Supplementary Material

1. Supplementary Heterogeneity Analysis

1.1 Temporal Heterogeneity Analysis

To further validate the performance of the proposed model, this paper conducts a heterogeneity analysis at a finer granularity. This analysis adopts the autonomous driving patent data covering the period 2010–2021 as the research sample, divides the full sample into 12 subsamples by calendar year, and sorts them in ascending chronological order. After sorting, each patent is assigned a corresponding time dummy variable based on its publication year, which takes an integer value ranging from 1 to 12. Subsequently, new interaction terms are constructed by combining the time dummy variables with the explanatory variables. The results of the heterogeneity analysis are presented in the table below.

Table S1 Heterogeneity analysis of year aspect

	SM1	**SM2**	**SM3**	**SM4**	**SM5**	**SM6**
DC	-0.279***	-0.197***				
	(-46.595)	(-8.226)				
HC			0.384***	0.384***		
			(74.759)	(19.686)		
BC					-0.124***	-0.070**
					(-22.282)	(-3.240)
Year		0.111***		0.037		0.063***
		(14.049)		(1.368)		(11.120)
DC Year*		-0.098***				
		(-4.022)				
HC Year*				-0.002		
				(-0.071)		
BC Year*						-0.057**
						(-2.638)
Cited_patents	0.028***	0.035***	-0.033***	-0.030***	0.006	0.011**
	(5.232)	(6.604)	(-6.610)	(-5.917)	(1.079)	(1.998)
Inventor_Num	0.035***	0.032***	0.023***	0.022***	0.028***	0.026***
	(6.594)	(5.966)	(4.573)	(4.250)	(5.216)	(4.745)
Assignee_Num	-0.067***	-0.049***	-0.281***	-0.275***	-0.162***	-0.152***
	(-11.169)	(-8.020)	(-53.672)	(-51.668)	(-28.849)	(-26.746)
N	33347	33347	33347	33347	33347	33347

Note: The coefficients presented in the table are standardized regression coefficients, with t-values shown in parentheses; *, p<0.05, **, p<0.01, ***, p<0.001.

1.2 IPC Heterogeneity Analysis

Similarly, this study also conducts a more fine-grained heterogeneity analysis in terms of

IPC. The IPC heterogeneity analysis presented in the manuscript corresponds to the Section level of the IPC system, while further analysis is performed at the Class level. Finer-grained IPC heterogeneity analysis is feasible at more detailed levels such as Sub-Class, Group, and Sub-group. However, these finer granularities may lead to deviation from the research's core topic, and analysis at the Class level is already sufficient to test the robustness of the empirical model and explore the heterogeneity of the IPC aspect. The further heterogeneity analysis is categorized based on 282 IPC codes at the Class level. Patents included in the sample of the benchmark regression are assigned dummy variable values based on their first IPC code, with the values ranging as integers between 1 and 282. The numeric labels are used only for empirical coding, and the results are interpreted as heterogeneity across technology categories, not as a linear effect of IPC ordering. Subsequently, new interaction terms are constructed by incorporating the IPC dummy variables and the explanatory variables. The results of the heterogeneity analysis are presented in the table below.

Table S2 Heterogeneity analysis of IPC Class aspect

	SM7	**SM8**	**SM9**	**SM10**	**SM11**	**SM12**
DC	-0.279***	-0.291***				
	(-46.595)	(-47.441)				
HC			0.384***	0.370***		
			(74.759)	(64.231)		
BC					-0.124***	-0.130***
					(-22.282)	(-21.079)
IPC_Class		-0.392***		0.093***		-0.341***
		(-52.121)		(6.485)		(-62.893)
DC IPC_Class*		0.108***				
		(13.535)				
HC IPC_Class*				-0.336***		
				(-24.345)		
BC IPC_Class*						0.071***
						(11.273)
Cited_patents	0.028***	0.025***	-0.033***	-0.029***	0.006	0.004
	(5.232)	(4.900)	(-6.610)	(-6.048)	(1.079)	(0.862)
Inventor_Num	0.035***	0.035***	0.023***	0.025***	0.028***	0.029***
	(6.594)	(6.946)	(4.573)	(5.124)	(5.216)	(5.661)
Assignee_Num	-0.067***	-0.073***	-0.281***	-0.269***	-0.162***	-0.165***
	(-11.169)	(-12.984)	(-53.672)	(-53.279)	(-28.849)	(-31.157)
N	33347	33347	33347	33347	33347	33347

Note: The coefficients presented in the table are standardized regression coefficients, with t-values shown in parentheses; *, p<0.05, **, p<0.01, ***, p<0.001.

2. Supplementary alternative variables analysis

1.1 TBT_NMF Model Test

This study also constructs another alternative LPS measure using a Neural Collaborative

Filtering (NMF) model [53]. The NMF model introduces a neural interaction layer to capture more flexible nonlinear relationships between firms and technological domains. Specifically, firm embeddings, IPC embeddings, and their element-wise interaction terms are concatenated and passed through multilayer neural networks to generate predicted firm–IPC preference scores. The model is trained using a pairwise ranking objective, where observed firm–IPC interactions are positive samples and unobserved interactions are negative samples.

Analogous to the RGNN model, to reflect temporal continuity in technological evolution, these two models are also trained recursively across different stages. After training, the final-stage firm–IPC score matrices are saved as the alternative LPS matrices and further aggregated into patent-level TBT using the same TF–IDF weighting procedure as in the baseline RGNN model. This design allows the robustness test to examine whether the empirical results depend on the RGNN architecture or remain stable under a nonlinear neural recommendation model or a classical matrix factorization framework.

Table S3 Empirical results by replacing the TBT_NMF Model

	SM13	**SM14**	**SM15**	**SM16**	**SM17**	**SM18**
DC	-0.090***	-0.085***				
	(-14.531)	(-11.522)				
HC			0.084***	0.052***		
			(15.090)	(6.957)		
BC					-0.058***	-0.061***
					(-10.320)	(-8.424)
Family_size		-0.168***		-0.426***		-0.143***
		(-13.342)		(-11.825)		(-15.942)
*DC*Family_size*		0.066***				
		(5.710)				
*HC*Family_size*				0.289***		
				(7.908)		
*BC*Family_size*						0.032***
						(4.034)
Cited_patents	0.048***	0.055***	0.031***	0.044***	0.044***	0.053***
	(8.758)	(9.920)	(5.647)	(8.053)	(7.947)	(9.597)
Inventor_Num	0.036***	0.037***	0.033***	0.035***	0.034***	0.036***
	(6.566)	(6.695)	(5.960)	(6.371)	(6.186)	(6.593)
Assignee_Num	-0.102***	-0.019*	-0.162***	-0.053***	-0.129***	-0.034***
	(-16.522)	(-2.275)	(-28.504)	(-6.662)	(-22.632)	(-4.196)
N	33347	33347	33347	33347	33347	33347

Note: The coefficients presented in the table are standardized regression coefficients, with t-values shown in parentheses; *, p<0.05, **, p<0.01, ***, p<0.001.

1.2 TBT_baselineNGCF Model Test

TBT_baselineNGCF Model applies the Neural Graph Collaborative Filtering (NGCF) method [54] to compute TBT. In the non-recursive multi-stage baseline, the interaction data are divided into multiple temporal stages, and the model is separately trained within each stage. However, the learned embeddings from previous stages are not transferred to subsequent

stages. Instead, each stage starts from a newly initialized parameter space and is optimized independently. As a result, no historical latent representations or accumulated graph knowledge are preserved across periods.

This baseline is designed to isolate the effect of temporal recursive knowledge transfer. Since the temporal segmentation strategy, graph construction process, optimization procedure, and hyperparameter settings remain consistent with those of the recursive model, the key difference lies in whether historical embeddings are inherited. Therefore, the comparison between the recursive and non-recursive settings allows us to evaluate the contribution of temporal representation continuity rather than the effect of temporal partitioning itself.

Table S4 Empirical results by replacing the TBT_baselineNGCF Model

	SM19	**SM20**	**SM21**	**SM22**	**SM23**	**SM24**
DC	-0.310***	-0.380***				
	(-52.817)	(-54.429)				
HC			0.175***	0.157***		
			(32.293)	(21.569)		
BC					-0.133***	-0.182***
					(-24.056)	(-25.790)
Family_size		-0.243***		-0.361***		-0.180***
		(-20.542)		(-10.345)		(-20.515)
*DC*Family_size*		0.250***				
		(22.970)				
*HC*Family_size*				0.197***		
				(5.558)		
*BC*Family_size*						0.115***
						(14.734)
Cited_patents	0.021***	0.025***	-0.034***	-0.019***	-0.005	0.007
	(3.918)	(4.858)	(-6.328)	(-3.580)	(-0.890)	(1.217)
Inventor_Num	0.019***	0.015**	0.009	0.011*	0.011*	0.012*
	(3.602)	(2.949)	(1.603)	(2.152)	(2.109)	(2.285)
Assignee_Num	-0.090***	-0.017*	-0.269***	-0.145***	-0.197***	-0.089***
	(-15.339)	(-2.147)	(-48.724)	(-18.707)	(-35.515)	(-11.188)
N	33347	33347	33347	33347	33347	33347

Note: The coefficients presented in the table are standardized regression coefficients, with t-values shown in parentheses; *, p<0.05, **, p<0.01, ***, p<0.001.

1.3 TBT_NGCF Model Test

TBT_NGCF Model also uses the NGCF method [54] to compute TBT. Unlike TBT_baselineNGCF, TBT_NGCF utilizes data samples from all time periods, while TBT_baselineNGCF only uses data from specific time periods for training.

Table S5 Empirical results by replacing the TBT_NGCF Model

	SM25	**SM26**	**SM27**	**SM28**	**SM29**	**SM30**
DC	-0.310***	-0.380***				
	(-52.836)	(-54.446)				

HC			0.175***	0.157***		
			(32.283)	(21.549)		
BC					-0.133***	-0.182***
					(-24.064)	(-25.793)
Family_size		-0.243***		-0.362***		-0.180***
		(-20.533)		(-10.361)		(-20.506)
*DC*Family_size*		0.250***				
		(22.968)				
*HC*Family_size*				0.198***		
				(5.576)		
*BC*Family_size*						0.115***
						(14.727)
Cited_patents	0.020***	0.025***	-0.034***	-0.019***	-0.005	0.006
	(3.906)	(4.846)	(-6.342)	(-3.594)	(-0.903)	(1.203)
Inventor_Num	0.019***	0.015**	0.009	0.012*	0.011*	0.012*
	(3.621)	(2.968)	(1.622)	(2.170)	(2.127)	(2.303)
Assignee_Num	-0.090***	-0.017*	-0.269***	-0.145***	-0.197***	-0.089***
	(-15.332)	(-2.149)	(-48.722)	(-18.709)	(-35.514)	(-11.192)
N	33347	33347	33347	33347	33347	33347

Note: The coefficients presented in the table are standardized regression coefficients, with t-values shown in parentheses; *, p<0.05, **, p<0.01, ***, p<0.001.

3. Supplementary explanation for network centrality measures

3.1 Network centrality indicators

To capture the structural position of patents within the technological knowledge system, this study constructs a patent–IPC bipartite network without projection, which is based on patent data extracted from the classification information.

Specifically, we define an undirected bipartite graph $G = (P \cup I,\ E)$, where P denotes the set of patent nodes and I represent the set of IPC nodes. An edge $e_{(p,i)} \in$ E is established between patent $p \in P$ and IPC subclass $i \in I$ if patent p is assigned to subclass i. Each patent may be connected to multiple IPC nodes, reflecting its technological composition and scope.

All network measures are computed directly on the bipartite graph without projection onto a single-mode network. This approach preserves the original affiliation structure between patents and technological classes and avoids additional assumptions introduced by projection methods.

Based on this network, three centrality measures are calculated to characterize different structural attributes of patent nodes:

(1) Degree Centrality (DC). Degree centrality is defined as the normalized number of edges connected to a node. For patent nodes, it corresponds to the number of IPC classes associated with the patent, capturing its technological breadth.

(2) Harmonic Centrality (HC). Harmonic centrality is computed as the sum of the reciprocal shortest-path distances from a node to all other nodes in the network, that is, the

sum over all other nodes u of 1 divided by the shortest-path distance between node v and node u. This measure is particularly suitable for networks with disconnected components, as it avoids the undefined values associated with traditional closeness centrality. In the present context, HC reflects the relative proximity of a patent to the overall technological space and its level of embeddedness within the knowledge network. This choice is particularly important in large-scale technological networks, where disconnected components are common due to domain specialization.

(3) Betweenness Centrality (BC). Betweenness centrality measures the extent to which a node lies on the shortest paths between other nodes. It captures the bridging role of patents in connecting different technological domains. Due to the large scale of the network, we compute betweenness centrality using a sampling-based approximation method with 1,000 randomly selected source nodes. This approach significantly reduces computational complexity while maintaining estimation accuracy.

All centrality measures are computed using the NetworkX library in Python. The network is treated as unweighted, meaning that all patent–IPC relationships are assigned equal importance. This design choice ensures interpretability and avoids introducing additional assumptions regarding edge strength.

We note that degree centrality in the bipartite network is closely related to the number of IPC subclasses associated with a patent, and thus reflects technological scope rather than centrality in a strict network-theoretic sense.

Finally, only centrality values corresponding to patent nodes are retained for subsequent empirical analysis.

3.2 Disconnected nodes in the network

In the constructed bipartite network, multiple disconnected components may exist due to the heterogeneous distribution of patent–IPC relationships. That is, some patents and IPC classes form isolated subgraphs with no paths connecting them to other parts of the network.

To address this issue, we adopt centrality measures that are robust to disconnected structures. Harmonic centrality is employed instead of traditional closeness centrality, as it remains well-defined even when nodes are not mutually reachable. Specifically, distances to unreachable nodes are treated as contributing zero to the harmonic centrality score, thereby avoiding the undefined values associated with infinite distances.

For betweenness centrality, the measure is computed based on existing shortest paths only. Node pairs that are not connected do not contribute to the calculation, which is consistent with standard definitions in network analysis.

Empirically, the network exhibits a largely connected structure. The largest connected component accounts for approximately 99.0% of all nodes, while the remaining nodes are distributed across a small number of minor disconnected components.

These design choices ensure that centrality measures remain meaningful and comparable across nodes, even in the presence of disconnected components.

4. Patent search strategy

Patent database: Derwent Innovations Index (DII)

Time-span (Year): 2010 to 2021

Search query:

(TI=("driverless car*" OR "driveless vehicle*" OR "unmanned vehicle*" OR "unmaned car*" OR "self-driv* vehicle*" OR "self-driv* vehicle*" OR "pilotless car*" OR "pilotless vehicle*" OR "automatic driv* car*" OR "automatic driv* vehicle*" OR "autonomous car*" OR "autonomous vehicle*" OR "autonomous driv* car*" OR "autonomous driv* vehicle*" OR "autonomic car*" OR "autonomic vehicle*" OR "intelligent connect* car*" OR "intelligent connect* vehicle*") NOT TI=("UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerial vehicle*" OR "arialvehicle*" OR "airvehicle*" OR "unmanneddrone*" OR "unmanned aerialvehicle*" OR drone OR flight OR air OR fly OR flies)) OR (AB=("driverless car*" OR "driveless vehicle*" OR "unmanned vehicle*" OR "unmaned car*" OR "self-driv* vehicle*" OR "self-driv* vehicle*" OR "pilotless car*" OR "pilotless vehicle*" OR "automatic driv* car*" OR "automatic driv* vehicle*" OR "autonomous car*" OR "autonomous vehicle*" OR "autonomous driv* car*" OR "autonomous driv* vehicle*" OR "autonomic car*" OR "autonomic vehicle*" OR "intelligent connect* car*" OR "intelligent connect* vehicle*") NOT AB=("UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerial vehicle*" OR "arialvehicle*" OR "airvehicle*" OR "unmanneddrone*" OR "unmanned aerialvehicle*" OR drone OR flight OR air OR fly OR flies)) OR (IP=(G08G-001/014 OR G08G-001/016 OR G06F-021* OR B60W-030 OR B60W-040 OR B60W-050 OR B62D) AND AB=(autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR “intelligent connect*” OR "AGV")) OR ((IP=(G05B- 013* OR G06N* OR G05B* OR G05D-001* OR G05D-013* OR G06F-008* OR G06F-009* OR G08G-001* OR G01S17/936 OR G01S-017/ 93 OR G01S-015/931 OR G01S-015/93 OR Y02T-090 OR G01S-013/931 OR G01S-013/93 OR G01S-007* OR G01S-017/88 OR G06K- 009* OR G06T-001* OR B60W OR B60L OR B60Y OR B60K-028/004 OR B60K-028 OR B60K-028/016 OR B60K-028/006 OR B60K- 031*) AND AB=((autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR “intelligent con- nect*” OR "AGV") AND (ground OR car OR cars OR lorry OR lorries OR road OR street OR highway OR convoy OR platoon OR fleet OR traffic OR automobile OR vehicle OR vehiclar))) NOT AB=("UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerial vehicle*" OR "arial vehicle*" OR "air vehicle*" OR "unmanned drone*" OR "unmanned aerial vehicle*" OR drone OR flight OR air OR fly OR flies)) OR (IP= (G08G-001/016 OR B60W-030 OR B60W-040 OR B60W-050 OR B62D OR Y02T-010 OR B60Y-2200/11 OR G08G-001/014) AND (TI= (autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR “intelligent connect*” OR "AGV") OR AB=(autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR “intelligent connect*” OR "AGV")))OR((IP=(G05D-001*ORG01S-017ORG01S-015ORY02T-090 OR G01S-013 OR B60Q-005 OR B60W OR B60L OR B60Y))AND (TI=(autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR intelligent connect* OR "AGV") AND TI=(ground OR car OR cars OR lorry OR lorries OR road OR street OR highway OR convoy OR platoon OR fleet OR traffic OR automobile OR vehicle OR vehiclar) NOTTI=("UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerialvehicle*" OR "arialvehicle*" OR "air vehicle*" OR "unmanned drone*" OR "unmanned aerial vehicle*" OR drone OR flight OR air OR fly OR flies))) OR ((AB=(autonomous OR autonomic OR self-driv* OR unmanned OR driverless OR driveless OR pilotless OR “intelligent connect*” OR "AGV") AND AB=(ground OR car OR cars OR lorry OR lorries OR

road OR street OR highway OR convoy OR platoon OR fleet OR traffic OR automobile OR vehicle OR vehicular OR V2V OR V2X OR “vehicle-to-vehicle” OR “vehicle to vehicle” OR V2I)) NOT AB=("UAV" OR "AUV" OR "ROV" OR "under- water" OR "aerial vehicle*" OR "arialvehicle*" OR "air vehicle*" OR "unmanned drone*" OR "unmanned aerial vehicle*" OR drone OR flight OR air OR fly OR flies) AND IP=(B60R-021* OR H04B-010* OR H04F-012* OR H04J-003* OR H04J-014* OR H04L-029/008 H04N-005* OR H04W-004/040 OR H04W-004/044 OR H04W-046* OR H04W-004/048 OR H04B-010* OR H04W-004/044 OR H04W-046 OR H04W-004/048 OR H04W-072* OR G01C-021/026 OR G01C-021/034 OR G06N-099* OR G0801*))

5. Top 10 IPC code meanings

The following lists the main IPC codes (Class level) that appear in the text and their corresponding meanings[1]. The specific content is as follows.

(1) B60W. Conjoint control of vehicle sub-units of different type or different function; control systems specially adapted for hybrid vehicles; road vehicle drive control systems for purposes not related to the control of a particular sub-unit.

(2) G05D. Systems for controlling or regulating non-electric variables.

(3) B62D. Motor vehicles; trailers.

(4) G01C. Measuring distances, levels or bearings; surveying; navigation; gyroscopic instruments; photogrammetry or videogrammetry.

(5) B60L. Propulsion of electrically-propelled vehicles; supplying electric power for auxiliary equipment of electrically-propelled vehicles ; electrodynamic brake systems for vehicles in general; magnetic suspension or levitation for vehicles; monitoring operating variables of electrically-propelled vehicles; electric safety devices for electrically-propelled vehicles.

(6) G01S. Radio direction-finding; radio navigation; determining distance or velocity by use of radio waves; locating or presence-detecting by use of the reflection or reradiation of radio waves; analogous arrangements using other waves.

(7) B60R. Vehicles, vehicle fittings, or vehicle parts, not otherwise provided for.

(8) G06F. Electric digital data processing.

(9) G08G. Traffic control systems.

(10) G06K. Graphical data reading; presentation of data; record carriers; handling record carriers.

[1] WIPO. IPC Publication. https://ipcpub.wipo.int/?notion=scheme&version=20260101&symbol=none&menulang=en&lang=en&viewmode=f&fipcpc=no&showdeleted=yes&indexes=no&headings=yes&notes=yes&direction=o2n&initial=A&cwid=none&tree=no&searchmode=smart, Accessed at May 19, 2026.