries, it separates from the releasing substrate. Next, in step **125**, when the coated layer has separated from the releasing substrate, it is removed from the releasing substrate.

[0043] With continued reference to FIG. **1**, in step **130**, the dried coated layer (or large flake) may be shredded into small flakes. Each flake has a surface area that is smaller than the surface area of the dried coated layer. The dried coated layer may be shredded using, e.g., a mechanical shredder or crusher, or forcing through a screen of appropriate mesh size. In an embodiment, the flakes prior to sintering may be referred to as "green flakes."

[0044] Next, in step **135**, the flakes may be heated to sinter the flakes to form one or more sintered flakes. Upon heating, the flakes may agglomerate to form one or more larger flakes. Sintering (or calcining) the flakes may include heating the flakes at a temperature less than or equal to about 1100° C., or less than or equal to about 1000° C., or less than or equal to about 900° C., for a time period greater than or equal to about 1 minute, or greater than or equal to about 10 minutes, or greater than or equal to about 60 minutes, or greater than or equal to about 5 hours, or greater than or equal to about 10 hours, or greater than or equal to about 20 hours. The flakes may be heated in a heating apparatus, such as, e.g., a heating oven or a furnace. Heating the flakes may effect the physical joining of the primary particles that comprise the flakes and provide inter-particle connectivity.

[0045] With continued reference to FIG. **1**, in step 140, the one or more sintered flakes may be subsequently crushed to form particles comprising $Li_zNi_{1-x-y}Mn_xCo_yO_2$ (NMC), wherein 'x' is a number greater than or equal to about 0 and less than 1, 'y' is a number greater than or equal to about 0 and less than 1, and 'z' is a number greater than or equal to about 0.8 and less than 1.3. In some embodiments, 'z' is a number greater than or equal to about 0.8 and less than about 1. Next, in step 145, the particles may be filtered to obtain a predetermined (or desired) NMC particle size distribution. The NMC particles thus formed may comprise cathode materials for use in lithium-ion batteries.

[0046] With reference to FIG. **2**, in an alternative embodiment, the slurry for forming the cathode active material (see above) may be formed by first forming a first slurry comprising the intermediate precursor, a binder and a solvent, and subsequently adding to the first slurry a Li compound to form a second slurry.

[0047] With reference to FIG. **2**, in step **210**, an intermediate precursor may be formed from one or more salts of Ni, Mn and Co. In an embodiment, the intermediate precursor may be formed by co-precipitating one or more salts of Ni, Mn and Co. The one or more of salts of Ni, Mn and Co may be selected from the group consisting of nitrates, chlorides, sulfates and acetates. In some cases, multiple salts may be used to provide Ni, Mn or Co in the intermediate precursor. For example, $NiNO_3$ and $NiSO_4$ may be used to provide Ni during the co-precipitation synthesis of the intermediate precursor.

[0048] Next, in step **215**, a first slurry may be formed by mixing the intermediate precursor with a binder and a solvent. The order of combination of the constituent elements of the first slurry may be selected as desired. For example, the intermediate precursor, binder and solvent may be combined simultaneously or substantially simultaneously to form the first slurry. As another example, the intermediate precursor and solvent may be combined first, and the binder may be added thereafter to form the first slurry.

[0049] The binder may include one or more of gelatin, cellulose, cellulose derivatives, polyvinylpyrrolidone (PVP), polyvinyl acetate (PVA), starch, sucrose and polyethylene glycol. In a preferable embodiment, the binder is PVP. The solvent for forming the slurry may include one or more of water and alcohols, such as, e.g., methanol, ethanol, propanol (e.g., isopropanol) and butanol. In a preferable embodiment, the solvent for forming the slurry is isopropanol.

[0050] Next, in step **220**, a lithium compound is added to the first slurry to form a second slurry. The Li compound may include a lithium-containing salt. In an embodiment, the Li compound may include one or more of lithium carbonate, lithium hydroxide, lithium nitrate and lithium acetate. In a preferable embodiment, the Li compound is lithium carbonate. The second slurry may then be used to form a cathode active material, as described above (see, e.g., steps **115-145** of FIG. **1**).

[0051] It will be appreciated that in forming the slurries described above, various mixing methods may be employed. For example, when an intermediate precursor is mixed with a solvent and a binder, a stirring or mixing mechanism may be employed to provide sufficient mixing of the constituent elements of the slurry. In an embodiment, the slurry may be formed in a stirred tank reactor, such as a continuous stirred tank reactor (CSTR). Various properties of the slurry upon mixing may be monitored and controlled to form a slurry having properties as desired. For instance, during mixing, the slurry temperature and pH may be monitored and controlled.

Cathode Active Material and Lithium-Ion Batteries

[0052] In another aspect of the invention, cathode active materials for use in lithium-ion batteries are provided. In embodiments, the cathode active materials have the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x', 'y' and 'z' are numbers, and wherein $0 \leqq x \leqq 1$, $0 \leqq y \leqq 1$ and $0.8 \leqq z < 1$. In various embodiments, 'z' is a number less than about 1, or less than or equal to about 0.95, or less than or equal to about 0.9, or less than or equal to about 0.85, or less than or equal to about 0.8. In an embodiment, 'z' is a number less than about 1 and greater than or equal to about 0.8.

[0053] In embodiments of the invention, the cathode active material is capable of providing a first cycle irreversible capacity loss less than or equal to about 10%, or less than or equal to about 5%, or less than or equal to about 3%.

[0054] Cathode active materials of embodiments of the invention may be formed via any methods described above, such as the method described in the context of FIGS. **1** and **2**.

[0055] In another aspect of the invention, cathode active materials formed according to methods of embodiments of the invention may be used as cathode materials of lithium-ion batteries. In embodiments, lithium-ion batteries are provided having a cathode comprising $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number less than about 1. In embodiments, 'z' may be less then or equal to about 0.95, or less than or equal to about 0.9, or less than or equal to about 0.85, or less than or equal to about 0.8. Lithium-ion batteries having cathode materials of embodiments of the invention may be capable of providing a first cycle irreversible capacity loss less than or equal to about 10%, or less than or equal to about 5%, or less than or equal to about 3%.

[0056] Cathode active materials and lithium-ion batteries comprising cathode active materials of embodiments of the invention may have the same or higher discharge capacity in relation to prior art cathode materials and lithium-ion batteries. In an embodiment, cathode active materials and lithium-ion batteries comprising cathode active materials of embodiments of the invention may have a capacity that is increased by as much as 3% or higher in relation to prior art cathode materials and lithium-ion batteries.

[0057] It will be appreciated that lithium-ion batteries formed from cathode materials of aspects and embodiments of the invention may comprise any anode, separator and electrolyte material suitable for optimizing the performance of such lithium-ion batteries. The cathode electrode may have a coating with the cathode active material of the invention, carbon black, and PVDF binder coated on the positive collector of aluminum foil. The anode electrode may have a coating with an active material of graphite, carbon black, and PVDF binder coated on the negative collector of copper foil. The separator may be 20 vim thick, for example, Celgard 2320. The electrodes and the separators may be arranged in various arrangements. The electrolyte may contain 1.3 M $LiPF_6$ in EC/EMC/DMC (1:1:1 ratio, by weight). In some cases, the electrolyte may contain VC or other additive.

[0058] In some embodiments, a band-shaped electrode may be laminated by winding itself spirally so that the side of the band-shaped electrode results in a flush wound end surface, in a jellyroll configuration to form a battery. Such bands may be of different dimensions such as lengths and thicknesses and heights, which may result in a battery in a jellyroll configuration of varying diameters. In some embodiments of the invention, the jellyroll batteries may be circular in cross-section, or may be spirally wound with other cross-sections, such as ovals, rectangles, or any other shape.

[0059] In some instances, the battery may have a cylindrical cell format, or a prismatic cell format, such as a 18650 cylindrical cell format, 26650 cylindrical cell format, 32650 cylindrical cell format, or 633450 prismatic cell format.

EXAMPLE 1

[0060] Flakes were prepared using a $(Ni_{1/3}Co_{1/3}Mn_{1/3})CO_3$ carbonate precursor, which was synthesized by the co-precipitation method. An aqueous solution of $NiSO_4$, $CoSO_4$, and $MnSO_4$ (Ni:Mn:Co=1:1:1 molar ratio) with a concentration of 2M was pumped into stirred tank reactor. A 2M aqueous solution of Na_2CO_3 and a solution of NH_4OH as a chelating agent were also fed into the reactor. The stirring speed and the pH value were carefully controlled throughout the mixing process. The spherical $(Ni_{1/3}Co_{1/3}Mn_{1/3})CO_3$ powder obtained was washed and filtered, and dried in a vacuum oven overnight at a temperature of about 100° C. A lithium compound, Li_2CO_3, was thoroughly mixed with the precursor $(Ni_{1/3}CO_{1/3}Mn_{1/3})CO_3$. The mixture was first heated at a temperature of about 55° C. for about 30 minutes in air and subsequently mixed with an 8 wt % PVP (binder) and isopropyl alcohol (IPA) to obtain a slurry. The slurry was coated on a plastic film (releasing substrate) to form a coated layer on the plastic film. The coated layer was then heated and peeled off of the plastic film. Then the peeled coated layer (flake) was calcined at about 900° C. for about 10 hours in air to obtain an $Li(NiCoMn)O_2$ flake. The metal elements were analyzed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) which showed the flake as having about 0.343 atm % Ni, 0.325 atm % Mn, 0.333 atm % Co and 0.813 atm % Li—i.e., the flake comprised $Li_{0.81}(Ni_{0.34}Mn_{0.33}Co_{0.33})O_2$.

[0061] Next, the flake was ground and placed on a zero background holder and put into a Philips X'Pert MPD pro diffractometer, which used Cu radiation at 45 KV/40 mA. XRD scans were taken over the range of 10° to 90° with a step size of 0.0158°. An XRD scan is shown in FIG. **3**. All strong diffraction peaks were indexed with a rhombohedral lattice (R-3m).

[0062] The electrochemical properties of the NMC powder were evaluated using CR2032 type coin cells assembled in an argon filled glove box and tested at room temperature. The positive electrode included about 80 wt % oxide powder (formed as described above), 10 wt % carbon black, and 10 wt % polyvinylidene fluoride binder coated onto an aluminum foil. Lithium foil was used as the negative electrode. Cells A, B and C used an electrolyte having about 1.3 M $LiPF_6$ in a mixture of EC, DMC, and EMC (1:1:1 v/v) with 1 wt % VC. Cells D, E and F used an electrolyte having about 1.2 M $LiPF_6$ in a mixture of EC and EMC (3:7 by weight). The coin cells were charged-discharged at a C/10 rate within a range of 2.5-4.3V at the room temperature. The results are shown in Table 1.

TABLE 1

6 coin cell test results for the first (1st) charge and discharge.

Cells	A	B	C	D	E	F
1st charge (mAh/g)	162.9	163.5	165.1	165.3	166.3	166.7
1st discharge (mAh/g)	158.5	158.3	160.4	160.1	160.3	161.5
Irreversible loss (%)	2.7	3.2	2.9	3.1	3.6	3.1

Example 2

[0063] Experiments were conducted to determine the irreversible losses of cathode materials as a function of the Li content of the cathode materials. Slurries were formed according to the methods described above, but for each cell (see FIG. **2**) a slurry having a predetermined lithium content was prepared. The lithium content was selected by varying the amount of Li_2CO_3 used to form each of the slurries. Cathode materials were then prepared as described above to form flakes having the general formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about '0' and 1, and 'z' is selected based on the amount (or quantity) of Li_2CO_3 used to form the flakes. Following heating treatment (sintering), the flakes were tested to determine the irreversible losses of the cathode materials incorporating each of the flakes. Results from the experiments are shown in Table 2. As shown in Table 2, for a flake having a lithium content ('z') of about 0.95, an irreversible loss of about 5.0 (i. e., 5.0%) was obtained. The irreversible loss increased as the lithium content of the cathode materials increased.

TABLE 2

Coin cell test results for cathode materials with different lithium content.

	Adjust lithium content in the cathode material	
	$Li_{0.95}(Ni_{0.34}Mn_{0.33}Co_{0.33})O_2$	$Li_{1.0}(Ni_{0.34}Mn_{0.33}Co_{0.33})O_2$
1^{st} charge capacity (mAh/g)	170.9	180.4
1^{st} discharge (mAh/g)	162.4	163.9
Irreversible loss (%)	5.0	9.2

[0064] All concepts of the invention may utilize, be incorporated in, or be integrated with other lithium mixed metal oxide materials, including, but not limited to, those described in U.S. Pat. No. 6,677,082 ("Lithium metal oxide electrodes for lithium cells and batteries"), issued on Jan. 13, 2004, U.S. Pat. No. 6,680,143 ("Lithium metal oxide electrodes for lithium cells and batteries"), issued on Jan. 20, 2004, U.S. Pat. No. 6,964,828 ("Cathode compositions for lithium-ion batteries"), issued on Nov. 15, 2005, U.S. Pat. No. 7,078,128 ("Cathode compositions for lithium-ion batteries"), issued on Jul. 18, 2006, and U.S. Pat. No. 7,205,072 ("Layered cathode materials for lithium ion rechargeable batteries"), issued on Apr. 17, 2007, which are entirely incorporated herein by reference.

[0065] It will be appreciated that methods and compositions, as described herein, may used to form other lithium-containing cathode materials for lithium-based cells (or batteries), such as lithium titanium oxide (LTO) cathode materials and lithium iron phosphate (LFP) cathode materials.

[0066] While preferable embodiments of the invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. It is intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.

1. A method for forming a cathode material for use in a lithium-ion battery, the method comprising sintering flakes formed from a nickel, manganese, cobalt and lithium-containing slurry to form the cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein 'x' is a number between about 0 and 1, 'y' is a number between about 0 and 1, and 'z' is a number greater than or equal to about 0.8 and less than 1.

2. A method for producing a cathode material having the formula $Li_zNi_{1-x-y}Mn_xCo_yO_2$, wherein $0 \leqq x \leqq 1$, $0 \leqq y \leqq 1$ and $0.8 \leqq z < 1$, the method comprising:

mixing a nickel (Ni) salt, manganese (Mn) salt and cobalt (Co) salt to form an intermediate precursor;

mixing the intermediate precursor with a lithium (Li) compound, a binder and a solvent to form a slurry;

coating a releasing substrate with the slurry to form a coated layer;

forming flakes from the coated layer; and

sintering the flakes to form the cathode material.

3. The method of claim **2**, further comprising drying the coated layer and separating the coated layer form the substrate prior to forming flakes.

4. The method of claim **2**, wherein forming flakes comprises shredding the coated layer.

5. The method of claim **2**, wherein the intermediate precursor is formed from salts of Ni, Mn and Co via coprecipitation synthesis.

6. The method of claim **2**, wherein the Li compound includes a lithium-containing salt.

7. The method of claim **2**, wherein one or more of the Ni salt, Mn salt and Co salt are selected from the group consisting of nitrates, chlorides, hydroxides, carbonates, sulfates and acetates.

8. The method of claim **2**, wherein the solvent is selected from the group consisting of water, methanol, ethanol, propanol, butanol and combinations thereof.

9. The method of claim **2**, wherein sintering the flakes comprises heating the flakes at a temperature less than or equal to about 1100° C.

10. The method of claim **2**, wherein sintering the flakes comprises heating the flakes at a temperature less than or equal to about 1000° C.

11. The method of claim **2**, wherein the binder includes poly vinyl pyrrolidone (PVP).

12. The method of claim **2**, wherein the releasing substrate comprises a polymeric material.

13. A method for forming lithium nickel manganese cobalt oxide (NMC) particles, comprising

forming a slurry comprising a Li compound, a binder, a solvent and an intermediate precursor having nickel (Ni), manganese (Mn) and cobalt (Co);

coating a substrate with the slurry to form a coated layer on the substrate;

drying the coated layer to separate the coated layer from the substrate;

shredding the coated layer into flakes;

heating the flakes to form sintered flakes; and

crushing the sintered flakes to form the NMC particles.

14. The method of claim **13**, wherein the intermediate precursor is formed from salts of Ni, Mn and Co.

15. The method of claim **14**, wherein the intermediate precursor is formed by co-precipitating the salts of Ni, Mn and Co.

16. The method of claim **13**, further comprising removing the coated layer from the substrate after drying the coated layer.

17. The method of claim **13**, further comprising filtering the NMC particles after crushing the sintered flakes to obtain a predetermined NMC particle size distribution.

18-25. (canceled)

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