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Network Science-based Analysis of the US Marine Highway Network and a Random Graph Model for the Intermodal Port Network

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1. Project Description

In 2007, the US Congress passed public law 110-140 to develop marine highways as waterborne alternatives (with respect to several criteria such as traffic congestion, fuel usage, wear and tear of the roads, public safety and security, etc) to ease the freight transportation load across the interstate roads connecting the major cities in the country. Accordingly, the US Maritime Administration (MARAD) identified marine highways (navigable waterways) that run parallel or close to the major interstate roads and designated them with numerical identifiers that correspond to the interstate roads for which they are meant to serve as an effective alternative. For example, M-55 refers to the marine highway (on the Mississippi river) that runs along with interstate I-55 from New Orleans, LA to Chicago, IL. We used the marine highway network map posted at the MARAD website [1] and the one-pager description of the marine highways in [2] to build a graph model of the US marine highway network (MHN). A node in the MHN corresponds to a marine highway and an edge connects two nodes if the corresponding marine highways intersect at one or more intermodal ports. An intermodal port is a port that is located on a marine highway and a nearby city supports at least two of the three major forms of transportation: rail, road and air.

Figure 1: US Marine Highway Network (extracted from MARAD website [1])

We model the US marine highway network (MHN) as an undirected graph of nodes (marine highways) and edges (two marine highways have an edge between them if there are one or more intermodal ports in the two highways). We focus on the 16 marine highways spanning over the gulf coast, east coast and mid west parts of the US. We also consider the 21 core intermodal ports through which two or more marine highways go through and are located either in the east coast, gulf coast or the mid western US. We model the US Marine Intermodal Port Network (MIPN) as an undirected graph of nodes represented by the intermodal ports and two nodes are connected by an edge if one or more marine highway goes through the corresponding ports. We conduct a comprehensive evaluation of the MHN and MIPN graphs with respect to a suite of node and edge centrality metrics as well as network-level metrics and identify prospective bottleneck ports and marine highways owing to their topological position. We also conduct a quantitative comparison of the MHN with road, rail and air transportation networks with respect to network-level metrics such as the assortativity index, bipartivity index, algebraic connectivity, randomness index and spectral radius ratio for node degree. In addition, we conduct principal component analysis on a dataset of these results to demonstrate the MIPN to be topologically unique compared to transportation networks already studied in the literature. Finally, we extend the MIPN to a network of 89 ports comprising of the 21 core ports and 68 stub ports that are located in only one marine highway and are connected to the closest core port in that highway. The extended MIPN is modeled as an undirected graph featuring the core ports and stub ports as nodes, and the marine highways as edges connecting them. We developed a web application that could be used to visualize the routes between any two intermodal ports of the MIPN: the web application will present the user with a pre-populated list of the 21 core intermodal ports between any two of which we could find and display the marine highway source-destination route. To the best of our knowledge, ours is the first work in the Network Science literature to model and evaluate the US MHN and MIPN using algorithms and metrics for complex network analysis.

2. Methodological Approach

Among the 22 marine highways reported in MARAD, we did not consider the M-146, M-295, M-495 and M-580 highways as their individual waterway spanning distance is much smaller compared to the rest of the marine highways, and we did not consider the M-5 and M-85 highways in the west coast as they were disconnected from the rest. Among the remaining 16 marine highways spanning the east coast, gulf coast and the mid western portion (EGMW) of the US: M-71 and M-77 had identical waterways (hence used just M-71 and did not consider M-77). We hence focused on the 15 marine highways spanning the east coast, gulf coast and the mid western portion of the US to construct our MHN. We identified a total of 89 intermodal ports located on the 15 marine highways of the MHN. We observed 21 of these 89 intermodal ports to be located on more than one marine highway and chose them as the basis to construct the graph model for a US marine intermodal port network (MIPN) as these ports (referred to as core ports) would serve as crucial hubs (similar to the hub airports in an airport network) for freight transfer across marine highways. The rest of the intermodal ports are more like stub ports that are located in just a particular marine highway and would not serve as hub for freight transfer.

Figure 2 presents an intersection matrix (corresponding to the MHN) of the 15 marine highways (starting with a prefix of M-) and the core intermodal ports (starting with a prefix of IP-) that are present at the intersections of two or more marine highways; the names of the 21 core intermodal ports are shown along with. These 21 core ports form the nodes of the MIPN whose intersection matrix is shown in Figure 3. There is an edge (represented using an 'x' in the intersection matrix of Figure 3) between two nodes in the MIPN (modeled as an undirected graph) if the corresponding core intermodal ports are present in one or more of the same marine highways.

		M-10	M-29	M-35	M-40	M-49	M-55	M-64	M-65	M-69	M-70	M-71	M-75	M-87	M-90	M-95
Albany, NY	IP-1													X	X	
Aransas Pass, TX	IP-2	X								X						
Brownsville, TX	IP-3	X								X						
Chicago, IL	IP-4						X								X	
Cleveland, OH	IP-5											X			X	
Corpus Christi, TX	IP-6	X								X						
Detroit, MI	IP-7												X		X	
Galveston, TX	IP-8	X								X						
Houston, TX	IP-9	X								X						
Jacksonville, FL	IP-10	X														X
Kansas City, MO	IP-11		X								X					
Memphis, TN	IP-12						X		X							
Mobile, AL	IP-13	X							X							
Morgan City, LA	IP-14	X				X				X						
New Orleans, LA	IP-15	X					X									
NewYork City, NY	IP-16													X		X
Norfolk, VA	IP-17							X								X
Paducah, KY	IP-18						X		X		X					
Port Arthur, TX	IP-19	X								X						
Rosedale, MS	IP-20				X		X									
St. Louis, MO	IP-21		X	X			X				X					

Figure 2: Intersection Matrix of the US Marine Highway Network and the Core Intermodal Ports

	IP-1	IP-2	IP-3	IP-4	IP-5	IP-6	IP-7	IP-8	IP-9	IP-10	IP-11	IP-12	IP-13	IP-14	IP-15	IP-16	IP-17	IP-18	IP-19	IP-20	IP-21
IP-1				X	X		X									X					
IP-2			X			X		X	X	X			X	X	X				X		
IP-3		X				X		X	X	X			X	X	X				X		
IP-4	X				X		X					X			X			X		X	X
IP-5	X			X			X														
IP-6		X	X					X	X	X			X	X	X				X		
IP-7	X			X	X																
IP-8		X	X			X			X	X			X	X	X				X		
IP-9		X	X			X		X		X			X	X	X				X		
IP-10		X	X			X		X	X				X	X	X	X	X		X		
IP-11																		X			X
IP-12				X									X		X			X		X	X
IP-13		X	X			X		X	X	X		X		X	X			X	X		
IP-14		X	X			X		X	X	X			X		X				X		
IP-15		X	X	X		X		X	X	X		X	X	X				X	X	X	X
IP-16	X									X							X				
IP-17										X						X					
IP-18				X							X	X	X		X					X	X
IP-19		X	X			X		X	X	X			X	X	X						
IP-20				X								X			X			X			X
IP-21				X							X	X			X			X		X	

Figure 3: Intersection Matrix of the Core Ports of the US Marine Intermodal Port Network (MIPN)

Centrality Metrics: Centrality metrics quantify the positional importance of nodes and edges in a network topology [3]. The node-based centrality metrics can be broadly classified as neighborhood-based and shortest path-based. The well known node-based centrality metrics [3] are the degree centrality (DEG), eigenvector centrality (EVC) [4], betweenness centrality (BWC) [5] and closeness centrality (CLC) [6]. While DEG and EVC are neighborhood-based, BWC and CLC are shortest path-based. The DEG of a node is the number of neighbors for the node. The EVC for a node is a measure of the DEG of the node as well as the DEG and EVC of the neighbors of the node. The BWC of a node is a measure of the number of shortest paths between any two vertices in the network going through the node. The CLC for a node is a measure of the distance (shortest paths) to the rest of the nodes in the network. We conduct a comprehensive centrality analysis of the MHN and MIPN using the algorithms proposed for these metrics.

Cluster Analysis: A cluster or a community in a complex network is a subset of the nodes that are more densely connected among themselves than to the rest of the nodes in the network [3]. We refer to the clusters of a complex network to be more modular [7] if the intra-cluster density (fraction of the actual number of edges to the maximum possible number of edges among the nodes within a cluster) is appreciably greater than the inter-cluster density (fraction of the actual number of edges connecting the nodes across two clusters to the maximum possible number of edges connecting the nodes across the two clusters). While most of the nodes in a cluster are likely to be connected "only" to nodes within the same cluster (home cluster), if the underlying graph is connected, there could be one or more "bridge" nodes for each cluster. A bridge node for a cluster has edges to bridge nodes in one or more other (alien) clusters; nevertheless, majority of the edges for a bridge node are expected to be with nodes in its home cluster [8]. Bridge nodes are critical for connectivity among clusters, for freight transportation and for the overall connectivity of the MIPN.

Bridge Nodes: We now briefly explain the NBNC (neighborhood-based bridge node centrality) tuple [8] used to quantify and rank the nodes on the basis of the extent with which they play the role of bridge nodes. The NBNC tuple for a node comprises of three entries and is determined based on the neighborhood graph of the node. The neighborhood graph of a node is considered to comprise of the neighbors of the node as vertices and the edges connecting these neighbors. Note that the neighborhood graph of a node does not comprise of the node itself and the edges incident on the node. The first entry in the NBNC tuple indicates the number of components in the neighborhood graph of the node; the second entry is the ratio of the algebraic connectivity [9] of the neighborhood graph and the degree of the node; the third entry is the degree of the node. If the number of components in the neighborhood graph of a node is more than 1, it implies the neighborhood graph is disconnected and the second entry (algebraic connectivity ratio) is 0.0. It also implies that the neighbors in any two components of the neighborhood graph of the node are reachable to each other in the overall connected graph only through the node. Such nodes are highly ranked as bridge nodes (the larger the number of components in the neighborhood graph of a node, the higher the ranking). The second entry is greater than 0.0 only if the neighborhood graph is connected; the algebraic connectivity of such a connected neighborhood graph is determined as the smallest non-zero Eigenvalue of the Laplacian matrix [9, 10] of the neighborhood graph. The sparser the connected neighborhood graph of a node, the lower is its algebraic connectivity ratio (greater than 0.0 though), and such nodes play a significant role in connecting the nodes within their home cluster and are considered to be bridge nodes as well (ranked after the nodes whose neighborhood graph has more than one component). Nodes with a dense connected neighborhood graph are not critical for connectivity within their home cluster as well as for connectivity of their home cluster to alien clusters, and such nodes are ranked lowly as bridge nodes.

Network-Level Metrics: We seek to show that the topological characteristics of the MHN and the MIPN are different from that of the other transportation related networks already studied in the literature. We choose the US Airports Network (USAN: 332 nodes and 2126 edges [11]), London Train Stations Network (LTSN: 381 nodes and 507 edges [12]), the EU Airports Network (EUAN: 418 nodes and 1999 edges [13]) and the EU Road Network (EURN: 1174 nodes an 1417 edges [14]) for our comparative analysis. The topological characteristics of these five networks are captured on the basis of five well-known network-level metrics for complex network analysis: Spectral radius ratio for node degree (SPR-K [15]), Assortativity index (AssI [3]), Randomness index (RanI [16]), Algebraic connectivity ratio (ACR [9]) and Bipartivity index (BPI [17]). We first briefly introduce each of these five metrics below. All these five metrics are independent of the number of nodes and edges in the network. (1) Spectral radius ratio for node degree (SPR-K) is a measure of the extent of variation in node degree, measured in a scale of [1, ∞): the farther the SPR-K value from 1.0, the larger the variation in node degree. SPR-K for a network is computed as the ratio of the spectral radius (largest Eigenvalue [10]) of the adjacency matrix of the graph and the average degree of the vertices. (2) Assortativity Index (AssI), with values ranging from -1.0 to 1.0, is a measure of the similarity between the end vertices of the edges with respect to node degree (i.e., whether high/low degree vertices are connected to other high/low degree vertices or low/high degree vertices). An assortative network (AssI > 0.1) is a network wherein the degrees of the end vertices of the edges are more likely to be similar to each other; a dissortative network (AssI < -0.1) is a network wherein the degrees of the end vertices are dissimilar from each other. If AssI values are closer to 0.0 (-0.1 to 0.1), we say the network is neither assortative nor dissortative. AssI is computed as the Pearson's correlation coefficient [10] of an X-Y dataset comprising of the degrees of the end vertices of the edges (x, y), where the IDs can be ordered as x < y, and DEG(x) belongs to the set X and DEG(y) belongs to the set Y. (3) Randomness Index (RanI), with values ranging from -1.0 to 1.0, is a measure of the extent with which the edges in the network are due to random associations between the nodes rather than preferential attachment. RanI quantifies the correlation between the local clustering coefficient of the nodes with node degree, and is measured as the Pearson's correlation coefficient between K vs. : the average of the LCC values of the nodes with degree K. (4) Algebraic Connectivity Ratio (ACR) is the ratio of the algebraic connectivity of the network and the number of nodes in the network. A network is said to be "connected" if the nodes are reachable to each other either directly or through multi-hop paths. The ACR for a network that is not connected is 0. The algebraic connectivity of a connected network is a measure of the extent with which the network will stay connected with node or edge removals, and is measured the smallest non-zero Eigenvalue of the Laplacian matrix [9] of the connected graph. (5) Bipartivity Index (BPI [17], with values ranging from 0.5 to 1.0) is a measure of the extent with which the nodes in the network can be partitioned to two disjoint sets such that the number of edges connecting the vertices across the two partitions is as large as possible. If a graph is truly bipartite (i.e., all the edges are between vertices across the two partitions and no edge exists between vertices in the same partition]), its BPI value is 1.0. For networks whose edge distribution among the vertices is independent of any possible partitioning, the BPI values are closer to 0.50. The BPI for a network is measured using the Eigenvalues of the adjacency matrix of the graph, as the ratio of the sum of the cosh values of the Eigenvalues to the ratio of the sum of the cosh and sum of the sinh values of the Eigenvalues.

3. Results/Findings

3.1 Centrality Analysis of the Marine Highway Network (MHN)

Figure 4 lists the DEG, EVC, BWC and CLC values for the marine highways, the edge BWC values for the edges connecting the marine highways as well as presents a comparative plot of the DEG vs. BWC values for the nodes: the larger the BWC values for the nodes, the bigger are the circles corresponding to these nodes; likewise, the larger the DEG values for the nodes, the lighter are the circles corresponding to these nodes. We observe M-55 to have the largest BWC value of 51.65, followed by M-70 (26), M-90 (23.6) and M-10 (21.85). The BWC metric can be considered as a measure of congestion of the marine highways on the basis of the network topology. It is interesting to see that the top four marine highways with respect to BWC are geographically distributed across the different regions of the US (M-70 in the central mid-west US, M-90 in the east coast, M-10 in the gulf coast and the M-55 running from the gulf coast to the upper mid-west coast). M-55 also incurs the largest CLC, implying that it is relatively more closer to the other marine highways in the MHN. On the other hand, M-29 and M-35 incur the lowest CLC value, implying that they are farther away from the rest of the marine highways.

Node	DEG	EVC	BWC	CLC
M-10	6	0.430817	21.85	0.037037
M-49	2	0.195228	0	0.025
M-55	6	0.419109	51.65	0.041667
M-65	5	0.412527	14.23333	0.035714
M-69	4	0.359901	4.566667	0.033333
M-75	2	0.172364	1.366667	0.028571
M-95	3	0.185776	5.166667	0.029412
M-29	2	0.040478	0	0.021277
M-35	2	0.040478	0	0.021277
M-70	3	0.123466	26	0.029412
M-40	1	0.103478	0	0.026316
M-90	5	0.267296	23.6	0.035714
M-64	3	0.209754	2.25	0.028571
M-71	4	0.251247	5.816667	0.030303
M-77	2	0.128028	0	0.025641
M-87	2	0.111863	1.5	0.027027

Edge	Edge BWC	Edge	Edge BWC
55--70	39	10--49	9.43333333
55--90	24.65	64--65	9.25
10--55	16.3666667	75--90	8.2
40--55	15	71--90	7.58333333
29--70	14	87--95	6.5
35--70	14	10--65	6.45
10--95	13.4166667	49--69	5.56666667
55--65	13.25	64--95	5.41666667
87--90	11.5	65--69	5.03333333
77--90	10.2666667	64--71	4.83333333
55--69	10.0333333	71--77	4.73333333
10--75	9.53333333	10--69	3.5
65--71	9.48333333	29--35	1

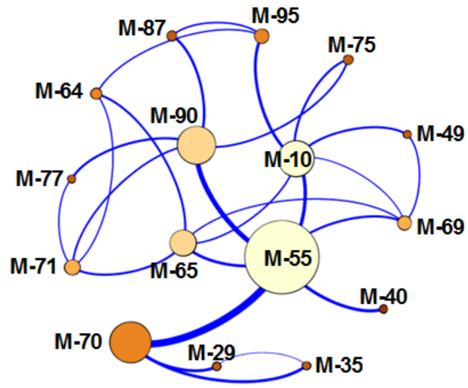


Figure 4: Centrality Metrics Values for the Nodes and Edges in the MHN and a Comparative Plot of DEG vs. BWC Metrics along with Edge BWC

With respect to EVC, we could construe that moderate-high DEG marine highways connected to high DEG and high EVC highways are also expected to incur relatively larger EVC/BWC values. This is vindicated by a relatively moderate-larger EVC/BWC values for M-65 and M-69. These two highways (though their geographical spread is smaller) are expected to be at least moderately loaded with traffic due to their proximity to both M-55 and M-10 (the two marine highways with larger DEG, BWC as well as EVC values). On the other hand, high-DEG nodes connected to nodes with lower DEG/EVC values are expected to only have moderate values for EVC (like the M-90 highway connected to the low degree M-64, M-75, M-77, M-87 and M-95 highways).

Figure 4 also presents the thickness of the blue-colored edges proportional to the Edge BWC values. The BWC for an edge (also referred to as EBWC) is a measure of the fraction of the shortest paths (among all possible source-destination pairs) going through the edge [3, 7]. We observe edges associated with the high BWC node M-55 to incur the larger EBWC values as well. This implies the intermodal ports (Chicago, IL on the intersection with M-90; St. Louis, MO on the intersection with M-70; Memphis, TN on the intersection with M-40; New Orleans, LA on the intersection with M-10, M-65 and M-69) on the intersection of M-55 with each of its neighboring marine highways are more likely to be heavily loaded with traffic (on the basis of the MHN topology). Among these, the M-55...M-70 edge featuring the St. Louis, MO port is observed to incur the largest EBWC value (39), followed by the M55...M-90 edge (with an EBWC value of 24.65) featuring the Chicago, IL port.

In the context of NBNC for bridge node analysis (see Figure 5), we observe M-55 (rank 0.0) and M-90 (rank 1.0) to be the top ranking nodes/marine highways, each of which if removed would disconnect their neighborhood graphs featuring 6 and 5 other marine highways respectively into four disconnected components. The larger the circle corresponding a node in Figure 5, the higher the NBNC rank for the node.

Node	# Components in NG	Alg. Conn. Ratio of NG	DEC	NBNC Ranking
M-55	4	0.00	6	0.0
M-90	4	0.00	5	1.0
M-10	3	0.00	6	2.0
M-95	3	0.00	3	3.0
M-65	2	0.00	5	4.0
M-71	2	0.00	4	5.0
M-70	2	0.00	3	6.5
M-64	2	0.00	3	6.5
M-75	2	0.00	2	8.5
M-87	2	0.00	2	8.5
M-69	1	0.25	4	10.0
M-49	1	1.00	2	12.5
M-29	1	1.00	2	12.5
M-35	1	1.00	2	12.5
M-77	1	1.00	2	12.5
M-40	1	1.00	1	15.0

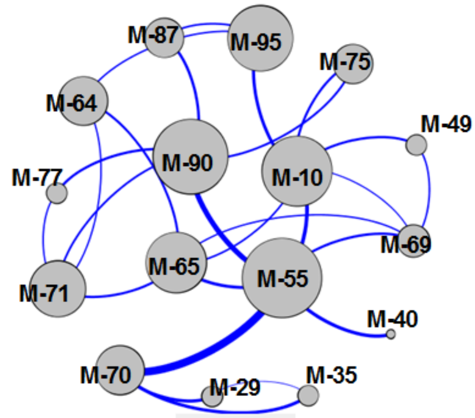


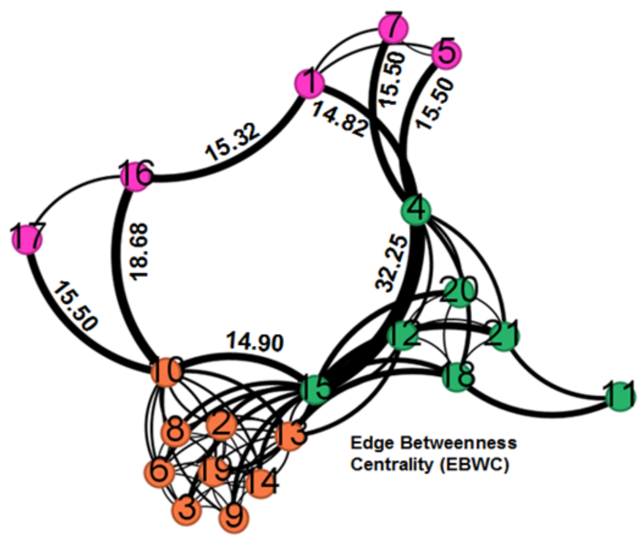
Figure 5: Neighborhood-based Bridge Node Centrality (NBNC) Tuple of Nodes and their Ranking

3.2 Centrality Analysis of the Marine Intermodal Port Network (MIPN)

Centrality analysis of the nodes and edges in the MIPN identifies the ports and the marine highways that are likely to incur the bulk of the traffic. Figure 6 displays the DEG, NBWC and CLC values for the 21 core ports of the MIPN as well as presents a comparative topological view of the node rankings (on the basis of the node size) with respect to each of these three centrality metrics. Figure 6 also illustrates a comparative view of the edge betweenness centrality (EBWC) values: edges with larger EBWC values are shown thicker and vice-versa. Overall, we observe the ports of IP-15: New Orleans, LA, IP-10: Jacksonville, FL and IP-4: Chicago, IL to incur larger centrality values with respect to all the three node-level metrics as well as the IP-4 ---- IP-15 edge (marine highway M-55) incurs the largest EBWC value of 32.25 that is about 70% greater than the next largest EBWC value of 18.68 incurred for the edge IP-10 --- IP-16 (marine highway M-95). The IP-4 --- IP-15 edge could be considered the primary edge for freight transportation between the nine M-10 cluster ports in the Gulf coast to the upper mid-west ports and east coast ports; the IP-10 --- IP-16 edge could be considered to provide a backup path (a longer shortest path) between the Gulf coast ports and the upper mid-west/east coast ports.

With respect to DEG, we observe the intermodal ports in the M-10 cluster (the ports in the Gulf coast) to incur significantly larger values compared to the ports in the other two clusters. However, a larger DEG centrality value does not guarantee a larger NBWC value for several of these ports. There are nine high-degree ports connected to each other in the M-10 cluster/Gulf coast and closer (through multi-hop minimum hop paths) to the ports in the other two clusters, but only three of them (New Orleans, LA; Jacksonville, FL; and Mobile, AL) are observed to incur high values for the node betweenness centrality and connect the other M-10/Gulf coast ports to the rest of the ports in the MIPN. We observe the ports in the M-90 cluster to incur the smallest centrality values with respect to all the three metrics. However, the EBWC values of the edges incident on these ports (in the upper mid-west/east coast: M-90 cluster) are relatively much larger than the edges in the M-10 cluster. Since the Gulf coast ports are directly connected to each other through M-10, the EBWC values for the edges within the M-10 cluster are much smaller. On the other hand, the edges connecting the ports in the M-90 cluster need to support traffic involving several pairs of ports. With respect to EBWC, we observe six of the top eight edges to involve a port in the M-90 cluster to be at least one of the two end vertices. The ports in the M-10 cluster are closer to the rest of the ports in the MIPN in terms of the shortest path lengths (hop counts; CLC metric); whereas, the ports in the M-90 cluster are the farthest from the rest of the ports.

NodeID	DEG	NBWC	CLC
IP-1	4	8.566667	0.022222
IP-2	9	0	0.028571
IP-3	9	0	0.028571
IP-4	8	41.31667	0.030303
IP-5	3	0	0.020833
IP-6	9	0	0.028571
IP-7	3	0	0.020833
IP-8	9	0	0.028571
IP-9	9	0	0.028571
IP-10	11	30.18333	0.03125
IP-11	2	0	0.018868
IP-12	6	1.916667	0.027778
IP-13	11	12.86667	0.03125
IP-14	9	0	0.028571
IP-15	14	63.98333	0.038462
IP-16	3	9.25	0.023256
IP-17	2	0	0.021277
IP-18	7	13.01667	0.028571
IP-19	9	0	0.028571
IP-20	5	0	0.027027
IP-21	6	6.9	0.027778



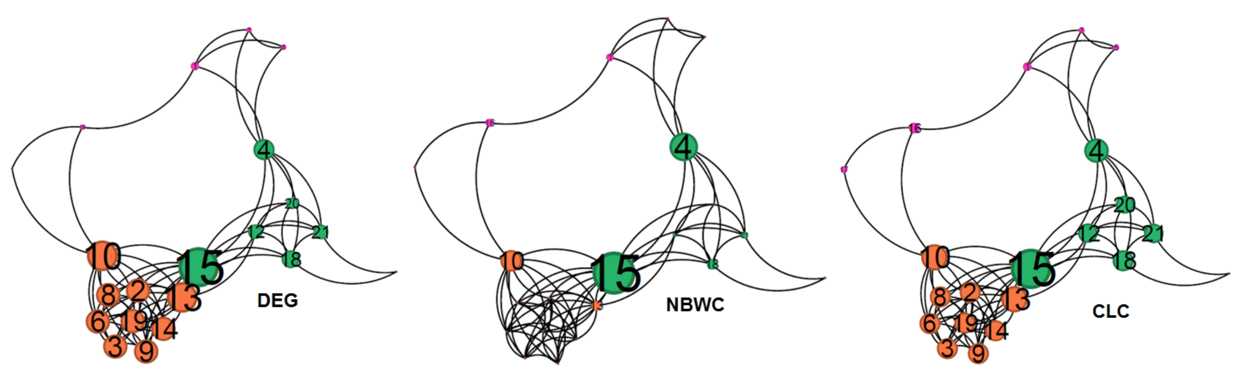


Figure 6: Node and Edge Centrality Metrics for the MIPN

3.3 Cluster Analysis of the MIPN

We ran the MIPN through the well-known Louvain community detection algorithm [18] and observed the following three clusters (referred to as the M-10 cluster, M-55 cluster and M-90 cluster) of the core intermodal ports whose individual identifier names coincide with the marine highways in which the majority of the ports in the particular clusters are located. The M-10 cluster comprises of the following nine core ports: IP-2: Aransas Pass, TX; IP-3: Brownsville, TX; IP-6: Corpus Christi, TX; IP-8: Galveston, TX; IP-9: Huston, TX; IP-10: Jacksonville, FL; IP-13: Mobile, AL; IP-14: Morgan City, LA and IP-19: Port Arthur, TX. The M-55 cluster comprises of the following seven core ports: IP-4: Chicago, IL; IP-11: Kansas City, MO; IP-12: Memphis, TN; I IP-15: New Orleans, LA; P-18: Paducah, KY; IP-20: Rosedale, MS and IP-21: St. Louis, MO. The M-90 cluster comprises of the following five core ports: IP-1: Albany, NY; IP-5: Cleveland, OH; IP-7: Detroit, MI; IP-16: New York City, NY and IP-17: Norfolk, VA. Figure 7 displays the MHN, the 21 core intermodal ports of the MIPN and their clusters (differentiated using the colors of the nodes representing the ports).

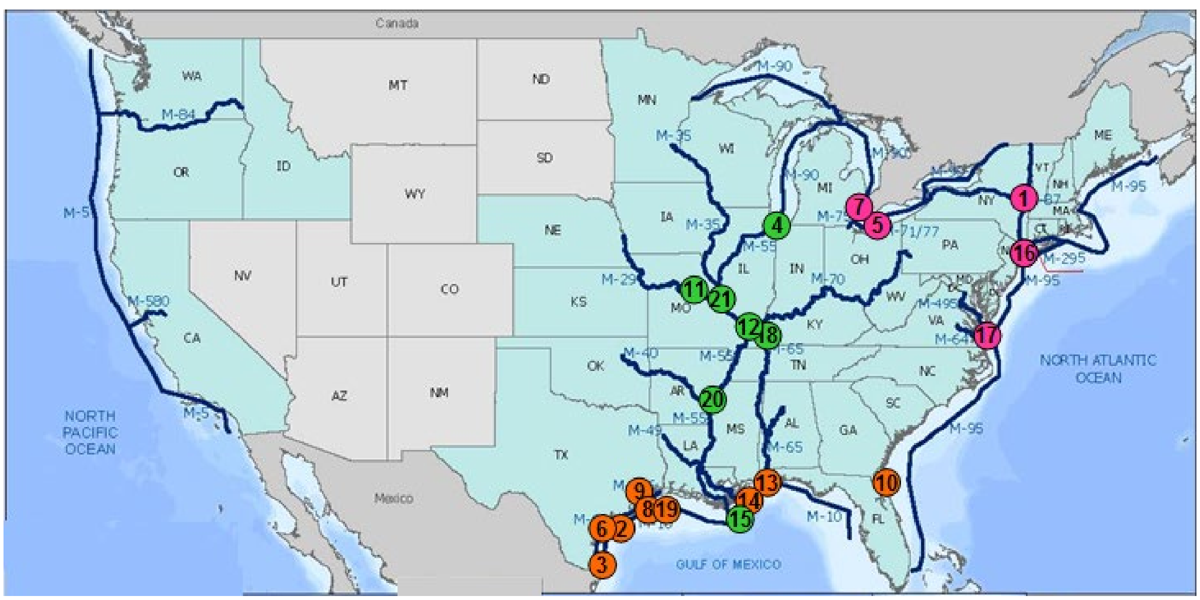


Figure 7: Map of the MHN and the Clusters of the Core Intermodal Ports of the MIPN

The M-10 cluster is the most densest with the M-10 highway running through all the 9 core ports (in other words, these core ports are directly reachable to each other). Nevertheless, the presence of just one marine highway connecting all the 9 core ports in the Gulf coast also makes these ports vulnerable for closure and disconnection from the rest of the MIPN in the wake of hurricanes approaching the coast. The M-90 cluster is the least densest, comprising of marine highways M-90, M-75, M-71, M-87 and M-95 that connect the five core ports (in other words, any two core ports of this cluster are more likely not directly reachable to each other and are reachable only through multi-hop paths) and the ports are vulnerable for disconnection if a "bridge" port (see more details below) such as the IP-1: Albany, NY port gets closed. The M-55 cluster is also moderately connected with four marine highways involved in connecting seven core ports. The low-moderate intra-cluster density of two of the three clusters is reflected in a low overall modularity score [7] of 0.338 (in a scale of 0.0 to 1.0).

Figure 8 presents the NBNC tuple values of the 21 core nodes of the MIPN in the order of their ranking (high to low) with regards to the extent with which they play the role of bridge nodes. The lower the rank number for a node in Figure 8, the higher is its ranking as a bridge node. If the first two entries in the NBNC tuples of two or more nodes are the same, the tie is broken on the basis of the degree of the nodes (the larger the degree, the higher the ranking). If all the three entries are the same, the nodes are ranked equally. Figure 8 also presents an Yifan Hu Proportional layout [19] of the MIPN (generated using Gephi [20]) that corroborates the NBNC-based ranking of the nodes as bridge nodes. The colors of the nodes in the three clusters of the MIPN layout in Figure 8 correspond to the colors of the nodes shown in the clusters in Figure 7.

Node ID	# Components	Algebraic Connectivity ratio	Degree	Ranking
IP-10	2	0	11	1
IP-4	2	0	8	2
IP-1	2	0	4	3
IP-16	2	0	3	4
IP-15	1	0.0332	14	5
IP-13	1	0.0909	11	6
IP-18	1	0.1325	7	7
IP-21	1	0.1667	6	8
IP-12	1	0.3333	6	9
IP-2	1	1	9	10
IP-3	1	1	9	10
IP-6	1	1	9	10
IP-8	1	1	9	10
IP-9	1	1	9	10
IP-14	1	1	9	10
IP-19	1	1	9	10
IP-20	1	1	5	11
IP-5	1	1	3	12
IP-7	1	1	3	12
IP-17	1	1	2	13
IP-11	1	1	2	13

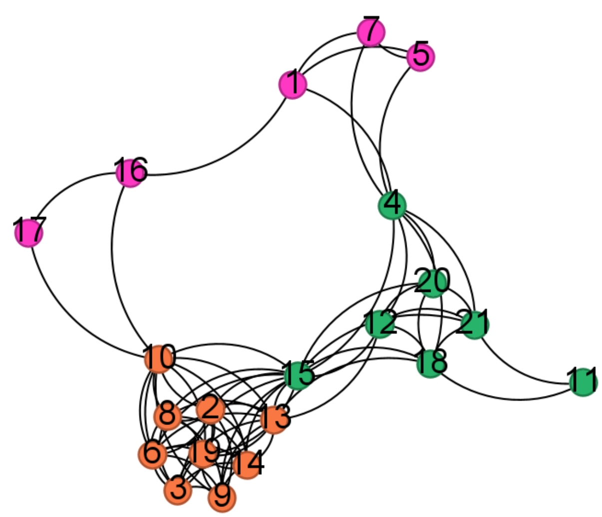


Figure 8: Neighborhood-based Bridge Node Centrality (NBNC) Tuples of the Nodes (Core Intermodal Ports: IP) in the MIPN and the Topological Layout of the Clusters

We conclude the following nine core ports as the top-ranked bridge nodes (in the order of the ranking shown in Figure 8) of the MIPN. We observe node IP-10 (Jacksonville, FL) to be critical in connecting the Gulf coast ports to the East coast ports and node IP-4 (Chicago, IL) to be critical in connecting the upper mid-west ports to both the Gulf coast ports and the lower mid-west ports. In the absence of IP-10 (Jacksonville, FL), the shortest paths between the Gulf coast ports and the East coast ports have to go through the mid-west ports in the M-55 cluster. Likewise, in the absence of IP-4 (Chicago, IL), the shortest paths between the Gulf coast ports and the mid-west ports have to go through the entire east coast. IP-1 (Albany, NY) is critical to facilitate connectivity between the East coast ports and the upper mid-west ports in the M-90 cluster. IP-16 (New York City, NY) facilitates connections between the Gulf coast ports and the East coast/upper mid-west ports. IP-15 (New Orleans, LA) is the only core port that provides direct connectivity for the Gulf coast ports to an upper mid-west port IP-4 (Chicago, IL) and is also connected to the majority of the lower mid-west ports in the M-55 cluster. Likewise, node IP-13 (Mobile, AL) connects the Gulf coast ports to the lower mid-west ports, but not to any upper mid-west port. Nodes IP-18 (Paducah, KY), IP-21 (St. Louis, MO) and IP-12 (Memphis, TN) are critical (in this order) for connectivity among the lower mid-west ports as well as their connection to ports in the upper mid-west and Gulf coast.

3.4 Network-Level Metrics

Table 1 presents the values incurred by the five above-mentioned transportation networks (including MHN) with respect to the above network-level metrics. We observe the MIPN to be relatively more scale-free (larger spectral radius ratio for node degree) and assortative (larger assortativity index) and less random in the distribution of the edges among the ports (randomness index relatively larger and more closer to 0) than the MHN. We also observe the MHN to be relatively more close-to-be-bipartite compared to the MIPN; whereas, the MIPN is relatively more strongly connected (larger Algebraic connectivity ratio) than the MHN.

Table 1: Network-Level Metrics for the MHN, MIPN and the Different Transportation Networks

Network	Spectral radius ratio: node degree (λ_{sp}^{k})	Assortativity index: Degree (AssI)	Randomness index (RanI)	Algebraic connectivity ratio (ACR)	Bipartivity index (BPI)
MHN	1.2462	0.1146	-0.8240	0.01704	0.7736
MIPN	1.3124	0.3271	-0.3850	0.0390	0.5029
USAN	3.2195	-0.1186	-0.8887	0.0003629	0.5000
LONTSN	3.6004	-0.7258	-0.3139	0.000224	0.9819
EUAN	3.8111	-0.2051	-0.8647	0.001099	0.5000
EURN	1.6613	-0.5195	-0.5387	0.0	0.9769

We observe the airport and train station networks to be scale-free (larger $\lambda_{sp}^{k} > 3$ values); the λ_{sp}^{k} values for the MHN (1.2462) and MIPN (1.3124) are in the vicinity of the λ_{sp}^{k} value (1.6613) incurred for EURN, a road transportation network. Thus, from the point of view of extent of variation in node degree and the extent of scale-freeness, the MHN and MIPN are more similar to a road network, rather than the airport and train station networks. While the assortativity index values for both the MHN and MIPN are positive, the rest of the transportation networks: USAN, EUAN, EURN and LONTSN networks exhibit dissortativity. The air transportation networks typically have the high-degree hub airports connected to the low-degree stub airports (such a characteristic has been even more dominantly observed for the LONTSN, a train stations network, and the EURN, a road transportation network). A low positive degree-based assortativity index for the MHN indicates that the marine highways are relatively less likely between a high-degree marine highway and a low-degree marine highway.

The MHN and MIPN incur relatively larger ACR values than the rest of the transportation networks. The EURN has an ACR value of 0.0 (as there are 26 components in the EURN). Though the USAN, EUAN and LONTSN have ACR values greater than 0.0, the low magnitude of the ACR values for these networks indicate that these three networks (vis-a-vis the MHN and MIPN) are more likely to get disconnected to two or more components due to the removal of a node or edge. For the MHN, we observe a BPI of 0.7736, and the two partitions of vertices are shown in Figure 9. We observe 18 of the total 25 edges (i.e., about 72% of the edges) to be between vertices across these two partitions. This also implies that the intermodal ports (located at the intersection of the marine highways) located in the marine highways within each of the two partitions are less likely to be directly connected to the intermodal ports located in the marine highways identified in the same partition. Very high BPI values for the LONTSN and EURN networks is an indication that these two networks have majority of their edges between nodes that are across the two partitions of vertices identified to form a graph that is close to a bipartite graph. The BPI of the two air transportation networks (USAN and EUAN) and the MIPN are 0.50 each.

	M-10	M-65	M-69	M-70	M-40	M-90	M-64
M-49	X		X				
M-55	X	X	X	X	X	X	
M-75	X					X	
M-95	X						X
M-29				X			
M-35				X			
M-71		X				X	X
M-87						X	

Figure 9: Edge Intersection Matrix for the two Bipartite Partitions of the MHN

3.5 Principal Component Analysis

For each of MHN and MIPN, we conducted a Principal Component Analysis (PCA) [21] of the results tabulated in Table 1 by considering the five network-wide metrics as the features and the transportation networks as the ids for the records forming the data set. For both the MHN and MIPN datasets, we observed that two principal components are needed to capture at least 80% of the variance among the feature values in the data set. Figure 10 present plots (for MHN and MIPN) of the entries for the five networks in the two principal components (PC1 and PC2) as the X (PC1) and Y (PC2) coordinate values. We observe the two airport networks (USAN and EUAN) to cluster together and the train stations and road transportation networks (LONTSN and EURN) to cluster together. The MHN is in the second quadrant and is farther away from these four networks. Likewise, the MIPN is in the third quadrant and is farther away from the rest of these networks. This shows that the MHN and MIPN are unique networks whose network-wide characteristics are not similar to any of the other four related transportation networks that have been already analyzed in the literature.

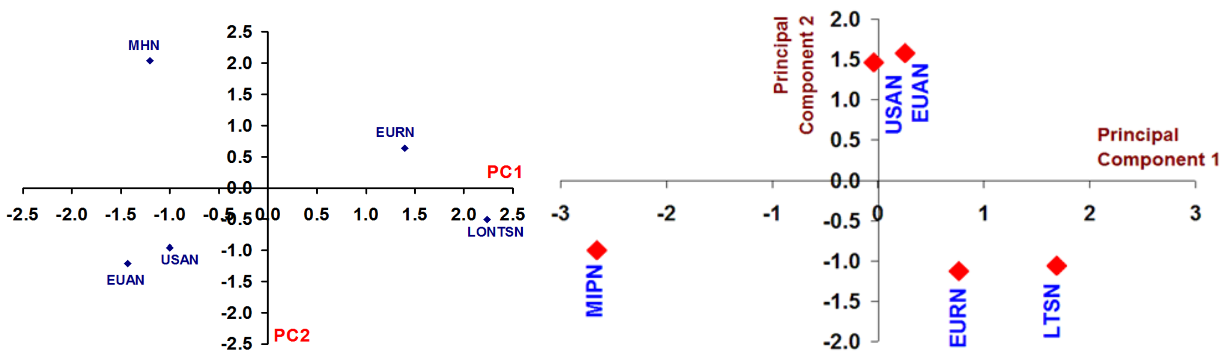


Figure 10: Plots of the First Two Principal Components of the Network-wide Metrics Results Data Set

4. Impacts/Benefits of Implementation (actual, not anticipated)

The high-level contribution of this project is a complex network model for the US marine highway network (MHN) and core US marine intermodal ports (MIPN) located on two or more marine highways. We have given detailed information regarding the nodes (core ports) and the edges (marine highways) connecting any two ports in the MIPN. To the best of our knowledge, this is the first such work to propose a marine intermodal port network (MIPN) as well as conduct a comprehensive analysis of the MHN and MIPN from various perspectives of Network Science. We also built a web application that would facilitate a user to obtain the shortest route (in terms of the number of marine highways/edges) between any two intermodal ports. The application is live on the public URL below where it can be accessed via browser: https://orange-stone-090e0c110.2.azurestaticapps.net/. After visiting this page, one can see two criterion displayed there. Criteria 1 has been planned to display the marine highway routes between any two cities in the US (through the nearest intermodal ports); this criteria is still under development. Criteria 2 displays the marine highway route between any two of the 21 core intermodal ports; this criteria has been fully implemented. Figure 11 shows a screenshot of the default visualization that appears once the above URL is visited; the screenshot shows all the marine highways and the intermodal ports. Figure 12 shows a screenshot of the marine highway route between two specific ports: Albany, NY to Jacksonville, FL going through marine highways M-90 and M-95; the Port of New York City, NY is displayed as an intermediate port (in orange color) as well.

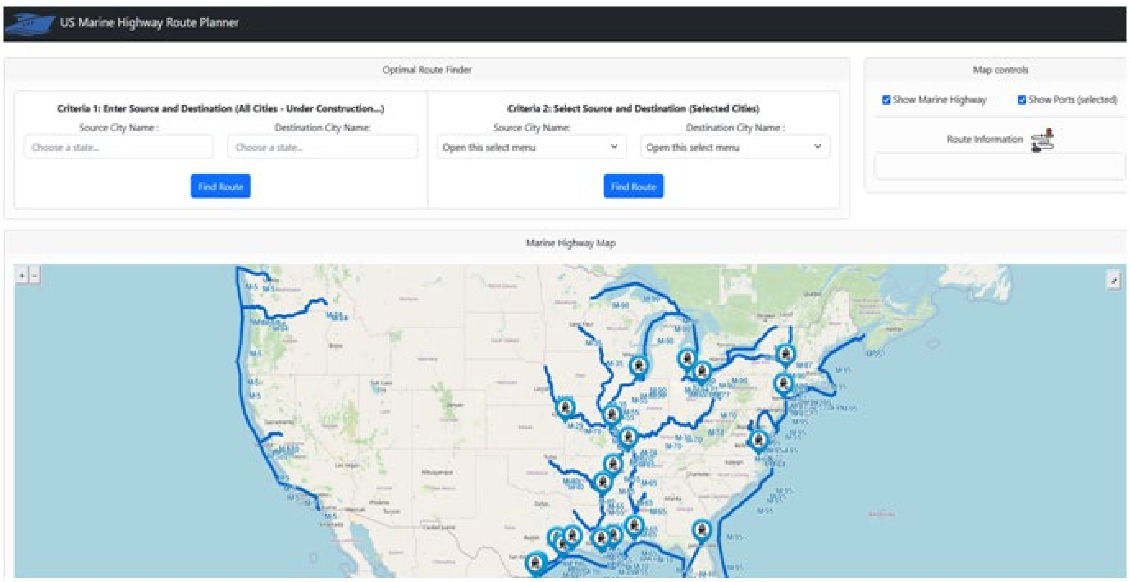


Figure 11: Default Homepage of the Web Application

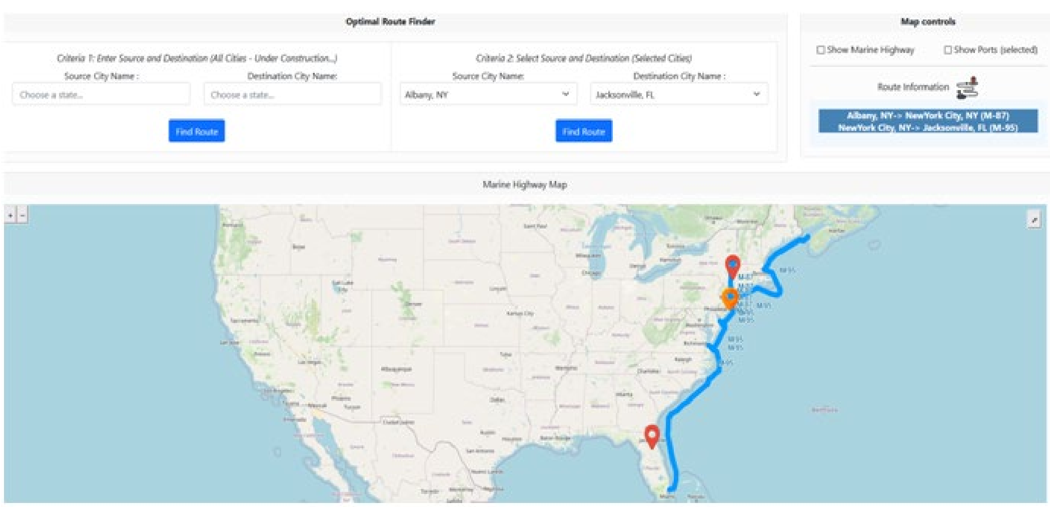


Figure 12: Marine Highway Route between Two Core Intermodal Ports (Albany, NY to Jacksonville, FL)

5. Recommendations and Conclusions

Among the 15 marine highways in the EGMW component, we identify the M-55, M-10 and M-90 to be more central in the network from the point of view of the node centrality metrics. The MIPN is observed to encompass three clusters, each comprising of a majority of ports located in a particular marine highway (and accordingly referred to as M-10, M-55 and M-90 clusters). The ports of New Orleans, LA, Jacksonville, FL and Chicago, IL are observed to be topologically critical (with respect to all the three centrality metrics) for the connectivity and transportation between several of the core ports. The New Orleans, LA --- Chicago, IL edge (involving M-55) incurs the largest EBWC value. However, we observe the edges involving the ports in the M-90 cluster to be among six of the top eight edges with the largest EBWC values. The average path length for the MIPN is 1.895, which is close to the logarithmic value of 21 (the number of nodes) and the randomness index is -0.3850 (not above 0.0), indicating the network can be expected to exhibit small-world characteristics and edge associations are not completely random in nature. Finally, we have run principal component analysis (PCA) on a dataset comprising values for a suite of five different network-level metrics incurred for the MHN and MIPN and four other transportation networks that have been already analyzed in the literature. Using PCA, we show that the MHN and MIPN are topologically unique compared to the other four transportation networks and our project is hence a worthy contribution to the literature of complex network analysis.

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