Role of vehicle movement in swine disease dissemination

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Summary

The transmission dynamics of infectious diseases in animal production are driven by several propagation routes. Contaminated vehicles traveling between farms have been associated with indirect disease transmission. In this study, we used transportation vehicle data to analyze the magnitude of farm visits by different vehicles and to propose a methodology to reconstruct vehicle contact networks considering pathogen stability and cleaning and disinfection effectiveness. Here, we collected information from 6,363 farms and Global Positioning System (GPS) records from 567 vehicles used to transport feed, animals, and people. We reconstructed vehicle contacts among the farms, conserving pathogen stability decay and different probabilities of cleaning and disinfection. Results showed that vehicle movement networks were densely connected, with up to 86% of farms connected by these movements. Movements of vehicle transporting feed and pig among farms showed the highest network connectivity. The cleaning effectiveness was variable among the different vehicle types and highly influenced by the frequency of vehicles stopping at clean stations. A large number of between-farm contacts with a pathogen stability >0.8 were present in the vehicle network even with 100% cleaning effectiveness. Finally, we identified that vehicles contacted farms from different companies. Thus, our results suggest the vehicle network is a potential mechanism for spreading pathogens among farms. Moreover, even with scenarios with high effectiveness of cleaning and disinfection, the risk of vehicles spreading diseases was not completely eliminated.

Keywords: Truck, disease modeling, contact trace, indirect contact, truck cleaning, and disinfection.

1. Introduction
Similar to how the movement of live animals leads to between-farm pathogen dissemination (Green et al., 2006; Galvis, Corzo and Machado, 2022), vehicle movements have been described as a potential pathway for disease spread, which includes porcine epidemic diarrhea virus (PEDV) (Lowe et al., 2014; Boniotti et al., 2018; Garrido-Mantilla et al., 2022), African swine fever (ASF) (Li et al., 2020; D. S. Yoo et al., 2021; Adedeji et al., 2022; Cheng and Ward, 2022) and avian influenza virus (Huneau-Salaün et al., 2020; D.-S. Yoo et al., 2021). In addition, (Dee et al., 2004; Mannion et al., 2008; Greiner, 2016; Boniotti et al., 2018; Gebhardt et al., 2022) showed viable infectious pathogens on vehicle surfaces, while more recent studies estimated the contribution of transportation vehicles in disseminating PEDV and PRRSV (Dee et al., 2002; VanderWaal et al., 2018; Galvis, Corzo and Machado, 2022). That said, the underlying mechanism of this indirect transmission route remains to be examined (Neumann et al., 2021; Galvis, Corzo and Machado, 2022). Information that would be needed to understand this transmission pathway better includes: the number of farm visits a truck would make in a short period of time; how long pathogens survive on truck surfaces at field conditions; and the effects of vehicle cleaning and disinfection may reduce vehicle contamination, and subsequently disease spread (Bernini et al., 2019; Neumann et al., 2021; Galvis, Corzo and Machado, 2022).

The extraordinary complexity of animal and vehicle movements, which change daily, presents a formidable challenge for decision-makers who must implement effective disease control measures under time constraints (Lee et al., 2019; D. S. Yoo et al., 2021). Some studies in North America and Europe utilized actual animal and vehicle movement data to reconstruct between-farm transmission dynamic of infectious diseases (Bernini et al., 2019; Andraud et al., 2022; Galvis, Corzo and Machado, 2022; Galvis, Corzo, Prada et al., 2022), while considering pathogen stability and the effects of cleaning and disinfection into the several transmission forces. Even though previous studies enhanced our understanding of indirect swine disease dissemination through vehicle movements, authors identified uncertainties about the association between i) the efficacy of cleaning and disinfection operations and ii) factors controlling pathogen stability with risk of between farm dissemination (Bernini et al., 2019; Andraud et al., 2022; Galvis, Corzo and Machado, 2022; Galvis, Corzo, Prada et al., 2022). Vehicle cleaning and disinfection
may not completely eliminate pathogens from surfaces, representing a risk of farm-to-farm transmission (Mannion et al., 2008; Boniotti et al., 2018; Li et al., 2020). Therefore, it is essential to consider that several factors impact vehicle cleaning and disinfection, including the use of chemical disinfectants products and warm water (32-54°C), which is associated with the time vehicles spend at cleaning stations (De Lorenzi et al., 2020). Similarly, pathogen stability is directly linked to the risk posed by vehicles to disseminate disease (Jacobs et al., 2010; Mazur-Panasiuk and Woźniakowski, 2020). Environmental conditions directly impact pathogen stability, such as temperature, pH, humidity, and ultraviolet (UV) radiation (e.g., some pathogens are more resistant to acid pH than to elevated temperatures) (Hijnen et al., 2006; Cutler et al., 2012; Carlson et al., 2020; Espinosa et al., 2020). For example, high temperature is known to reduce the viability of ASF, PRRSV, PEDV, and FMD over time (Jacobs et al., 2010; Bøtner and Belsham, 2012; Kim et al., 2018; Mazur-Panasiuk and Woźniakowski, 2020).

The scarcity of vehicle data and the lack of methodologies capable of combining contact networks, factors associated with the stability of pathogens and uncertainty of cleaning and disinfection, limits our ability to better understand the contribution of vehicles in disease transmission. Here, we collected Global Positioning System (GPS) data from 567 transportation vehicles and developed a novel methodology to reconstruct the vehicle contact network while considering environmental variables and vehicle cleaning and disinfection. Thus, with this new methodology, our goal was to reconstruct a vehicle contact network from three different swine companies in the U.S. and use ASF as a reference pathogen to modulate the pathogen stability in between farm contacts.

2. Materials and methods

2.1 Databases: In this study, we used information from two different regions in the U.S. Region one with 1,974 commercial swine farms managed by six swine companies (coded hereafter A, B, C, D, E, and F), and region two with 4,389 commercial swine farms managed by 13 swine companies (coded here as G, H, I, J, K, L, M, N, O, P, Q, R, and S). For each farm, the data includes a unique premise identification, animal capacity stratified by age, latitude, and longitude representing the farm's centroid, and company
identification. In addition, for 95.8% and 29.5% of farms located in regions one and two, respectively, we utilized farm enhanced on-farm biosecurity plans, of which we utilized geolocated features (subsection 2.1). An enhanced biosecurity plan is formed by a written component describing the biosecurity features and farm map (Center for Food Security and Public Health, 2017). Furthermore, farms were classified into 24 types based on the swine production phase. Briefly, in North American swine production, a site can have more than one production phase (i.e. farrow-to-finisher). Thus, farms were categorized based on the farm capacity of the production phases. Because of the inconsistency of each company's farm classification, we simplified the farm type classification. For example, a farm with breeding age animals was classified as sow farm, while a farm that reported space for breeding animals and finishers was considered a sow-finisher farm (see Supplementary Material Table S1 for the complete list of farm types). For 16% and 20% of farms in region one and two, respectively, did not provide pig capacity information, we used farm types provided by participating companies (Supplementary Material Table S1).

We collected data on five types of transportation vehicles used by companies A, B, and G from January 01, 2020, to December 31, 2020. Company A operated with 398 vehicles which included: (i) 230 trucks delivering feed to farms, named hereafter “feed-vehicle”; (ii) 169 vehicles utilized in the transportation of live pigs between farms, named hereafter “pig-farm-vehicle;” (iii) 127 vehicles used in the transportation of pigs to markets (slaughterhouse) named hereafter “pig-market-vehicle”; (iv) 44 vehicles used in the transportation of crew members named hereafter “crew-vehicle,” which correspond to the movement of personnel performing a wide range of farm tasks: vaccination, power washing at closeout, pig loading, and unloading; and (v) 84 vehicles without a defined role were named hereafter “undefined-vehicle.” For company B, 105 vehicles were tracked, including 41 feed-vehicles, 19 pig-farm-vehicles, 30 pig-market-vehicles, and 15 crew-vehicles. Company G 64 vehicles were monitored, and all were classified as undefined-vehicles roles. From each vehicle, GPS tracker records were collected, which comprised geographic coordinates for every five seconds of any vehicle in movement. In addition, each vehicle movement included a unique identification number, speed (in km/h), date, and time. We also gathered
information on 14, 3, and 15 “company-owned cleaning stations” (CCS) from companies A, B, and G, respectively. Each CCS included centroid coordinates (latitude and longitude), address, and name.

2.1 On-farm biosecurity: We extracted biosecurity data from the Rapid Access Biosecurity (RAB) application (RABapp™) database. Briefly, the RABapp™ serves as a platform for standardizing the approval of SPS biosecurity plans while storing and analyzing animal and semen movement data. SPS biosecurity plans are part of a USDA and Pork Checkoff initiative (https://www.securepork.org/) to enhance business continuity by helping swine producers implement enhanced on-farm biosecurity measures on individual farms. An SPS biosecurity plan encompasses 169 unique biosecurity measures and maps for individual farms (Center for Food Security and Public Health, 2017). Each farm map (Supplementary Material Figure S1) is formed of twelve biosecurity features, one of which is the Perimeter Buffer Area (PBA) is an outer control boundary around the line of separation to limit possible contamination near animal housing. It is not rare for farms to have more than one PBA because of how swine barns are distributed at a premise (Supplementary Material Figure S1). Therefore, because we measure vehicle contacts to a group of barns within a PBA, farms with more than one PBA, we created a unique “farm unit” identification to allow for measuring vehicle contact to each group of barns (Supplementary Material Figure S1). Our final farm population database for region one consisted of 2,519 farm units, of which 2,437 (96.7%) used PBA’s geolocation, while 82 (3.3%) farms did not have an on-farm biosecurity plan; we alternatively used the farm's centroid geolocation. Region two consisted of 4,619 farm units with 1,523 (33%) PBA’s geolocation and 3,096 (67%) farms in which we used farm centroid geolocation due to the lack of on-farm biosecurity plans.

2.3 Vehicle movement network

2.3.1 Vehicle visit: We defined a farm visit as a risky event in which vehicles pose a significant risk of disease introduction (Guinat et al., 2016; Li et al., 2020; Neumann et al., 2021; Galvis, Corzo and Machado, 2022). Thus, a vehicle visit was defined as vehicle coordinates (latitude and longitude) located within a risk buffer around a “farm unit” at a speed of zero km/h (indicating a full vehicle stop), named hereafter as “vehicle buffer distance” (VBD), and and within an interval range of time, here named “vehicle visit time”
(VVT) (Figure 1). From each farm unit geolocation, a VBD of 50, 100, and 300 meters was tested. The VBD of 50 meters was based on the average length of vehicles, which usually ranges from 12.5 meters to 53.5 meters (Walton et al., 2009), while VBD of 100 and 300 were utilized for sensitivity analysis. Similarly, we tested a VVT of 5, 20, and 60 minutes. It is worth noting that in some scenarios, different companies could share vehicles (e.g., feed deliveries), or farm units are located at short distances from the roads (e.g., 100 meters), which represents a risk of transmission given that vehicles from different companies may transit such roads (Jara et al., 2020). Because, between farm vehicle movements could be associated with transmission among companies we also computed the contacts among companies A, B, and G to farm units from companies C, D, E, and F in region one and H, I, J, K, L, M, N, O, P, Q, R, and S in region two.

2.3.2 Indirect farm-to-farm contact network: We assumed a vehicle could become contaminated after visiting a farm unit (Dee et al., 2002), with the potential to propagate pathogens into the subsequently visited farm units. Thus, in chronological order, we computed indirect contacts among farm units visited by each vehicle and referred to these contacts as edges \((E)\) (Figure 1). For this study, we reconstructed indirect contacts among farm units of \(VBD = 50\) meters and \(VVT = 5\) minutes.

2.3.3 Pathogen stability: For most pathogens, the stability outside the host (a.k.a. environment) decreases as temperature increases (Espinosa et al., 2020). This phenomenon has been demonstrated for PEDV (Kim et al., 2018) and PRRSV (Jacobs et al., 2010). Here, we model pathogen stability decay as a function of time and pathogen exposure to environmental temperature. Thus, vehicle network edges are weighted by pathogen decay over time (Nuanualsuwan et al., 2022). Briefly, edge weight between two farm units is modulated by two variables: i) the number of minutes a vehicle takes to go from one farm unit to another \((\Gamma)\); and ii) the average environmental temperature the vehicle was exposed to along the route between these two farm units \((\omega)\) (Figure 1 and Supplementary Material Figure S2). We downloaded daily temperature raster layers with 1 km² resolution from Daily Surface Weather and Climatological Summaries \((\text{daynet})\) (https://daymet.ornl.gov/). Here, the GPS geolocation of each truck was matched with
the respective daily temperature raster along its route between farm units (Figure 1). In addition, we assumed that pathogens' stability decay obeys an exponential distribution, which is a function of the environmental temperature decay rate and cumulative time that the pathogen was exposed to the environment modulated by \( \lambda \) and \( \Gamma \), respectively (Figure 1). Finally, the edge weight values range between 1 and 0, being 1 a high pathogen stability, and 0 a low pathogen stability. To avoid edges with extremely low weights, we assumed a weight <0.0006 were zero.

2.3.4 Vehicle disinfection: An effective farm vehicle visit to a CCS was when a vehicle came to a full stop (0 km/h) within 500 meters of a CSS for at least 60 minutes (60 minutes was based on personal communication from the standard operating procedures for a large swine producing company) (Figure 1). We remark that eliminating 100% of organisms in vehicle surfaces via cleaning and disinfection is an optimistic assumption (Dee et al., 2004; Mannion et al., 2008; Deason et al., 2020). Thus, here we simulated cleaning effectiveness \( (d) \), defined as a standard proportion of vehicles successfully disinfected after a CCS visit, with all possible values ranging from 0 to 1.

2.4 African swine fever (ASF), case study: Here we utilized the new network methodology developed in subsections 2.3.1-2.3.4, to simulate the vehicle network spread of ASF virus. The between-farm indirect dissemination of ASF via contaminated transportation vehicles has been described elsewhere (Neumann et al., 2021; Gebhardt et al., 2022), while recent studies evaluated ASF stability under different temperatures (Supplementary Material Table S2) of which we extracted ASF stability information used in our model via an exponential decay curve with different decay rates \( \lambda \) for each temperature (see section 2.3.3 and Supplementary Material Figure S2). Results of Mazur-Panasiuk et. al., 2020 were used for ASF stability, because it provided several stability metrics at different points in time that allowed us to reconstruct a robust decay stability curve (Supplementary Material Figure S2). Briefly, Mazur-Panasiuk et. al., 2020 suggested that ASF remains stable in soil for up to 9 days at 23 °C and 32 days at 4 °C, half-time was 0.44 days at 23 °C and 1.88 days at 4 °C, and 90% decay of 1.48 days at 23 °C and 6.26 days at 4 °C (Mazur-Panasiuk and Woźniakowski, 2020). We used a range of temperatures from 4 °C to 23 °C, and assumed ASF virus stability decay rate \( \lambda \) was 0.001 at 4 °C and this rate increased by 4.48*10^-5 for each temperature degree.
increase. Given that ASF stability on temperatures lower than 4 °C and higher than 23 °C was not available, we assumed that environmental temperatures lower than 4 °C use the same decay rate as 4 °C, and temperatures higher than 23 °C use the same decay rate as 23 °C. Finally, because of the variation of cleaning and disinfection effectiveness demonstrated in other pathogens, for example, 18% to 6% of disinfected vehicles tested positive for salmonella (Mannion et al., 2008), that could be translated to $d$ of 82% and 94%. Similarly, in a PED study, 46% of disinfected vehicles were positive for PEDV via swab (Boniotti et al., 2018), here would be $d$ of 54%. Even though cleaning and disinfection procedures have been investigated in ASF (De Lorenzi et al., 2020), the contributions of cleaning and disinfection procedures in eliminating the virus from vehicle surfaces are still to be fully demonstrated (Li et al., 2020; Neumann et al., 2021). Because of that, we decided to simulate a range of pathogen reductions ($d$) from 0, 0.1, 0.5, 0.8, 0.9, and 1.

2.5 Vehicle network outputs

We evaluated nine different scenarios of vehicle visit which included a factorial combination of three VBD (50, 100 and 300 meters) and three VVT (5, 20 and 60 minutes). We evaluated the frequency, ratio of farm unit visits, and cumulative time vehicles spent within farm units and at cleaning stations. Results were stratified by farm types and regions. The ratio of farm unit visits was calculated as the number of times each vehicle visited a farm divided by the number of times each vehicle visited a cleaning station.

In total, for each studied region, we reconstructed 60 vehicle network scenarios with VBD of 50 meters and VVT of five minutes, and six cleaning and disinfection effectiveness scenarios. Each scenario was run for ten repetitions. We used eight network metrics to compare the reconstructed vehicle networks; these metrics were: network density, number of edges in the static and temporal networks, in-degree, out-degree, degree and betweenness centralization, and outgoing contact chains (Supplementary Material Table S3). In addition, we combined all vehicle categories into one named combined-vehicle. The combined-vehicle’s network was only included in the region one because the vehicles transportation types are stratified in several categories, while in region two we only consider one transportation type (undefined-vehicles), thus undefined-vehicles result in the section shows vehicle contact network analysis for region
Figure 1. Network reconstruction framework. According to the GPS records from the vehicles, it was defined that a vehicle contacted a farm unit if it is inside a vehicle buffer distance (VBD) and for a minimum time defined by the vehicle visit time (VVT) (red box). An edge among the different farm units is recorded if all of them were visited by the same vehicle, and the edge weight (E) that represents the pathogen stability is different from 0 (green box). The pathogen stability is calculated through an exponential distribution, where $\lambda$ is the decay rate for each average temperature ($\omega$) from the source of the contact (green dot) until the destination (red dot), and $\Gamma$ is the cumulative time from the source of the contact (green dot) until the destination (red dot) (blue box). Finally, the cleaning and disinfection probability $d$ was compared with a random value $X$ from a uniform distribution that ranges from 0 to 1 (green box), when effective ($d > X \sim U[0,1]$), interrupted the chronological indirect contacts from the vehicles visiting farms units, and when ineffective ($d \leq X \sim U[0,1]$), the chronological indirect contacts are not interrupted and the edge is computed.

3. Results
3.1 The number of vehicle visits: The higher the VBD, the larger the number of farm units visited while increasing VVT from five minutes to 20 and 60 minutes decreased the number of visits (Table 1). In region one, the total number of vehicle visits varied between 47,847 and 301,774 visits (Supplementary Material Table S4), while the median by vehicle varied between 59 and 432 visits (Table 1). For region two, the total number of vehicle visits ranged from 6,951 and 15,094 (Supplementary Material Table S4), while the median by vehicle varied between 112 and 231 (Table 1 and Supplementary Material Table S4).

Results from vehicle visit at VBD of 50, 100, and 300 meters along with VVT of 5 and 20 minutes resulted in each feed-vehicle visiting in median from 474 to 827 farm units (Supplementary Material Figure S3), while pig-farm-vehicle visited 388 and 522 farm units, pig-market-vehicle 277 and 360 farm units, undefined-vehicles region one 210 and 309 farm units, undefined-vehicles region two 205 and 231 farm units, and crew-vehicles 2 and 8 farm units. On the other hand, a VVT of 60 minutes reduced the number of visits from all vehicle types (Supplementary Material Figure S3), but this showed a marked reduction in feed-vehicles visiting in a median between 22 and 29 farm units (Supplementary Material Figure S3).

We demonstrated that for region one with VBD of 50 and 100 meters and VVT of five minutes, vehicles from company A visited 11 farm units of other companies, while with a VBD of 300 meters, 16 farm units were visited (results of VVT of 20 and 60 minutes are available in Supplementary Material Table S5). Similarly, with VBD of 50 and 100 meters and VVT of five minutes, vehicles from company B visited up to three farm units of other companies and VBD of 300 meters, the number of farm units visited increased to 19. For vehicles in region two, VBD of 50 and 300 meters with VVT of five minutes, company G’s vehicles visited up to 12 farm units from other companies (Supplementary Material Table S5).

Regarding the farm types visited with VBD of 50 meters and VVT of five minutes, finish farms were the most visited, with 33% of feed-vehicles and as low as 0.0003% crew-vehicles (Supplementary Material Figure S4). Nursery farm visits were dominated by pig-farm-vehicles, with 8.9% of all visits (Supplementary Material Figure S4). In addition, sow farms were visited mostly by feed-vehicles 7.5%, followed by pigs-farm-vehicles with 7.2% of visits (more details about other farm unit types are available in Supplementary Material Figure S4).
Table 1. Distribution of the number of farm units visited by each vehicle for one year.

| VBD/VVT          | 5 minutes (IQR25%-IQR75%) | 20 minutes (IQR25%-IQR75%) | 60 minutes (IQR25%-IQR75%) |
|------------------|---------------------------|-----------------------------|-----------------------------|
|                  |                           |                             |                             |
| 50 meters (IQR25%-IQR75%) | 364 (170-680) (R1)       | 326 (141-540) (R1)          | 59 (23,150) (R1)            |
|                  | 205 (148-278) (R2)       | 196 (143-274) (R2)          | 112 (83-147) (R2)           |
| 100 meters (IQR25%-IQR75%) | 374 (175-703) (R1)       | 338 (147-552) (R1)          | 62 (25-157) (R1)            |
|                  | 215 (152-293) (R2)       | 207 (146-285) (R2)          | 118 (88-156) (R2)           |
| 300 meters (IQR25%-IQR75%) | 432 (202-820) (R1)       | 378 (162-651) (R1)          | 70 (28-183) (R1)            |
|                  | 231 (158-319) (R2)       | 218 (147-309) (R2)          | 127 (97-166) (R2)           |

(R1) = region 1; (R2) = region 2

3.2 Frequency of clean station visits: At 500 meters of CCSs for at least 60 minutes, in region one pigs-market-vehicles and pigs-farm-vehicles were the vehicles with more visits to cleaning stations (Table 2 and Supplementary Material Figure S13). The ratio between clean station and farm units visits showed that for every CCS visited, undefined-vehicles visits in median 4.4 (IQR 2.2-27.8) farm units, followed by feed-vehicles 2.9 (IQR 2.9-10.6), pig-farm-vehicles 2.4 (IQR 1.8-2.9), crew-vehicles 1.6 (IQR 1.6-1.6), and pig-market-vehicles 2.4 (IQR 1.8-2.9). Similarly, in region two, undefined-vehicles visit in median 1.6 (IQR 1.3-2.1) farm units by each CCS visited (Supplementary Material Table S6-S10 and Figure S14-S15 for additional scenarios).

Table 2. Distribution of the number of clean stations visited by each vehicle for one year.

| Transportation role                  | Median (IQR25%-IQR75%) |
|--------------------------------------|------------------------|
| Vehicle transporting feed (R1)       | 136 (21-359)           |
| Vehicle transporting pigs to farms (R1) | 188 (99-238)           |
| Vehicle transporting pigs to market (R1) | 206 (95-300)           |
| Vehicle transporting crew (R1)       | 5 (5-5)                |
| Vehicle undefined (R1)               | 39 (7-78)              |
| Vehicle undefined (R2)               | 138 (62-166)           |

(R1) = region 1; (R2) = region 2
3.3 Vehicle movement network with cleaning and disinfection effectiveness: Our results showed low network volatility among ten cleaning and disinfection scenarios in both study regions. Figure 2 and Supplementary Material Table S11 and S12 show node-level network metrics and edge weights are available in Supplementary Material Figure S16 and Supplementary Material Table S13 and S14.

Figure 2. Distribution of network metrics from ten different reconstructed vehicle contact networks using a VBD of 50 meters and a VVT of five minutes and six cleaning probabilities. Bar graphs
represent the median values for each clean probability and the error line as the minimum and maximum ranges for each distribution.

![Graph showing the number of farm units contacted through the outgoing contact chain from vehicle movements.](image)

Figure 3. The number of farm units contacted through the outgoing contact chain from vehicle movements.

### 3.3.1 Combined-vehicles contact network: Our result for region one showed that the median number of connected farm units was 2,159 with $d = 0\%$ (Supplementary Material Table S11), and 2,158 with $d = 100\%$ which reduced in 0.05\% the number of connected farm units (Supplementary Material Table S11 show IQR intervals results of $d$ from 0\% to 100\%). In the static network, the median number of edges...
was 1,232,684 with \( d = 0\% \), and 793,827 \( d = 100\% \); the former scenarios reduced 36\% of edges. The median network density was 0.19 with \( d = 0\% \) and 0.12 with \( d = 100\% \). The in-degree showed a median of 476 contacts with \( d = 0\% \) and 306 with \( d = 100\% \), 36\% reduction in in-degree. Similarly, the out-degree exhibited a median of 477 contacts with \( d = 0\% \) and 299 with \( d = 100\% \), a 37\% reduction in out-degree. The degree and betweenness centralization did not vary significantly among simulated \( d \). Although the number of edges decreased as \( d \) increased, the hubs did not differ significantly among \( d \) value. In the temporal network, the median number of edges was 5,583,703 with \( d = 0\% \) and 2,370,612 when \( d = 100\% \), 57\% edge reduction. Finally, through the outgoing contact chain on average 2,156 farm units were contacted with \( d = 0\% \) and 2,141 with \( d = 100\% \), thus 100\% effective cleaning and disinfection would only reduce the contact chain by 1\% over one year of vehicle movements (Figure 3).

The median number of edges with the highest probability of pathogen stability “\( >0.8 - 1\)” varied between 6\% and 13\%, while the category “\( >0.6 - <0.8\)” varied between 5\% and 8\%, “\( >0.4 - <0.6\)” 6\% and 8\%, “\( >0.2 - <0.4\)” 10\% and 12\% and the lowest category “\( >0 - <0.2\)” between 61\% and 72\% (Supplementary Material Table S13). In addition, the edge weight distribution with \( d = 0\% \) for category “\( >0.8 - 1\)” exhibited a median frequency of 339,490 edges, while the lowest category of “\( >0 - <0.2\)” exhibited a median of 4,031,537 edges (Supplementary Material Table S14). However, with \( d = 100\% \), category “\( >0.8 - 1\)” exhibited a median of 317,556 edges, and the category “\( >0 - <0.2\)” 1,451,931 edges, a reduction of 6\% and 64\% edges in each category when cleaning was 100\% effective, respectively.

3.3.2 Feed-vehicles contact network: In region one the median number of farm units connected was 2,151 regardless of \( d \) (Supplementary Material Table S11). In the static network, the median number of edges was 1,018,941 with \( d = 0\% \), and 703,726 when \( d = 100\% \), a difference of 31\% less edges. The median network density was 0.16 with \( d = 0\% \) and 0.11 with \( d = 100\% \). The in-degree showed a median of 338 contacts with \( d = 0\% \) and 243 when \( d = 100\% \), 28\% in-degree reduction. The out-degree showed a median of 336 contacts with \( d = 0\% \) and 239 when \( d = 100\% \), 29\% lower out-degree. We identified that increasing \( d \) slightly reduced the degree centralization, while no high variation was observed for betweenness centralization. Thus, our results suggest that hubs by direct contacts among farm units are less frequent with
a more effective cleaning. In the temporal network, the median number of edges identified was 3,846,333 with $d = 0\%$, and 1,828,595 when $d = 100\%$, 52\% fewer edges. Finally, the outgoing contact chain on average connected 2,146 farms when $d = 0\%$ and 2,125 when $d = 100\%$, thus 100\% effective cleaning reduced by 1\% the number of farm units in the receiving end of the vehicle contact network (Figure 3).

The median number of edges in which simulated pathogen stability was “$>0.8 - 1$” varied between 5\% and 10\%, while the category “$>0.6 - <0.8$” varied between 5\% and 8\%, “$>0.4 - <0.6$” 7\% and 8\%, “$>0.2 - <0.4$” 10\% and 12\% and the lowest category “$>0 - <0.2$” between 63\% and 73\% (Supplementary Material Table S13). In addition, the edge weight distribution with $d = 0\%$ showed that the category “$>0.8 - 1$” exhibited a median of 198,947 edges, while the lowest category of “$>0-<0.2$” exhibited a median of 2,799,520 edges (Supplementary Material Table S14). However, with $d = 100\%$, the category “$>0.8 - 1$” exhibited a median of 182,157 edges, and the category “$>0-<0.2$” 1,170,273 edges, a reduction of 8\% and 58\% edges in each category when cleaning is 100\% effective, respectively.

### 3.3.3 Pig-farm-vehicles contact network:

Our result in region one showed that the median number of farm units connected was 2,103 when $d = 0\%$ (Supplementary Material Table S11), and 2,101 with $d = 100\%$, 0.1\% fewer farm units in the network. In the static network, the median number of edges identified was 207,232 with $d = 0\%$, and 34,769 with $d = 100\%$, 83\% fewer edges. The median network density was 0.03 when $d = 0\%$ and 0.005 when $d = 100\%$, 83\% lower density. The median in-degree was 63 contacts with $d = 0\%$ and 10 with $d = 100\%$, 84\% lower in-degree. The out-degree showed a median of 61 contacts when $d = 0\%$ and 7 when $d = 100\%$, 88\% lower out-degree. On the contrary of combined-vehicles and feed-vehicles networks, here it was evident that degree centralization decreased as $d$ increases, while no high variation was observed for betweenness centralization. Thus, with 100\% effective cleaning, hubs by degree centrality in the pig-farm-vehicle network are less frequent. In the temporal network the median number of edges identified was 841,987 with $d = 0\%$, and 135,173 when $d = 100\%$, 84\% fewer edges. Finally, the outgoing contact chain connected on average 1,718 farm units with $d = 0\%$ and 1,235 when $d = 100\%$, 28\% lower number farm units contacted through the outgoing contact chain (Figure 3).
The median number of edges in the highest probability of pathogen stability “>0.8 - 1” varied between 10% and 64%, while the category “>0.6 - <0.8” varied between 4% and 14%, “>0.4 - <0.6” 2% and 6%, “>0.2 - <0.4” 4% and 15% and the lowest category “>0 - <0.2” between 15% and 69% (Supplementary Material Table S13). In addition, the edge weight distribution with $d = 0\%$ showed that the category “>0.8 - 1” exhibited a median frequency of 87,603 edges, while the lowest category of “>0-<0.2” exhibited a median frequency of 582,593 edges (Supplementary Material Table S14). However, with $d = 100\%$, the category “>0.8 - 1” exhibited a median of 86,886 edges and the category “>0-<0.2” 20,337 edges, a reduction of 1% and 96% edges in each category when cleaning is 100% effective, respectively.

3.3.4 Pig-market-vehicles contact network: Our result in region one showed that the median number of farm units connected in the network was 1,618 when $d = 0\%$ (Supplementary Material Table S11), and this value decreased to 1,593 with $d = 100\%$, 1.6% less farm units in the network. In the static network the median number of edges identified was 139,786 with $d = 0\%$, and that value decreased to 16,973 with $d = 100\%$, 88% fewer edges. The median network density was 0.02 when $d = 0\%$ and 0.003 when $d = 100\%$, static network 88% less connected. The in-degree and out-degree showed a median of 38 contacts with $d = 0\%$ and 3 when $d = 100\%$, 92% lower in-degree and out-degree. Similar to the pig-farm-vehicle network, degree centralization decreased as d increases, while no high variation was observed in the betweenness centralization. Thus, with 100% effective cleaning, hubs by direct contact in the pig-market-vehicle network are less frequent. In the temporal network the median number of edges identified was 359,796 with $d = 0\%$, and 33,520 when $d = 100\%$, 91% less edges. Finally, the outgoing contact chain connected on average 1,421 farms when $d = 0\%$ and 671 when $d = 100\%$, a reduction of 52% farm units connected through the outgoing contact chain with 100% effective cleaning (Figure 3).

The median number of edges in the highest probability of pathogen stability “>0.8 - 1” varied between 6% and 51%, while the category “>0.6 - <0.8” varied between 5% and 18%, “>0.4 - <0.6” 6% and 11%, “>0.2 - <0.4” 8% and 16% and the lowest category “>0 - <0.2” between 15% and 73% (Supplementary Material Table S13). In addition, the edge weight distribution with $d = 0\%$ showed that the category “>0.8 - 1” exhibited a median frequency of 20,226 edges, while the lowest category of “>0-<0.2”
exhibited a median frequency of 261,215 edges (Supplementary Material Table S14). However, with \( d = 100\% \), the category \( \geq 0.8 - 1 \) exhibited a median of 16,945 edges and the category \( \geq 0 - <0.2 \) 5,184 edges, a reduction of 16% and 98% edges in each category when cleaning is 100% effective, respectively.

3.3.5 Crew-vehicles contact network: Our result of the vehicle batch network in region one showed that the median number of farm units connected in the network was 7 when \( d = 0\% \) (Supplementary Material Table S11), and this value decreased to 6 with \( d = 100\% \), a reduction of 14% farm units with 100% cleaning effectiveness. In the static network the median number of edges identified was 23 with \( d = 0\% \), and 7 with \( d = 100\% \), 69% less edges. The median network density was 0.000004 with \( d = 0\% \) and 0.000001 with \( d = 100\% \), 69% lower network density. The in-degree and out-degree showed in median 0 contacts independent of \( d \). The crew-vehicle network exhibited a low degree and betweenness centralization values independent of \( d \), indicating that most of the farm units are similarly connected with a low influence of hubs to connect the network. In the temporal network the median number of edges identified was 24 with \( d = 0\% \), and 7 when \( d = 100\% \), 71% less edges. Finally, the outgoing contact chain connected on average 3 farms when \( d = 0\% \) and 1 when \( d = 100\% \), 66% lower number farm units connected with 100% effective cleaning (Figure 3).

The median number of edges in the highest probability of pathogen stability \( \geq 0.8 - 1 \) varied between 29% and 100%, while the category \( \geq 0.6 - <0.8 \) varied around 0%, \( \geq 0.4 - <0.6 \) around 0%, \( \geq 0.2 - <0.4 \) 0% and 31% and the lowest category \( >0 - <0.2 \) between 0% and 54% (Supplementary Material Table S13). In addition, the edge weight distribution showed that the category \( \geq 0.8 - 1 \) exhibited a median frequency of 7 edges independently of \( d \), while the lowest category of \( >0-<0.2 \) exhibited a median frequency of 13 edges with \( d = 0\% \) and 0 with \( d = 100\% \), a reduction of 100% edges when cleaning is 100% effective (Supplementary Material Table S14).

3.3.6 Undefined-vehicles contact network: Our result in region one showed that the median number of farm units in the network was 1,848 when \( d = 0\% \) (Supplementary Material Table S11), and t 1,847 with \( d = 100\% \), 0.1% lower number of farm units in the network. In the static network the median number of edges identified was 290,960 with \( d = 0\% \), and 204,761 with \( d = 100\% \), 30% less edges. The median
network density was 0.05 with $d = 0\%$ and 0.03 with $d = 100\%$, a reduction of 30% in the static network density with 100% cleaning effectiveness. The in-degree and out-degree showed a median of 100 contacts with $d = 0\%$ and 46 when $d = 100\%$, 54% lower in-degree and out-degree. Similar to pig-farm-vehicle and pig-market-vehicle, the degree centralization of undefined-vehicles in region one decreases as $d$ increases, thus increasing clean effectiveness reduces the number of farm units highly connected by direct contact in the network. On the other hand, there was not a clear pattern in betweenness centralization, increasing and decreasing as $d$ increased. In the temporal network the median number of edges identified was 535,563 with $d = 0\%$, and 373,317 when $d = 100\%$, 30% lower number of edges. Finally, the outgoing contact chain connected on average 1,671 farms when $d = 0\%$ and 1,664 when $d = 100\%$, 0.4% lower number of farm units connected through the outgoing contact chain with completely effective cleaning (Figure 3).

The median number of edges in the highest probability of pathogen stability “$>0.8 - 1$” varied between 6% and 8%, while the category “$>0.6 - <0.8$” varied between 5% and 6%, “$>0.4 - <0.6$” 6% and 7%, “$>0.2 - <0.4$” 10% and 11% and the lowest category “$>0 - <0.2$” between 68% and 72% (Supplementary Material Table S13). In addition, the edge weight distribution with $d = 0\%$ showed that the category “$>0.8 - 1$” exhibited a median frequency of 32,707 edges, while the lowest category of “$>0-<0.2$” exhibited a median frequency of 388,136 edges (Supplementary Material Table S14). However, with $d = 100\%$, the category “$>0.8 - 1$” exhibited a median of 31,561 edges and the category “$>0-<0.2$” 256,137 edges, a reduction of 3% and 34% edges in each category when cleaning is 100% effective, respectively.

The network in region two showed that the median number of farm units in the network was 450 when $d = 0\%$ (Supplementary Material Table S11), and 442 with $d = 100\%$, 2% lower number of farm units in the network. In the static network the median number of edges identified was 21,385 with $d = 0\%$, and that value decreased to 3,857 with $d = 100\%$, 82% lower number of edges. The median network density was 0.001 with $d = 0\%$ and 0.0001 with $d = 100\%$, 82% lower density. The in-degree and out-degree showed a median of 0 contacts independent of $d$. Similar to undefined-vehicles in region 1, the degree centralization of undefined-vehicles in region 2 decreases as $d$ increases, thus increasing clean effectiveness reduces the number of farm units highly connected by direct contact in the network. On the other hand,
there was not a clear pattern in betweenness centralization. In the temporal network the median number of edges identified was 128,483 with $d = 0\%$, and 14,336 when $d = 100\%$, 89% lower number of edges. Finally, the outgoing contact chain connected on average 383 farms with $d = 0\%$ and 132 with $d = 100\%$, meaning 65% lower number of farm units connected in the outgoing contact chain with 100% cleaning effectiveness over one year of movements (Figure 3).

The median number of edges in the highest probability of pathogen stability “$>0.8 - 1$” varied between 5% and 47%, while the category “$>0.6 - <0.8$” varied between 4% and 15%, “$>0.4 - <0.6$” 5% and 9%, “$>0.2 - <0.4$” 10% and 17% and the lowest category “$>0 - <0.2$” between 20% and 75% (Supplementary Material Table S13). In addition, the edge weight distribution with $d = 0\%$ showed that the category “$>0.8 - 1$” exhibited a median frequency of 6,973 edges, while the lowest category of “$>0 - <0.2$” exhibited a median frequency of 95,888 edges (Supplementary Material Table S14). However, with $d = 100\%$, the category “$>0.8 - 1$” exhibited a median of 6,775 edges and the category “$>0 - <0.2$” 2,809 edges, a reduction of 3% and 97% edges in each category when cleaning is 100% effective, respectively.

4. Discussion

In this study, we developed a novel transportation vehicle contact network methodology that included environmental pathogen stability and vehicle cleaning and disinfection. Overall, our result indicated that with a completely inefficient cleaning ($d = 0\%$) vehicle movements created 5,583,703 connections among farm units in region one and 128,483 in region two, and through the outgoing contact chain a disease could spread among 86% and 8% of the farm units in region one and two, respectively. The 100% effective cleaning reduced the number of connections among farm units by 57% in region one and 8% in region two, which reduced the number of farm units connected through the contact chain to 85% and 3% in region one and two, respectively. In addition, 13% and 47% of these between-farm connections with $d = 100\%$ showed a high risk of disease transmission due to a pathogen stability weight between 100% and 80%. Thus, our simulated cleaning and disinfection scenarios reduced the vehicle network connectivity, but it was not
sufficient to eliminate the possibility of this indirect contact spreading disease to a significant number of farms.

This vehicle network methodology is expanded from a previous study in PRRS and PED transmission (Galvis, Corzo and Machado, 2022; Galvis, Corzo, Prada et al., 2022), and uses a similar approach used for Bernini, et. al., 2019, where farms visited by the same vehicle are indirectly connected. As an example of this methodology, we reconstructed a vehicle movement network for ASF, which at the moment we published this study represents one of the most important animal diseases worldwide due to a high economic impact associated to the pathogen introduction into free areas (Carriquiry et al., 2020; Mason-D’Croz et al., 2020; Sykes et al., 2022). Besides, ASF virus DNA was detected on vehicle surfaces (Gebhardt et al., 2022); hence, vehicle movements represent a potential route of ASF introduction into naive regions (Mur et al., 2012; Sykes et al., 2022). Therefore, evaluate the role of vehicle movement is necessary to understand the complete transmission dynamic of ASF or other infectious pathogens among animal productions (Lowe et al., 2014; Neumann et al., 2021; Galvis, Corzo and Machado, 2022).

Among the different vehicle types, cleaning and disinfection were more effective in disconnecting pig-farm-vehicles and pig-market-vehicle networks, which is directly associated with the frequency of cleaning, pig-farm-vehicles and pig-market-vehicles visited between one and three farm units before stopping at clean stations. On the other hand, feed-vehicles visited between two and 12 farm units, and undefined-vehicles visited between three and 80 farm units before cleaning and disinfecting. This frequency of cleaning is probably related to the perception of the risk posed by contamination vehicles in the dissemination of pathogens (Boniotti et al., 2018; Henry et al., 2018). Indeed, pig-farm and pig-market vehicles transporting animals direct contact with infected organic material is usually perceived as high-risk disease dissemination (Alarcón et al., 2021). While, studies in Mexico and Vietnam found feed-vehicles equally contaminated (Garrido-Mantilla et al., 2022; Gebhardt et al., 2022) and associated with the dissemination of ASF in Vietnam (Gebhardt et al., 2022) and PEDV in Mexico (Garrido-Mantilla et al., 2022). We remark that the importance of enhancing the frequency vehicles disinfected between farm visits in reducing the number of indirect between-farm contacts. It is important to mention that if the cost of
cleaning and disinfecting is prohibited due to cost or other logistic challenges (e.g., freezing weather), vehicles transporting animals should be prioritized. Alternatively, new strategies to reduce the risk of pathogen spread could include redirecting vehicle movements based on the health status of farms or distance, as suggested for the movement of live animals in Sweden (Nöremark et al., 2009).

From the outgoing contact chain results, it was clear that the network was highly connected regardless of cleaning and disinfection effectiveness, thus it would contribute to a larger ASF epidemic due to its capability to connecting a farm units in a short period of time. Among the vehicle network types, we inferred that combined-vehicles network structure was highly dependent on feed-vehicles due to similarities between both network structures. Individually, pig-farm-vehicles, pig-market-vehicles, and undefined-vehicles in region one have the potential to cause a similar number of infected farms over time when \( d = 0 \); however, with \( d = 100\% \) this number was much lower in pig-farm and pig-market-vehicles. Interestingly, the contact chain of the undefined-vehicles network in region two showed a slight increase of connected farm units in the first 120 days of 2020, independent of \( d \). This pattern could be associated with the number of available movements, the frequency of cleaning station visits or vehicles transporting into a limited group of farms, restricting the network connectivity. Our results showed that independent of cleaning effectiveness, most of the vehicle types are potentially able to disseminate pathogens among farms greater than the movement of live pigs (VanderWaal et al., 2018; Galvis, Corzo and Machado, 2022).

Interestingly, we identified that vehicles visited farm units of different companies. Jara, et. al., 2020, identified that different swine companies shared similar PRRS strains and distance from farms to roads represented a risk for transmission (Jara et al., 2020). In addition, Seedorf and Schmidt, 2017, simulated the potential dispersion of bioaerosols in the environment by vehicle movements and identified that a proportion might be released to the vicinity, which represent a risk of infection to farms located at short distance from roads (Seedorf and Schmidt, 2017). Given the proximity between farms and roads, it is likely that infectious pathogens are circulating among swine companies via transportation vehicles. Companies also contract with third-parties, which could also explain the contact among different companies, which poses additional risk to indirect disease dissemination across swine companies (Porphyre
et al., 2020; Sykes et al., 2021). Therefore, surveillance and control actions may need to include collaboration among production companies.

Our result showed that movements with a pathogen stability <0.2 were the most frequent in all vehicle networks. This high frequency of movements with low pathogen stability was an expected result according to the ASF stability decay curve used in this study (Supplementary Material Figure S2), which after 1.48 and 6.26 days the pathogen stability decay 90% (Mazur-Panasiuk and Woźniakowski, 2020). Movements with low pathogen stability represent a lower risk of infection due the pathogen may no be able to infect animals (Carlson et al., 2020; Mazur-Panasiuk and Woźniakowski, 2020; Nuanualsuwan et al., 2022). Thus, most between-farm vehicle movements have a low probability of infection. Interestingly, increasing cleaning and disinfection effectiveness reduced the number of between-farm contacts, especially those with pathogen stability <0.2, from 68% fewer edges in the combined-vehicle network to 99% fewer edges in the pig-market-vehicle network with $d = 100\%$. On the other hand, the reduction in the number of between-farm contacts with pathogen stability >0.8 was not significantly impacted by cleaning and disinfection effectiveness, reaching the maximum reduction in the pig-farm-vehicle network with 12% fewer edges with $d = 100\%$. In pig-farm-vehicle, pig-market-vehicle, and undefined-vehicles networks, the proportion of edges with pathogen stability >0.8 were higher than 47% when cleaning was 100% effective, but this result was directly influenced by the lower number of edges with pathogen stability <0.2 when cleaning was 100% effective. Finally, feed-vehicles and pig-farm-vehicles were the vehicle types with a higher number of movements with pathogen stability >0.8 with $d = 100\%$, pig-farm-vehicles are especially relevant due to the high risk of contamination through direct contact with organic material (Alarcón et al., 2021). Thus, our results suggest that increasing cleaning effectiveness has a limited impact on reducing the number of vehicle movements for pathogens that exhibit prolonged stability in the environment.

**Final statements and limitations**

We identified a number of limitations related to the methodology implemented to reconstruct the vehicle movement network. First, the absence of vehicle movements from all swine companies in both study regions. It is worth noticing that the VBD and VVT values represent the level of uncertain we introduced
in this study, it is possible that contaminated vehicles continue to disseminate disease in the event the truck stop at further distances from the farm premise (e.g., 500 meters or 10 km). Such transmission could occur via air or carried into farms by caretakers (Dee et al., 2009; Otake et al., 2010; Seedorf and Schmidt, 2017). We assumed 60 minutes was sufficient effectively clean and disinfect a vehicle (Personal communication). However, this may not be the same in regions, especially in region two to the increase in weather events. In addition, crew-vehicles and undefined-vehicles clean, and disinfection might take place at regular cleaning stations at gas stations or with other third parties, data that we did not have access to. Another limitation is related to the cleaning and disinfection methods used in each one of the clean stations (e.g., high pressure, hot water), which may have a direct impact on the cleaning effectiveness of each clean station (De Lorenzi et al., 2020). Finally, we remark that our methodology does not consider the trailer in the vehicle movement, because vehicles may use different trailers, and companies do not collect GPS data for trailers. Despite that, the movement of trailers also represents a high risk for disease transmission (Lowe et al., 2014; Boniotti et al., 2018) and should be included in future studies. Similarly, drivers with contaminated boots have been indicated as a potential source of transmission (Dee et al., 2002), also Perri, et al., 2020, showed that vehicle drivers may step out the truck when at farms (Perri et al., 2020); thus, the between-farm movement of drivers should also be included in future studies.

Regarding pathogen stability, our main limitation was the use of soil as a reference material for ASF stability (Mazur-Panasiuk and Woźniakowski, 2020), which is not the only material found on vehicle's surfaces (Dee et al., 2002). There are other studies that evaluate ASF stability in different materials (Nuanualsuwan et al., 2022), but we decided to use findings by Mazur-Panasiuk and Woźniakowski, 2020, because the study provided a wide range of metrics that allowed us to develop an adequate decay curve. However, future studies may compare the vehicle movement network using different pathogen stability results. Similarly, our methodology uses a decay rate for each temperature, and such information was not available in the literature that in most cases is restricted to two temperature degrees (warm and cold) (Carlson et al., 2020; Mazur-Panasiuk and Woźniakowski, 2020; Nuanualsuwan et al., 2022). Despite the limitations, this is the first study that recreates between-farm networks from actual vehicle movement data.
from different companies, while also considering pathogen stability and uncertainty in the cleaning and disinfection. This study is unique because it provides the swine industry and regulatory agencies with valuable information about the role that vehicles may play in the dynamic of between-farm swine diseases, offering an opportunity to design adequate control strategies for future threats.

6. Conclusion
We expanded a previously developed methodology to identify vehicle movements among farms (Galvis, Corzo and Machado, 2022), in this new study, we account for uncertainty in vehicle cleaning and disinfection and pathogen stability decay based on environmental temperatures. Our results demonstrate that 100% cleaning effectiveness reduces the number of between-farm contacts of all vehicle network types. In addition, a 100% cleaning effectiveness reduces mostly between-farm contacts with low pathogen stability (<0.2), while it did not reduce significantly the number of contacts when pathogen stability was still high (>0.8). We observed that vehicles contacted farms from different companies, which increased the risk of transmission among companies. Ultimately, this study provides a better understanding of the role of transportation vehicles for ASF dissemination, and potentially other diseases affecting the swine industry. Thus, this new methodology could be utilized to design new disease control strategies which could include disease spread simulation scenarios, identify hub farms to increase disease surveillance and movement redirection.

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Authors’ contributions
JAG and GM conceived the study, participated in the design of the study, and coordinated the data collection. JAG conducted data processing, cleaning, designing the model, and simulated scenarios. JAG
designed the computational analysis. JAG and GM wrote and edited the manuscript. Both authors discussed the results and critically reviewed the manuscript. GM secured the funding.

**Conflict of interest**

All authors confirm that there are no conflicts of interest to declare.

**Ethical statement**

The authors confirm the ethical policies of the journal, as noted on the journal’s author guidelines page. Since this work did not involve animal sampling nor questionnaire data collection by the researchers, there was no need for ethics permits.

**Data Availability Statement**

The data that support the findings of this study are not publicly available and are protected by confidential agreements, therefore, are not available.

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Role of vehicle movement in swine disease dissemination

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Section 1. Transportation vehicle movements networks and network metrics.

Figure S1. On-farm biosecurity plan components, the perimeter buffer area (PBA) represented by blue polygons.

Figure S2. Simulated relationship among temperature and time of African swine fever virus stability on vehicle surfaces. Exponential decay curve for each temperature, vertical lines represent ASF stability, half-time and D-value (90% decay) described by (Mazur-Panasiuk and Woźniakowski, 2020).

Table S1. Production types defined for the farm units in region 1 and 2.
| Farm type                        | Region one | Region two |
|---------------------------------|------------|------------|
| **Boar stud**                   | 23         | 16         |
| **Finisher**                    | 1371       | 2,265      |
| **Gilt**                        | 15         | 46         |
| **Gilt-finisher**               | 3          | 1          |
| **Gilt-nursery**                | 1          | 0          |
| **Gilt-sow**                    | 106        | 46         |
| **Gilt-sow-nursery**            | 1          | 0          |
| **Gilt-sow-boar stud**          | 0          | 35         |
| **Gilt-sow-finisher-boar stud** | 0          | 1          |
| **Gilt-sow-nursery-finisher**   | 0          | 1          |
| **Gilt-sow-wean**               | 0          | 1          |
| **Gilt-sow-wean-boar stud**     | 0          | 7          |
| **Isolation**                   | 0          | 6          |
| **Nursery**                     | 546        | 403        |
| **Nursery-finisher**            | 22         | 253        |
| **Sow**                         | 183        | 314        |
| Material                  | Temperature (℃) | Time     | Reference                        |
|---------------------------|-----------------|----------|----------------------------------|
| Sow-finisher              | 4               | 1        |                                  |
| Sow-nursery               | 10              | 3        |                                  |
| Sow-nursery-finisher      | 15              | 6        |                                  |
| Sow-nursery-finisher-isolation | 1          | 0        |                                  |
| Sow-nursery-isolation     | 1               | 0        |                                  |
| Sow-wean                  | 0               | 1        |                                  |
| Wean                      | 214             | 1,206    |                                  |
| Wean-finisher             | 3               | 7        |                                  |

**Table S2. Stability of ASF at different temperatures**

- **Soil**
  - 25  3 days  (Carlson et al., 2020)
  - -4  7 days

- **Soil**
  - 23  9 days  (Mazur-Panasiuk and Woźniakowski, 2020)
  - 4  32 days

- **Soil - half-life**
  - 23  0.44 days
  - 4  1.88 days

- **Soil-decay 90%**
  - 23  1.48 days
  - 4  6.26 days
| Material | Metric | Description | Reference |
|----------|--------|-------------|-----------|
| Metal    | Node   | Element of the network representing the farms. | - |
|          | Edge   | Link among two nodes. | - |
| Glass    | Static network | Once an edge exists between two nodes, it is present for the whole time period. | (Kao et al., 2007) |
| Rubber   | Temporal network | The edges between two nodes only exist at different time steps. | (Lentz et al., 2016) |
|          | Density | Represent the proportion of edges among nodes in the network that are actually present. | (Wasserman and Faust, 1994) |
|          | In-degree | Number of nodes providing animals to a specific node. | (Wasserman and Faust, 1994) |
|          | Out-degree | Number of nodes obtaining animals from a specific node. | (Wasserman and Faust, 1994) |
|          | Degree centralization | It is a graph-level centrality | (Wasserman and Faust, 1994) |
score based on degree node-level centrality. It equals 1 when one node chooses all other nodes in the network (star graph). It equals 0 when all degrees are equal (circle graph).

Betweenness centralization
It is a graph-level centrality score based on betweenness node-level centrality. The score takes on values between 0 and 1. The maximum score is reached when one node has the largest possible betweenness, while the others the smallest possible (star graph).

(Wasserman and Faust, 1994)

Outgoing contact chain (OCC)
Subsets of nodes that can be reached by a specific node by direct contact or indirect contacts through a sequential order of edges through other nodes using the temporal network.

(Nöremark and Widgren, 2014)

Section 2. Vehicle visits

Table S4. Number of farm units visited vehicles for one year.

| VBD/VVT            | 5 minutes (IQR25%-IQR75%) | 20 minutes (IQR25%-IQR75%) | 60 minutes (IQR25%-IQR75%) |
|--------------------|----------------------------|-----------------------------|-----------------------------|
| 50 meters (IQR25%-IQR75%) | 252,355 (R1) 13,016 (R2) | 191,349 (R1) 12,482 (R2) | 47,847 (R1) 6,951 (R2)   |
| 100 meters (IQR25%-IQR75%) | 262,114 (R1) 13,834 (R2) | 199,012 (R1) 13,218 (R2) | 50,335 (R1) 7,365 (R2)   |
| 300 meters (IQR25%-IQR75%) | 301,774 (R1) 15,094 (R2) | 229,747 (R1) 14,394 (R2) | 58,940 (R1) 7,944 (R2)   |

(R1) = region one; (R2) = region two
Figure S3. Frequency of farm units visited by different vehicles from company A, B and G from January to December 2020. The y-axis represents the number of farm units visited, box plot fill colors represent the vehicle’s transportation type and are grouped by region one (R1) and region two (R2). The columns and rows represent the three different vehicle buffer distances (VBD) and three vehicle visit time (VVT).

Table S5. Number and proportion of farm units visited by vehicles from different companies.

| Companies of origin | Companies of origin | VBD   | VVT > 5 minutes | VVT > 20 minutes | VVT > 60 minutes |
|---------------------|---------------------|-------|-----------------|------------------|------------------|
| A                   | B-F                 | <50 meters | 11 (2.7%) | 10 (2.4%) | 6 (1.4%) |
| A                   | B-F                 | <100 meters | 11 (2.6%) | 10 (2.4%) | 6 (1.4%) |
| A                   | B-F                 | <300 meters | 16 (3.9%) | 14 (3.4%) | 7 (1.7%) |
| B                   | A and C-F           | <50 meters | 2 (0.1%)  | 2 (0.1%)  | 2 (0.1%)  |
| B                   | A and C-F           | <100 meters | 3 (0.1%)  | 3 (0.1%)  | 2 (0.1%)  |
| B                   | A and C-F           | <300 meters | 19 (0.9%) | 16 (0.7%) | 13 (0.6%) |
| G                   | H-S                 | <50 meters | 9 (0.2%)  | 9 (0.2%)  | 6 (0.15%) |
| G                   | H-S                 | <100 meters | 10 (0.2%) | 10 (0.2%) | 7 (0.17%) |
| G                   | H-S                 | <300 meters | 12 (0.3%) | 11 (0.3%) | 8 (0.2%)  |
Figure S4. Vehicle visit frequency company by farm type

Figure S5. Vehicle visit frequency company by farm type
Figure S6. Vehicle visit frequency company by farm type

Figure S7. Vehicle visit frequency company by farm type
Figure S8. Vehicle visit frequency company by farm type

Figure S9. Vehicle visit frequency company by farm type
**Figure S10. Vehicle visit frequency company by farm type**

![Graph showing vehicle visit frequency by farm type for different distances and visit times.](image)

**Figure S11. Vehicle visit frequency company by farm type**

![Graph showing vehicle visit frequency by farm type for different distances and visit times.](image)
Figure S12. Vehicle visit frequency company by farm type

VBD = 300 meters and VVT = 60 minutes

Figure S13. The frequency of vehicle visits to cleaning stations. The y-axis represents the number of cleaning stations for each vehicle in 12 months. Vehicle types are grouped in region one (R1) and region two (R2).
Figure S14. The ratio of vehicles visiting farms and cleaning stations. The y-axis represents the ratio of the number of farms divided by the number of clean stations visited by each vehicle for one year. Vehicle transporting role types in the legend are grouped in region 1 (R1) and region 2 (R2).
Figure S15. Ratio of vehicles visiting farms and cleaning stations. The y-axis represents the ratio of the number of farms divided by the number of clean stations visited by each vehicle for one year. Vehicle transporting role types in the legend are grouped in region 1 (R1) and region 2 (R2). The y-axis maximum was limited to 80 to avoid distortion created by the outliers.

Table S6. The ratio of vehicles transporting feed visiting farm units and cleaning stations.

| VBD/VVT          | 5 minutes (IQR25%-IQR75%) | 20 minutes (IQR25%-IQR75%) | 60 minutes (IQR25%-IQR75%) |
|------------------|----------------------------|----------------------------|----------------------------|
| 50 meters (IQR25%-IQR75%) | 2.9 (2.1-10.6) (R1) | 4 (1.8-10.8) (R1) | 0.5 (0.1-2.5) (R1) |
| 100 meters (IQR25%-IQR75%) | 3 (2.1-10.9) (R1) | 4.1 (1.8-10.9) (R1) | 0.5 (0.1-2.5) (R1) |
| 300 meters (IQR25%-IQR75%) | 3.3 (2.3-12.1) (R1) | 4.4 (2-12.7) (R1) | 0.5 (0.1-2.7) (R1) |

(R1) = region 1; (R2) = region 2

Table S7. The ratio of vehicles transporting pigs to farms, visiting farm units, and cleaning stations.

| VBD/VVT          | 5 minutes (IQR25%-IQR75%) | 20 minutes (IQR25%-IQR75%) | 60 minutes (IQR25%-IQR75%) |
|------------------|----------------------------|----------------------------|----------------------------|
| 50 meters (IQR25%-IQR75%) | 2.4 (1.8-2.9) (R1) | 2.5 (1.7-3) (R1) | 0.8 (0.6,1.1) (R1) |
### Table S8. The ratio of vehicles transporting pigs to market, visiting farm units and cleaning stations.

| VBD/VVT            | 5 minutes (IQR25%-%75%) | 20 minutes (IQR25%-%75%) | 60 minutes (IQR25%-%75%) |
|--------------------|-------------------------|--------------------------|--------------------------|
| 50 meters (IQR25%-%75%) | 1.3 (1.2-1.5) (R1)    | 1.7 (1.4-1.8) (R1)    | 1 (0.9,1.2) (R1)          |
| 100 meters (IQR25%-%75%) | 1.4 (1.3-1.6) (R1)  | 1.7 (1.6-1.9) (R1)  | 1.1 (0.9-1.3) (R1)         |
| 300 meters (IQR25%-%75%) | 1.6 (1.5-1.8) (R1)  | 2 (1.8-2.2) (R1)  | 1.3 (1-1.5) (R1)           |

(R1) = region 1; (R2) = region 2

### Table S9. The ratio of vehicles transporting crew visiting farm units and cleaning stations.

| VBD/VVT            | 5 minutes (IQR25%-%75%) | 20 minutes (IQR25%-%75%) | 60 minutes (IQR25%-%75%) |
|--------------------|-------------------------|--------------------------|--------------------------|
| 50 meters (IQR25%-%75%) | 1.6 (1.6-1.6) (R1)    | 0.4 (0.4-0.4) (R1)    | 0 (R1)                   |
| 100 meters (IQR25%-%75%) | 1.6 (1.6-1.6) (R1)  | 0.4 (0.4-0.4) (R1)  | 0 (R1)                   |
| 300 meters (IQR25%-%75%) | 1.6 (1.6-1.6) (R1)  | 0.4 (0.4-0.4) (R1)  | 0 (R1)                   |

(R1) = region 1; (R2) = region 2

### Table S10. The ratio of undefined vehicles visiting farm units and cleaning stations.

| VBD/VVT            | 5 minutes (IQR25%-%75%) | 20 minutes (IQR25%-%75%) | 60 minutes (IQR25%-%75%) |
|--------------------|-------------------------|--------------------------|--------------------------|
| 50 meters (IQR25%-%75%) | 4.4 (2.2-27.7) (R1) | 6.8 (2.7-69.3) (R1) | 7.3 (2.1-48.4) (R1) |
|                    | 1.6 (1.3-2.1) (R2) | 1.6 (1.4-2.1) (R2) | 1 (0.8-1.3) (R2)       |
|                  | 100 meters (IQR25% - IQR75%) | 300 meters (IQR25% - IQR75%) |
|------------------|-------------------------------|-----------------------------|
|                  | 4.6 (2.4-30.2) (R1) 1.6 (1.4-2.2) (R2) | 5.2 (2.8-34.6) (R1) 1.7 (1.5-2.3) (R2) |
|                  | 6.7 (2.7-71) (R1) 1.7 (1.4-2.3) (R2) | 7.5 (3.3-80.1) (R1) 1.8 (1.5-2.5) (R2) |
|                  | 7.6 (2.2-58) (R1) 1.1 (0.9-1.4) (R2) | 7.9 (2.6-64.8) (R1) 1.2 (0.9-1.4) (R2) |

(R1) = region 1; (R2) = region 2
### Section 3. Vehicle batch network

#### Table S11. Network metric of vehicle movements networks.

| Metric     | d (%) | Combined vehicles (R1) | Feed-vehicle (R1) | Pig-vehicle (R1) | Market-vehicle (R1) | Undefined (R1) | Crew-vehicle (R1) | Undefined (R2) |
|------------|-------|------------------------|-------------------|------------------|---------------------|-----------------|-------------------|-----------------|
| Nodes      | 0     | 2,159 (2,159-2,159)    | 2,151 (2,151-2,151) | 2,103 (2,103-2,103) | 1,618 (1,618-1,618) | 1,848 (1,848-1,848) | 7 (7-7)           | 450 (450-450)  |
|            | 10    | 2,159 (2,159-2,159)    | 2,151 (2,151-2,151) | 2,103 (2,103-2,103) | 1,617 (1,617-1,618) | 1,848 (1,848-1,848) | 7 (7-7)           | 450 (450-450)  |
|            | 50    | 2,158 (2,158-2,158)    | 2,151 (2,151-2,151) | 2,103 (2,103-2,103) | 1,617 (1,616-1,617) | 1,848 (1,848-1,848) | 7 (7-7)           | 449 (448-449)  |
|            | 80    | 2,159 (2,158-2,159)    | 2,151 (2,151-2,151) | 2,103 (2,103-2,103) | 1,613 (1,612-1,614) | 1,847 (1,847-1,848) | 7 (6-7)           | 447 (446-448)  |
|            | 90    | 2,158 (2,158-2,158)    | 2,151 (2,151-2,151) | 2,101 (2,101-2,101) | 1,607 (1,606-1,608) | 1,847 (1,847-1,847) | 6 (6-6)           | 444 (444-444)  |
|            | 100   | 2,158 (2,158-2,158)    | 2,151 (2,151-2,151) | 2,101 (2,101-2,101) | 1,593 (1,593-1,593) | 1,847 (1,847-1,847) | 6 (6-6)           | 442 (442-442)  |
| Edge static| 0     | 1,232,684 (1,232,684-1,232,684) | 1,018,941 (1,018,941-1,018,941) | 207,232 (207,232-207,232) | 139,786 (139,786-139,786) | 290,960 (290,960-290,960) | 23 (23-23)        | 21,385 (21,385-21,385) |
|            | 10    | 1,161,367 (1,160,572-1,161,602) | 963,302 (962,734-963,416) | 185,566 (185,172-185,596) | 116,278 (116,160-116,305) | 270,083 (269,998-270,761) | 21 (19-22)        | 19,131 (19,124-19,170) |
|    | 50   | 80   | 90   | 100  | Edge temporal |
|----|------|------|------|------|--------------|
|    | 954,686 (954,596-954,724) | 812,866 (812,846-813,090) | 106,731 (106,541-106,798) | 53,642 (53,581-53,810) | 228,591 (228,084-228,951) | 13 (12-13) | 11,300 (11,212-11,306) |
|    | 850,690 (850,674-850,828) | 741,903 (741,604-741,990) | 61,236 (61,138-61,246) | 29,107 (29,078-29,142) | 211,415 (211,381-221,724) | 11 (9-11) | 6,616 (6,585-6,626) |
|    | 821,359 (821,326-821,369) | 721,863 (721,770-721,940) | 47,960 (47,934-48,008) | 22,540 (22,512-22,626) | 208,134 (208,074-208,149) | 7 (7-8) | 5,139 (5,096-5,182) |
|    | 793,827 (793,827-793,827) | 703,726 (703,726-703,726) | 34,769 (34,769-34,769) | 16,973 (16,973-16,973) | 204,761 (204,761-204,761) | 7 (7-7) | 3,857 (3,857-3,857) |
| Edge temporal 0 | 5,583,703 (5,583,703-5,583,703) | 3,846,333 (3,846,333-3,846,333) | 841,987 (841,987-841,987) | 359,796 (359,796-359,796) | 535,563 (535,563-535,563) | 24 (24-24) | 128,483 (128,483-128,483) |
|    | 4,675,727 (4,672,705-4,676,375) | 3,249,237 (3,248,208-3,251,449) | 668,302 (668,282-669,956) | 263,821 (263,713-264,188) | 490,620 (490,270-491,469) | 22 (20-23) | 95,267 (94,284-101,021) |
|    | 3,058,907 (3,058,200-3,059,398) | 2,242,281 (2,242,121-2,242,540) | 309,054 (308,383-309,316) | 96,384 (96,352-96,806) | 411,035 (410,399-411,588) | 13 (12-13) | 36,119 (35,949-36,193) |
|    | 2,574,088 (2,574,086-2,574,479) | 1,952,458 (1,951,668-1,952,606) | 187,001 (186,915-187,034) | 51,563 (51,476-51,634) | 383,544 (383,470-383,986) | 11 (9-11) | 20,348 (20,339-20,490) |
| Density | 0     | 0.194343 (0.194343-0.194343) | 0.160644 (0.160644-0.160644) | 0.032672 (0.032672-0.032672) | 0.022038 (0.022038-0.022038) | 0.045872 (0.045872-0.045872) | 4e-06 (4e-06-4e-06) | 0.001003 (0.001003-0.001003) |
|---------|------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|----------------------|--------------------------|
| 10      | 0.183099 (0.182973-0.183136) | 0.151872 (0.151783-0.15189)  | 0.029256 (0.029194-0.029261)  | 0.018332 (0.018314-0.018336)  | 0.042581 (0.042567-0.042688)  | 3e-06 (3e-06-3e-06)  | 0.000897 (0.000897-0.000899) |
| 50      | 0.150514 (0.1505-0.15052)   | 0.128155 (0.128152-0.12819)  | 0.016827 (0.016797-0.016838)  | 0.008457 (0.008447-0.008483)  | 0.036039 (0.035959-0.036096)  | 2e-06 (2e-06-2e-06) | 0.00053 (0.000526-0.00053)   |
| 80      | 0.134118 (0.134116-0.13414) | 0.116967 (0.11692-0.116981)  | 0.009654 (0.009639-0.009656)  | 0.004589 (0.004584-0.004594)  | 0.033331 (0.033326-0.03338)   | 2e-06 (1e-06-2e-06) | 0.00031 (0.000309-0.000311)  |
| 90      | 0.129494 (0.129489-0.129495) | 0.113808 (0.113793-0.11382)  | 0.007561 (0.007557-0.007569)  | 0.003554 (0.003549-0.003567)  | 0.032814 (0.032805-0.032816)  | 1e-06 (1e-06-1e-06) | 0.000241 (0.000239-0.000243) |
| 100     | 0.125153 (0.125153-0.125153) | 0.110948 (0.110948-0.110948) | 0.005482 (0.005482-0.005482)  | 0.002676 (0.002676-0.002676)  | 0.032282 (0.032282-0.032282)  | 1e-06 (1e-06-1e-06) | 0.000181 (0.000181-0.000181) |
| In-degree | 0    | 476 (476-476) | 338 (338-338) | 63 (63-63) | 38 (38-38) | 100 (100-100) | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|-----------|------|---------------|---------------|------------|------------|----------------|----------------|----------------|
|           | 10   | 448 (447-448) | 327 (326-327) | 56 (56-56) | 31 (31-31) | 91 (90-91)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 50   | 370 (370-370) | 288 (287-288) | 30 (30-30) | 14 (14-14) | 64 (63-64)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 80   | 329 (328-329) | 260 (259-260) | 17 (17-17) | 7 (7-7)    | 51 (51-51)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 90   | 317 (317-318) | 250 (249-250) | 14 (14-14) | 5 (5-5)    | 48 (48-48)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 100  | 306 (306-306) | 243 (243-243) | 10 (10-10) | 3 (3-3)    | 46 (46-46)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
| Out-degree| 0    | 477 (477-477) | 336 (336-336) | 61 (61-61) | 38 (38-38) | 100 (100-100) | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 10   | 449 (448-450) | 326 (326-327) | 54 (54-54) | 32 (32-32) | 90 (88-90)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 50   | 368 (368-368) | 286 (286-286) | 28 (28-28) | 13 (13-13) | 63 (63-64)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 80   | 326 (326-326) | 257 (256-258) | 14 (14-14) | 7 (7-7)    | 52 (52-52)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 90   | 312 (312-312) | 247 (247-248) | 11 (10-11) | 5 (5-5)    | 50 (50-50)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
|           | 100  | 299 (299-299) | 239 (239-239) | 7 (7-7)    | 3 (3-3)    | 46 (46-46)    | 0.0 (0.0-0.0) | 0.0 (0.0-0.0) |
| degree centrality | 0    | 0.29823 (0.29823-0.29823) | 0.311481 (0.311481-0.311481) | 0.136366 (0.136366-0.136366) | 0.116809 (0.116809-0.116809) | 0.178384 (0.178384-0.178384) | 0.001586 (0.001586-0.001586) | 0.028995 (0.028995-0.028995) |
| Betweenness centralit y | 10  | 0.300068 (0.299833-0.300303) | 0.311119 (0.311001-0.312003) | 0.128063 (0.126667-0.128721) | 0.099261 (0.098981-0.099654) | 0.16279 (0.15962-0.163904) | 0.001586 (0.001387-0.001586) | 0.026498 (0.025904-0.026663) |
|------------------------|-----|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|
| 50                     | 0.295195 (0.294792-0.296699) | 0.299614 (0.299053-0.300646) | 0.051929 (0.051803-0.052932) | 0.130773 (0.130296-0.13153) | 0.00119 (0.000991-0.00119) | 0.017122 (0.01691-0.017339) |
| 80                     | 0.299087 (0.298467-0.299184) | 0.293887 (0.293429-0.295131) | 0.031573 (0.031563-0.031866) | 0.124881 (0.124538-0.125228) | 0.000793 (0.000694-0.000992) | 0.012902 (0.012739-0.013066) |
| 90                     | 0.299934 (0.298741-0.300237) | 0.294599 (0.293679-0.294783) | 0.026242 (0.024441-0.027141) | 0.125099 (0.1246-0.125108) | 0.000595 (0.000595-0.000595) | 0.012209 (0.011996-0.012319) |
| 100                    | 0.299708 (0.299708-0.299708) | 0.293855 (0.293855-0.293855) | 0.043583 (0.043583-0.043583) | 0.123645 (0.123645-0.123645) | 0.000595 (0.000595-0.000595) | 0.01184 (0.01184-0.01184) |
| Betweenness centralit y | 0   | 0.05903 (0.05903-0.05903)    | 0.066982 (0.066982-0.066982) | 0.091472 (0.091472-0.091472) | 0.047358 (0.047358-0.047358) | 0.025259 (0.025259-0.025259) | 0.0 (0.0-0.0) | 0.000964 (0.000964-0.000964) |
| 10                     | 0.061604 (0.061105-0.061623) | 0.063927 (0.062793-0.064351) | 0.091432 (0.091428-0.091446) | 0.044994 (0.044941-0.045762) | 0.025346 (0.024607-0.025874) | 0.0 (0.0-1e-06) | 0.000983 (0.000906-0.00103) |
| 50                     | 0.064725 (0.064494-0.064809) | 0.060491 (0.060158-0.061634) | 0.091187 (0.091001-0.091556) | 0.044643 (0.044326-0.050244) | 0.023347 (0.023119-0.023509) | 1e-06 (0.0-1e-06) | 0.000799 (0.000731-0.000917) |
| 80                     | 0.064081 | 0.063127 | 0.091817 | 0.046029 | 0.026783 | 1e-06 (0.0-1e-06) | 0.000998 |
| Metri  | $d$ (%) | Combined vehicles (R1) (%) | Feed-vehicle (R1) (%) | Pig-vehicle (R1) (%) | Market-vehicle (R1) (%) | Undefined (R1) (%) | Crew-vehicle (R1) (%) | Undefined (R2) (%) |
|--------|---------|---------------------------|----------------------|---------------------|------------------------|---------------------|----------------------|---------------------|
| Nodes  | 0       | 0                         | 0                    | 0                   | 0                      | 0                   | 0                    | 0                   |
|        | 10      | 0                         | 0                    | 0                   | 0.06                   | 0                   | 0                    | 0                   |
|        | 50      | 0.05                      | 0                    | 0                   | 0.06                   | 0                   | 0                    | 0.22                |
|        | 80      | 0                         | 0                    | 0                   | 0.31                   | 0.05                | 0                    | 0.67                |
|        | 90      | 0.05                      | 0                    | 0.1                 | 0.68                   | 0.05                | 14.29                | 1.33                |
|        | 100     | 0.05                      | 0                    | 0.1                 | 1.55                   | 0.05                | 14.29                | 1.78                |

Table S12. Cumulative reduction of network metrics as cleaning effectiveness ($d$) increase
| Edge static | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|-------------|----|----|----|----|----|----|----|----|
| 10          | 5.79 | 5.46 | 10.45 | 16.82 | 7.18 | 8.7 | 10.54 |
| 50          | 22.55 | 20.22 | 48.5 | 61.63 | 21.44 | 43.48 | 47.16 |
| 80          | 30.99 | 27.19 | 70.45 | 79.18 | 27.34 | 52.17 | 69.06 |
| 90          | 33.37 | 29.16 | 76.86 | 83.88 | 28.47 | 69.57 | 75.97 |
| 100         | 35.6 | 30.94 | 83.22 | 87.86 | 29.63 | 69.57 | 81.96 |
| Edge temporal | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 10          | 16.26 | 15.52 | 20.63 | 26.67 | 8.39 | 8.33 | 25.85 |
| 50          | 45.22 | 41.7 | 63.29 | 73.21 | 23.25 | 45.83 | 71.89 |
| 80          | 53.9 | 49.24 | 77.79 | 85.67 | 28.38 | 54.17 | 84.16 |
| 90          | 55.88 | 51 | 81.13 | 88.5 | 29.38 | 70.83 | 86.82 |
| 100         | 57.54 | 52.46 | 83.95 | 90.68 | 30.29 | 70.83 | 88.84 |
| Density     | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 10          | 5.78 | 5.46 | 10.44 | 16.83 | 7.17 | 0  | 10  |
| 50          | 22.55 | 20.23 | 48.48 | 61.62 | 21.43 | 0  | 47  |
| 80          | 30.99 | 27.19 | 70.46 | 79.17 | 27.34 | 0  | 69  |
| 90          | 33.37 | 29.15 | 76.86 | 83.89 | 28.47 | 0  | 76  |
|     |     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|-----|
| **In-degree** |     |     |     |     |     |     |     |
| 100 | 35.6| 30.93| 83.23| 87.84| 29.63| 0   | 82  |
| 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 10  | 5.88| 3.25| 11.11| 18.42| 9    | 0   | 0   |
| 50  | 22.27| 14.79| 52.38| 63.16| 36   | 0   | 0   |
| 80  | 30.88| 23.08| 73.02| 81.58| 49   | 0   | 0   |
| 90  | 33.4 | 26.04| 77.78| 86.84| 52   | 0   | 0   |
| 100 | 35.71| 28.11| 84.13| 92.11| 54   | 0   | 0   |
| **Out-degree** |     |     |     |     |     |     |     |
| 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 10  | 5.87| 2.98| 11.48| 15.79| 10   | 0   | 0   |
| 50  | 22.85| 14.88| 54.1  | 65.79| 37   | 0   | 0   |
| 80  | 31.66| 23.51| 77.05| 81.58| 48   | 0   | 0   |
| 90  | 34.59| 26.49| 81.97| 86.84| 50   | 0   | 0   |
| 100 | 37.32| 28.87| 88.52| 92.11| 54   | 0   | 0   |
Table S13. Proportion of edges in each pathogen stability category.

| $d$ (%) | Pathogen stability | Combined vehicles (R1) | Feed-vehicle (R1) | Pig-vehicle (R1) | Market-vehicle (R1) | Undefined (R1) | Crew-vehicle (R1) | Undefined (R2) |
|---------|--------------------|------------------------|-------------------|------------------|---------------------|-----------------|------------------|-----------------|
| 0       | 1-0.8              | 6.080015               | 5.172381          | 10.40432         | 5.621519            | 6.107031        | 29.16667         | 5.427177        |
|         | 0.8-0.6            | 4.938855               | 5.197704          | 3.899585         | 4.738241            | 4.848729        | 0                | 4.358553        |
|         | 0.6-0.4            | 6.20907                | 6.588587          | 4.446981         | 6.002568            | 6.392712        | 0                | 4.690893        |
|         | 0.4-0.2            | 10.57021               | 10.2572           | 12.05648         | 11.02013            | 10.17901        | 16.6667          | 10.89249        |
|         | 0.2-0              | 72.20185               | 72.78413          | 69.19264         | 72.61754            | 72.47252        | 54.1667          | 74.63089        |
| 10      | 1-0.8              | 7.212205               | 6.068686          | 13.09752         | 7.538824            | 6.642004        | 31.81818         | 7.303683        |
|         | 0.8-0.6            | 5.678347               | 5.932839          | 4.692489         | 6.007103            | 5.191187        | 0                | 5.589554        |
|         | 0.6-0.4            | 6.927393               | 7.330059          | 5.000135         | 7.212466            | 6.756961        | 0                | 5.76695         |
|         | 0.4-0.2            | 11.44774               | 11.09962          | 13.32242         | 12.75941            | 10.56765        | 18.18182         | 12.96776        |
|         | 0.2-0              | 68.7232                | 69.58588          | 63.89282         | 66.53337            | 70.86544        | 50               | 68.37625        |
| 50      | 1-0.8              | 10.73769               | 8.494564          | 28.23099         | 19.23556            | 7.811744        | 53.84615         | 18.98724        |
|         | 0.8-0.6            | 7.402023               | 7.416778          | 8.23513          | 11.50917            | 5.729196        | 0                | 10.63429        |
|     | 0.6-0.4 | 0.4-0.2 | 0.2-0   | 80     | 0.8-0.6 | 0.6-0.4 | 0.4-0.2 | 0.2-0   | 90     | 0.8-0.6 | 0.6-0.4 | 0.4-0.2 | 0.2-0   | 100    | 0.8-0.6 | 0.6-0.4 |
|-----|---------|---------|---------|--------|---------|---------|---------|---------|--------|---------|---------|---------|---------|--------|---------|---------|
| 0.6-0.4 | 8.096258 | 8.428203 | 5.948151 | 10.8047 | 7.209362 | 0 | 8.757164  | 12.16278 | 11.78755 | 15.12616 | 16.4851 | 10.81781 | 30.76923 | 17.49218 |
| 0.4-0.2 | 12.16278 | 11.78755 | 15.12616 | 16.4851 | 10.81781 | 30.76923 | 17.49218 |
| 0.2-0   | 61.61191 | 63.86314 | 42.33791 | 41.98518 | 68.44989 | 15.38462 | 43.79966 |
| 80     | 12.50532 | 9.502637 | 46.52649 | 34.09615 | 8.284578 | 63.63636 | 33.46766 |
| 0.8-0.6 | 7.76811 | 7.602263 | 11.55181 | 15.48785 | 5.753447 | 0 | 14.03086 |
| 0.6-0.4 | 7.853617 | 8.209805 | 4.898904 | 10.67238 | 7.093058 | 0 | 8.590525 |
| 0.4-0.2 | 11.16085 | 11.16782 | 11.4748  | 14.35332 | 10.57063 | 9.090909 | 15.41675 |
| 0.2-0   | 60.71704 | 63.51353 | 25.60307 | 25.35733 | 68.36556 | 9.090909 | 28.91685 |
| 90     | 12.97483 | 9.748369 | 54.73418 | 41.7136 | 8.377599 | 100  | 40.13585 |
| 0.8-0.6 | 7.769318 | 7.567386 | 12.72204 | 16.69849 | 5.730399 | 0 | 14.92026 |
| 0.6-0.4 | 7.640466 | 8.042463 | 3.788098 | 9.706344 | 7.026237 | 0 | 8.446545 |
| 0.4-0.2 | 10.7131 | 10.92216 | 8.592147 | 11.96616 | 10.43333 | 0 | 12.95924 |
| 0.2-0   | 60.90305 | 63.72111 | 20.24096 | 20.09426 | 68.41922 | 0 | 23.4554 |
| 100    | 13.39553 | 9.961583 | 64.27763 | 50.55191 | 8.454209 | 100  | 47.25865 |
| 0.8-0.6 | 7.725769 | 7.50456 | 13.93991 | 17.5537 | 5.676945 | 0 | 15.30413 |
| 0.6-0.4 | 7.418633 | 7.879875 | 2.306674 | 8.111575 | 6.94825 | 0 | 7.896205 |
| Pathogen stability | d (%) | Combined vehicles (R1) | Feed-vehicle (R1) | Pig-vehicle (R1) | Market-vehicle (R1) | Undefined (R1) | Crew-vehicle (R1) | Undefined (R2) |
|--------------------|-------|------------------------|------------------|-----------------|----------------------|----------------|------------------|-----------------|
| 1-0.8              | 0     | 339,490 (339,490-339,490) | 198,947 (198,947-198,947) | 87,603 (87,603-87,603) | 20,226 (20,226-20,226) | 32,707 (32,707-32,707) | 7 (7-7) | 6,973 (6,973-6,973) |
|                    | 10    | 337,223 (337,200-337,260) | 197,186 (197,169-197,247) | 87,531 (87,531-87,532) | 19,889 (19,882-19,895) | 32,587 (32,581-32,598) | 7 (7-7) | 6,958 (6,956-7,564) |
|                    | 50    | 328,456 (328,418-328,494) | 190,472 (190,456-190,566) | 87,249 (87,241-87,267) | 18,540 (18,539-18,556) | 32,109 (32,101-32,132) | 7 (7-7) | 6,858 (6,856-6,864) |
|                    | 80    | 321,898 (321,837-321,917) | 185,535 (185,463-185,535) | 87,005 (87,001-87,022) | 17,581 (17,580-17,594) | 31,775 (31,774-31,775) | 7 (7-7) | 6,810 (6,803-6,822) |
|                    | 90    | 319,608 (319,598-319,633) | 183,732 (183,718-183,736) | 86,954 (86,944-86,960) | 17,259 (17,245-17,263) | 31,685 (31,675-31,692) | 7 (7-7) | 6,795 (6,791-6,796) |

Table S14. Number of edges according the pathogen stability categories.
|       | 100   | 0.8-0.6 | 10    | 50    | 80    | 90    | 100   | 0.6-0.4 | 10    |
|-------|-------|---------|-------|-------|-------|-------|-------|---------|-------|
|       | 317,556 (317,556-317,556) | 182,157 (182,157-182,157) | 86,886 (86,886-86,886) | 16,945 (16,945-16,945) | 31,561 (31,561-31,561) | 7 (7-7) | 6,775 (6,775-6,775) | 0.0 (0.0-0.0) | 5,600 (5,600-5,600) |
| 0     | 275,771 (275,771-275,771) | 199,921 (199,921-199,921) | 32,834 (32,834-32,834) | 17,048 (17,048-17,048) | 25,968 (25,968-25,968) | 0.0 (0.0-0.0) | 5,325 (5,260-5,689) | 0.0 (0.0-0.0) | 3,841 (3,834-3,880) |
| 10    | 265,504 (265,332-265,584) | 192,772 (192,712-192,861) | 31,360 (31,320-31,408) | 15,848 (15,804-15,860) | 25,469 (25,440-25,484) | 0.0 (0.0-0.0) | 5,325 (5,260-5,689) | 0.0 (0.0-0.0) | 3,841 (3,834-3,880) |
| 50    | 226,421 (226,209-226,504) | 166,305 (166,126-166,376) | 25,451 (25,446-25,538) | 11,093 (11,084-11,110) | 23,549 (23,449-23,572) | 0.0 (0.0-0.0) | 3,841 (3,834-3,880) | 0.0 (0.0-0.0) | 2,855 (2,850-2,870) |
| 80    | 199,958 (199,894-200,098) | 148,431 (148,325-148,486) | 21,602 (21,574-21,620) | 7,986 (7,922-8,008) | 22,067 (22,049-22,073) | 0.0 (0.0-0.0) | 2,855 (2,850-2,870) | 0.0 (0.0-0.0) | 2,526 (2,515-2,530) |
| 90    | 191,381 (191,378-191,450) | 142,626 (142,604-142,670) | 20,211 (20,172-20,237) | 6,909 (6,874-6,932) | 21,673 (21,662-21,695) | 0.0 (0.0-0.0) | 2,526 (2,515-2,530) | 0.0 (0.0-0.0) | 2,194 (2,194-2,194) |
| 100   | 183,148 (183,148-183,148) | 137,228 (137,228-137,228) | 18,843 (18,843-18,843) | 5,884 (5,884-5,884) | 21,193 (21,193-21,193) | 0.0 (0.0-0.0) | 2,194 (2,194-2,194) | 0.0 (0.0-0.0) | 2,194 (2,194-2,194) |
| 0     | 346,696 (346,696-346,696) | 253,419 (253,419-253,419) | 37,443 (37,443-37,443) | 21,597 (21,597-21,597) | 34,237 (34,237-34,237) | 0.0 (0.0-0.0) | 6,027 (6,027-6,027) | 0.0 (0.0-0.0) | 5,494 (5,457-5,930) |
| 10    | 323,906 | 238,171 | 33,416 | 19,028 | 33,151 | 0.0 (0.0-0.0) | 5,494 (5,457-5,930) | 0.0 (0.0-0.0) | 5,494 (5,457-5,930) |
|   | 50 (247,370-247,667) | 80 (202,027-202,226) | 90 (188,157-188,343) | 100 (175,867-175,867) | 0.4-0.2 | 10 (535,125-535,328) | 50 (371,605-372,256) | 80 (287,140-287,290) |
|---|----------------------|----------------------|----------------------|----------------------|---------|----------------------|----------------------|----------------------|
| 50| 247,657              | 202,159              | 188,207              | 175,867              | 590,209 | 535,265              | 372,048              | 287,290              |
|   | (247,370-247,667)   | (202,027-202,226)   | (188,157-188,343)   | (175,867-175,867)   | (590,209-590,209) | (535,125-535,328) | (371,605-372,256)   | (287,140-287,290)   |
|   | 188,984 (188,841-189,061) | 160,293 (160,216-160,306) | 151,580 (151,571-151,704) | 144,091 (144,091-144,091) | 394,526 (394,526-394,526) | 360,653 (360,392-360,752) | 264,310 (264,185-264,512) | 218,047 (217,894-218,047) |
|   | 18,383 (18,360-18,475) | 9,161 (9,054-9,251) | 6,018 (5,954-6,070) | 3,118 (3,118-3,118) | 101,514 (101,514-101,514) | 89,034 (89,030-89,166) | 46,748 (46,723-47,110) | 21,458 (21,320-21,458) |
|   | 10,414 (10,410-10,439) | 5,503 (5,476-5,540) | 4,016 (3,982-4,054) | 2,719 (2,719-2,719) | 39,650 (39,650-39,650) | 33,662 (33,580-33,739) | 15,889 (15,869-16,071) | 7,401 (7,350-7,444) |
|   | 29,633 (29,600-29,730) | 27,205 (27,168-27,244) | 26,574 (26,559-26,596) | 25,939 (25,939-25,939) | 54,515 (54,515-54,515) | 51,847 (51,822-51,930) | 44,465 (44,438-44,630) | 40,543 (40,451-40,543) |
|   | 3,163 (3,156-3,188) | 1,748 (1,744-1,770) | 1,430 (1,407-1,458) | 1,132 (1,132-1,132) | 4 (4-4) | 13,995 (13,995-13,995) | 12,354 (12,211-13,034) | 3,137 (3,099-3,162) |
|    | 287,476) | 218,086) | 21,576) | 40,572) |          |          |
|----|----------|----------|---------|---------|----------|----------|
| 90 | 263,895  | 205,855  | 13,650  | 4,951   | 39,460   | 0.0      |
|    | (263,888-263,996) | (205,666-205,987) | (13,584-13,836) | (4,944-4,968) | (39,402-39,507) |
|    |          |          |         |         | 2,194    | 2,186-2,252 |
| 100| 242,110  | 194,846  | 5,989   | 2,788   | 38,487   | 0.0      |
|    | (242,110-242,110) | (194,846-194,846) | (5,989-5,989) | (2,788-2,788) | (38,487-38,487) |
|    |          |          |         |         | 1,426    | 1,426-1,426 |
| 0.2-0| 0        | 2,799,520| 582,593 | 261,275 | 388,136  | 13      |
|    | (4,031,537-4,031,537) | (2,799,520-2,799,520) | (582,593-582,593) | (261,275-261,275) | (388,136-388,136) |
|    |          |          |         |         | 95,888   | 95,888-95,888 |
| 10 | 3,213,309| 426,997  | 175,529 | 347,680 | 11       | 11      |
|    | (3,211,056-3,214,240) | (426,982-428,070) | (175,458-175,734) | (347,308-348,373) |
|    |          |          |         |         | 65,140   | 64,399-68,806 |
| 50 | 1,884,651| 1,431,991| 130,847 | 40,467  | 2       | 2       |
|    | (1,884,478-1,884,760) | (1,431,864-1,432,563) | (130,397-130,952) | (40,417-40,673) |
|    |          |          |         |         | 15,820   | 15,716-15,926 |
| 80 | 1,562,910| 1,240,075| 47,878  | 13,075  | 1.0      | 1.0     |
|    | (1,562,771-1,563,240) | (1,239,660-1,240,266) | (47,694-47,886) | (13,049-13,138) |
|    |          |          |         |         | 5,884    | 5,798-5,954 |
| 90 | 1,500,220| 1,200,981| 32,156  | 8,314   | 0.0      | 0.0     |
|    | (1,500,027-1,500,640) | (1,200,880-1,201,244) | (32,152-32,192) | (8,273-8,360) |
|    |          |          |         |         | 3,971    | 3,934-4,008 |
| 100| 1,451,931| 1,170,273| 20,337  | 5,184   | 0.0      | 0.0     |
|    | (1,451,931-1,451,931) | (1,170,273-1,170,273) | (20,337-20,337) | (5,184-5,184) |
|    |          |          |         |         | 2,809    | 2,809-2,809 |
Figure S16. Distribution of edge weight from ten different reconstructed vehicle contact networks using a VBD of 50 meters and a VVT of 5 minutes and six cleaning probabilities. Bar graph represent the median values for each clean probability and error line the minimum and maximum ranges for each distribution.
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